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Studying on the Joint Method in Groundwater Exploration in Mountainous Area based on DEM and High-density Resistivity

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Abstract

The distribution of groundwater resources in mountainous areas is uneven, groundwater resources are limited, and the problems of drought and groundwater shortage are serious. It is difficult to explore groundwater in mountainous areas. High-density electrical method is the main method for surveying in mountainous areas. Due to the complex terrain and geological conditions in mountainous areas, it is difficult to determine the groundwater source through field exploration. In order to solve the difficulties of wate exploration in mountainous areas, this article comprehensively uses digital elevation model (DEM) to extract the characteristics of watersheds and high-density electrical method to quickly and accurately determine the characteristics of groundwater systems. Based on the basic characteristics of hydrogeological shallow groundwater recharge, runoff, and discharge, it is jointly used to survey potential locations of groundwater in southern Jiangxi Province, with significant demonstration effects.

Keywords

Groundwater Exploration in Mountainous Areas; Electrical Resistivity Tomography; Extraction of the Digital Watershed Features; DEM.

1. Introduction

Groundwater scarcity in mountainous regions is a widespread issue, primarily arising from climatic factors, geomorphological features, as well as soil and rock strata characteristics. The intricate terrain and significant elevation changes in mountainous areas lead to uneven distribution of groundwater resources, making it difficult to form large-scale water bodies[1]. Furthermore, the existence of infertile soil and impermeable rock layers hinders the formation and storage of groundwater. This water scarcity in mountainous regions has a profound impact on the production and daily lives of local residents.

With the development of remote sensing technology, Digital Elevation Model (DEM) data can be used for terrain analysis in watersheds[2]. DEM serves as the key signal for the identification of watershed terrain and ground features, containing abundant information on landforms, geomorphology, and hydrology[3]. The extracted digital river systems and flow networks are indispensable basic data for digital watersheds. The approach for extracting digital watershed

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characteristics based on DEM involves determining the flow direction of individual grids, connecting the grids into flow networks based on flow directions, and extracting digital river systems and other watershed characteristics. It encompasses research areas such as flow direction analysis, flow path analysis, and watershed characteristic extraction.

High-density electrical method is an array-based exploration technique that relies on the conductivity differences between rocks (ores) to infer and interpret the structure of underground geological bodies by observing and studying the distribution patterns and characteristics of artificial electric fields underground[4]. Compared to traditional resistivity methods, it offers advantages such as high efficiency, rich information, and convenient interpretation, making it effective in solving geological problems.

This article adopts a comprehensive groundwater exploration method that combines watershed feature extraction based on GIS technology with geophysical surveying, fully leveraging the combined advantages to explore high-accuracy and efficient groundwater exploration techniques. We conducted applied research in four counties in southern Jiangxi, jointly utilizing DEM watershed feature extraction and high-density electrical method to locate potential groundwater positions.

2. Joint Groundwater-exploring Method

Changes in surface elevation can affect the flow and storage patterns of groundwater, thereby influencing its distribution and availability. In mountainous regions, features such as mountain ranges, hills, rivers, and lakes influence groundwater[5]. For instance, mountains often affect the flow paths of groundwater, creating alluvial fans or springs at the foot of the mountains. Hills may lead to local accumulation of groundwater and changes in flow directions. Rivers and lakes, on the other hand, can influence the water level and quality of surrounding groundwater through infiltration and recharge mechanisms.

Variations in surface elevation also impact groundwater recharge and discharge[6]. In mountainous areas, rainwater may quickly drain into rivers through surface runoff, resulting in insufficient groundwater recharge. In contrast, plains or low-lying areas may accumulate rainwater in wetlands or sediments, thereby enhancing groundwater recharge[7].Integrating watershed characteristics and water networks with electrical method surveys for line placement can enhance the efficiency of locating potential groundwater sources.

By comprehensively utilizing DEM watershed feature extraction and high-density electrical methods, the following steps can be taken:

(1) Identify water-deficient areas and analyze the watershed characteristics of mountainous regions based on DEM data to obtain local multi-level water networks.

(2) Within the selected target area for water sources, integrate the watershed features extracted from DEM with the positioning of electrical survey lines, and select survey lines located in key areas of the water network.

(3) Arrange electrodes and measure resistivity to identify potential locations of groundwater and the distribution of aquifers, thereby determining the location for well drilling.

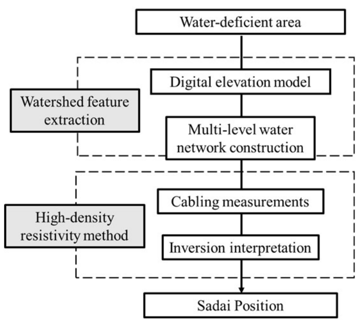

Figure 1. Flowchart of Combined Groundwater Exploring Method

2.1 DEM-based Basin Feature Extraction

In DEM, the plane coordinates of the watershed are generally measured using a square grid[8]. If the size of the plane grid is denoted as $\Delta l \times \Delta l$, then the plane coordinates (x, y) can be replaced by the grid (i, j), i.e., $x = i \cdot \Delta l$ and $y = j \cdot \Delta l$. Here, i = 1, 2, 3, ..., NX represents the grid in the x-direction, with a maximum of NX; and j = 1, 2, 3, ..., NY represents the grid in the y-direction, with a maximum of NY.

The flow direction of overland flow on the watershed is irregular and uneven. Typically, in DEM, the flow direction is simplified into eight directions, corresponding to the eight adjacent spatial points. Assuming that the elevation of point (i, j) is $z(i, j)$, its eight adjacent points are represented as follows: ① southwest (SW) direction at (i-1, j-1); ② west (W) direction at (i-1, j); ③ northwest (NW) direction at (i-1, j+1); ④ south (S) direction at (i, j-1); ⑤ north (N) direction at (i, j+1); ⑥ southeast (SE) direction at (i+1, j-1); ⑦ east (E) direction at (i+1, j); and ⑧ northeast (NE) direction at (i+1, j+1).

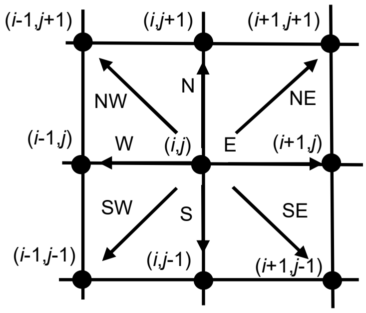

Figure 2. Schematic Diagram of DEM Plane Grid Division and Flow Direction in the Watershed[9]

(1) Surface slope

If the surface slope is denoted as S or tanβ, then the surface slopes from point (i, j) to its eight adjacent points can be calculated as follows:

Table 1. Formulas for Calculating Surface Slopes in Different Directions

Direction	Formulas
SW	$S_1 = \tan\beta_1 = \frac{z(i,j) - z(i-1,j-1)}{\sqrt{2} \cdot \Delta l}$
W	$S_2 = \tan\beta_2 = \frac{z(i,j) - z(i-1,j)}{\Delta l}$
NW	$S_3 = \tan\beta_3 = \frac{z(i,j) - z(i-1,j+1)}{\sqrt{2} \cdot \Delta l}$
S	$S_4 = \tan\beta_4 = \frac{z(i,j) - z(i,j-1)}{\Delta l}$
N	$S_5 = \tan\beta_5 = \frac{z(i,j) - z(i,j+1)}{\Delta l}$
SE	$S_6 = \tan\beta_6 = \frac{z(i,j) - z(i+1,j-1)}{\sqrt{2} \cdot \Delta l}$
E	$S_7 = \tan\beta_7 = \frac{z(i,j) - z(i+1,j)}{\Delta l}$
NE	$S_8 = \tan\beta_8 = \frac{z(i,j) - z(i+1,j+1)}{\sqrt{2} \cdot \Delta l}$

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When the calculated value of S_k (k=1, 2, 3, ..., 8) using the formula in the table above is greater than 0, the overland flow will flow from point (i, j) to point (i+m, j+n), where (m=-1, 0, 1; n=-1, 0, 1) and m and n cannot be zero simultaneously. If the S_k value is less than 0, the overland flow will flow from point (i+m, j+n) to point (i, j). If the S_k value is equal to 0, then there will be no water exchange between point (i, j) and point (i+m, j+n).

(2) flow direction and flow distribution coefficient

When there are more than one possible flow directions, the flow distribution needs to be determined based on the surface slope. Commonly used flow distribution methods include the steepest descent method and the multiple-direction distribution method.

The steepest descent method, also known as the single-flow-direction distribution method, involves all the flow always following the steepest slope. This method is simple to calculate, but it cannot effectively simulate divergent flow in flat areas[10].

The multiple-direction distribution method assumes that on any slope with S > 0, water will flow downstream[11], and the proportion of water flow from point (i, j) to any of its eight adjacent points in a lower direction to the total outflow volume is:

$$f_k = \frac{S_k^p}{\sum_{S_K>0} S_k^p} \tag{1}$$

In the formula, f_k represents the flow distribution coefficient from point (i, j) to any of its eight adjacent points in a lower direction, where k=1, 2, 3, …, 8; and p is an empirical exponent. When p =0, the multiple-direction distribution method becomes the equal distribution method; when p=+∞, it becomes the steepest descent method. According to the multiple-direction flow distribution method, the steeper the slope, the greater the flow in that direction. In the multiple-direction flow distribution method, the contour line widths corresponding to the eight possible flow directions originating from point (i, j) are as follows: for the four flow directions parallel to the coordinate axes (W, S, N, E), the contour line width C_k=0.5·Δl (k=2, 4, 5, 7); and for the four flow directions intersecting the plane coordinate axes (SW, NW, SE, NE), the contour line width C_k=0.354·Δl (k=1, 3, 6, 8).

(3) Single-width catchment area and total catchment area

The single-width catchment area refers to the upstream inflow area corresponding to each unit width of the contour line, denoted as a. The total catchment area represents the upstream inflow area corresponding to the flow passing through a certain segment of contour line width, denoted as A_c. The relationship between the total catchment area and the single-width catchment area is A_c=C·a[12].

For point (i, j), its catchment area is denoted as $A_c^{(i,j)}$, and the total contour line width of its outflow is:

$$C^{(i,j)} = \sum_{S_K>0} C_k \tag{2}$$

In the formula, k=1,2,3,…,8. The single-width catchment area is:

$$a^{(i,j)} = \frac{A_c^{(i,j)}}{C^{(i,j)}} \tag{3}$$

If the elevation of point (i, j) is higher than its surrounding areas, the water flow represented by the catchment area $A_c^{(i,j)}$ will continue to propagate downstream, increasing the downstream catchment

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area. According to the multiple-direction flow distribution method, the catchment area $A_c^{(i,j)}$ will be distributed to its eight adjacent points.

The extraction of river systems and watersheds involves a series of data processing steps using multiple tools to achieve the final result. To reduce redundant manual operations, the ArcGIS ModelBuilder feature can be utilized to create a "Water Network and Watershed Extraction" model, enabling batch processing and rapid calculation of multi-level water networks and watershed boundaries.

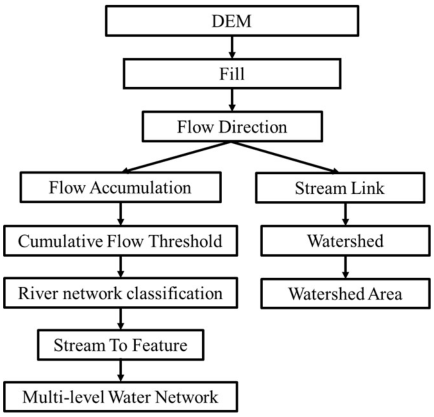


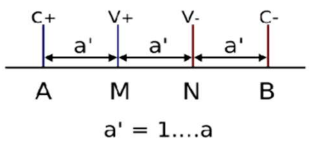
Figure 3. Process of Watershed Feature Extraction Based on DEM

2.2 High-density Resistivity Method

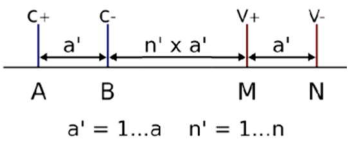
During field measurements, all electrodes (ranging from tens to hundreds) are placed on various measurement points along the observation profile[13]. Then, a programmed electrode switching device is used to control the switching of electrodes between the measuring electrodes and the power electrodes. Microcomputers are employed to rapidly and automatically collect data, and relevant geoelectric cross-section distribution maps can be obtained after processing the measured data[14]. The power electrodes provide current (*I*) to the subsurface, while the measuring electrodes measure the potential difference (ΔU) between them. The apparent resistivity(ρ_s) is calculated using the formula:

$$\rho_s = k \cdot \frac{\Delta U}{I} \tag{4}$$

In the formula, k represents the device coefficient. High-density resistivity method employs various measurement devices such as *Wenner*, *Dipole*, and *Schlumberger* configurations. Each device has its unique electrode movement pattern and device coefficient[15].



A. Schematic Diagram of Wenner Configuration



B. Schematic Diagram of Dipole Configuration

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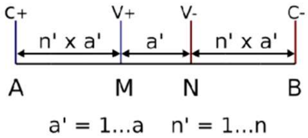

C. Schematic Diagram of Schlumberger Configuration

Figure 4. Schematic Diagram of Common Devices Used in High-density Resistivity Method

Previous experience has shown that *Wenner* devices have high construction efficiency, high vertical resolution, and strong anti-interference capabilities, making them suitable for exploring potential locations of groundwater. This article mainly uses Wenner devices for forward and inverse modeling. The formula for calculating the apparent resistivity ρ_s of Wenner device:

$$\rho_s = 2\pi a \frac{\triangle U_{MN}/I}{1} \tag{5}$$

During measurements, the distances between electrodes are set as AM=MN=NB=a. Electrodes A, M, N, and B are moved point by point along the survey line to obtain a single profile. Subsequently, the distance between adjacent electrodes is increased by one unit electrode spacing, and the process of moving A, M, N, and B along the survey line is repeated to obtain the next profile. This scanning and measurement process is repeated continuously, ultimately resulting in an inverted trapezoidal cross-section.

3. Experimental Study in Gannan Region

The test area for this experiment is located in the Gannan Region (referring to the southern part of Jiangxi Province in China), where the total water resources are abundant[16]. However, the utilization of groundwater resources in the water supply structure is still inadequate. Additionally, due to the climatic characteristics of the region, seasonal water scarcity is a serious issue. Exploring a stable source of groundwater has become an urgent task to address the local drinking water problem. In 2019, the Ganzhou area encountered a once-in-a-century drought disaster that lasted for six months, resulting in dried-up rivers and ponds, discontinued streams, and difficulties in obtaining water for daily use. Some water plants had to restrict their water supply or even had no water to supply, and seasonal water scarcity issues existed in some mountainous areas.

The geological structure of the Gannan region is complex, primarily composed of rocks and sediments. Geologically, Gannan is located at the transitional zone between the Nanling tectonic belt and the South China continental tectonic belt, resulting in a diverse array of strata[17]. The main geological structural types include mountains, hills, plains, and basins. Since the Qingbaikou period of the Neoproterozoic era, all strata of different ages have developed and been exposed, except for the absence of Ordovician and Silurian strata. Due to the constraints of different tectonic backgrounds, the strata are complex and variable, with diverse sedimentary types. The Qingbaikou series of the Proterozoic era is the oldest stratum in the region. The strata are clearly divided into three tectonic layers: the basement (P_{t3}-∈), the cover (D-T), and the fault basin deposits (K-T). The basement rock series of the Early Paleozoic era and earlier are widely exposed, while the Cretaceous strata are mainly exposed in patches in the central and northern parts of the region. Additionally, there are scattered distributions of minor amounts of Devonian, Carboniferous, Permian, and Tertiary strata. The Precambrian system consists of a suite of metamorphic sandstone and slate-dominated flysch-like formations, interspersed with large lenticular crystalline limestones. The Devonian to Carboniferous strata are dominated by carbonate rocks, with intercalations of clastic rocks. The Cretaceous to Tertiary strata consist of variegated to red lacustrine deposits scattered throughout the fault basins of the entire region.

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The Gannan region is endowed with numerous rivers, primarily including the Ganjiang River, the Xinjiang River, and the Yujiang River. These rivers originate from the surrounding mountains, providing vital water resources for the region[18]. The Ganjiang River, the largest river in Jiangxi Province, flows through the Gannan area and empties into Poyang Lake, exerting a significant influence on the region's hydrological environment and water resources. The Gannan region is also abundant in groundwater resources, which are primarily stored in rock fractures, river sediments, and aquifers.

3.1 Extraction of Watershed Characteristics in the Study Area

To extract the multi-level water network in the Gannan region, various analysis and calculation tools within the hydrological analysis module of the ArcMap application are primarily utilized. These tools include Fill, Flow Direction, Flow Accumulation, Stream Order, and Stream To Feature. Additionally, tools such as Stream Link and Watershed are mainly used for watershed delineation. By following the steps outlined in Figure 3, the watershed characteristics and water network of the Gannan region are extracted.

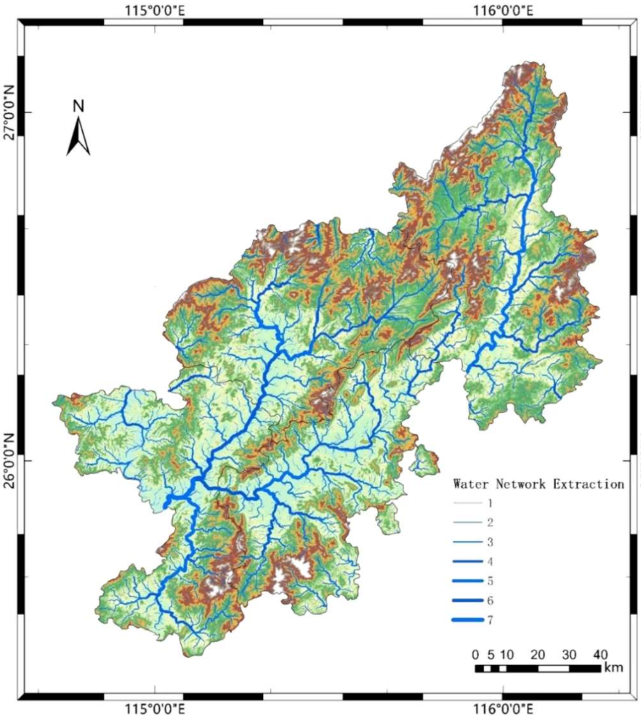

Figure 5. DEM and Watershed-Based Water Network Extraction in the Gannan Region

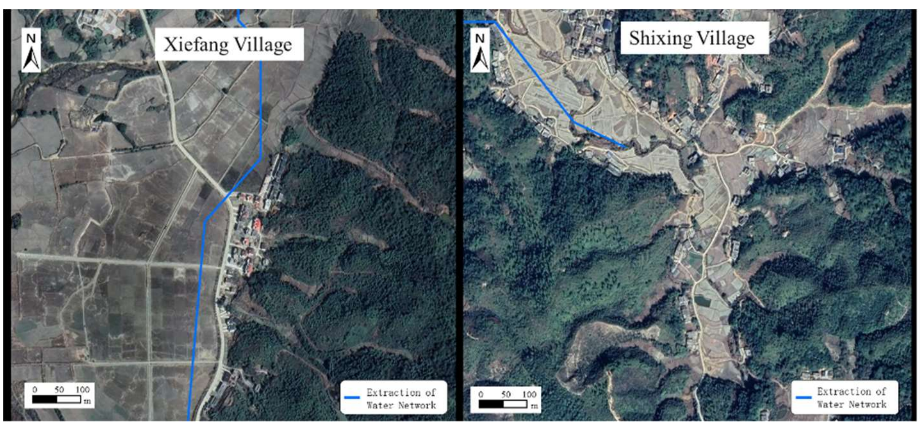

Figure 6. Distribution of Characteristic Water Networks in the Watershed of Shixing Village and Xiefang Village in the Work Area

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3.2 Groundwater Searching Application in Xiefang Village

The water network lines in Xiefang Village run in a north-south direction. Therefore, two survey lines were selected, one along the water network lines and the other perpendicular to them.

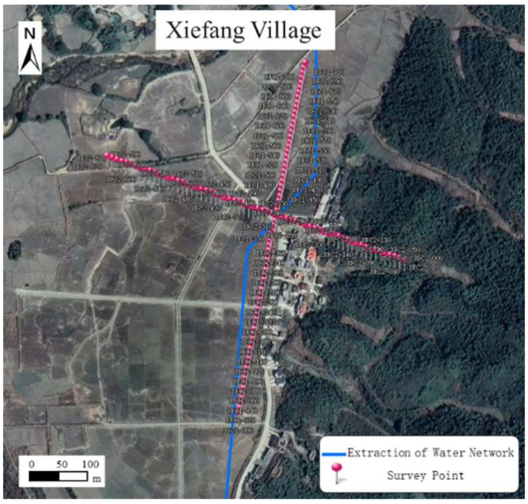

Figure 7. Location Map of Survey Points in Xiefang Village

The survey line XFC1 extends in a north-northeast direction, with a total length of 710 meters. The distance between each survey point is 10 meters, resulting in a total of 72 survey points. The survey line XFC2, meanwhile, extends in a northwest direction, starting from the east and ending at the west. It has a total length of 630 meters, with a 10-meter spacing between survey points, totaling 64 survey points.

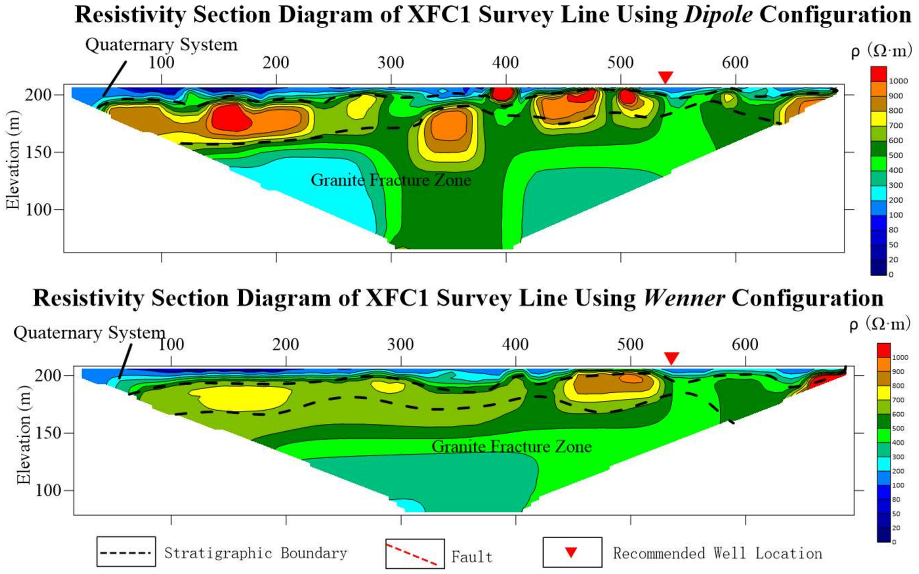

Figure 8. Inversion and Interpretation of High-Density Resistivity Survey for Survey Line XFC1

As shown in Figure 8, which presents the inversion profile of high-density resistivity for the XFC1 survey line, the line is located in the fine-grained dolerite-monzonitic granite area of the late Triassic period. In the figure, there is a cover layer with a thickness of approximately 12 meters on the surface. The middle layer consists of high-resistivity granite interspersed with fracture development zones. Based on the inversion results obtained from the dipole device, it is evident that there is a similar channel feature in the high-resistivity granite area at point 450.

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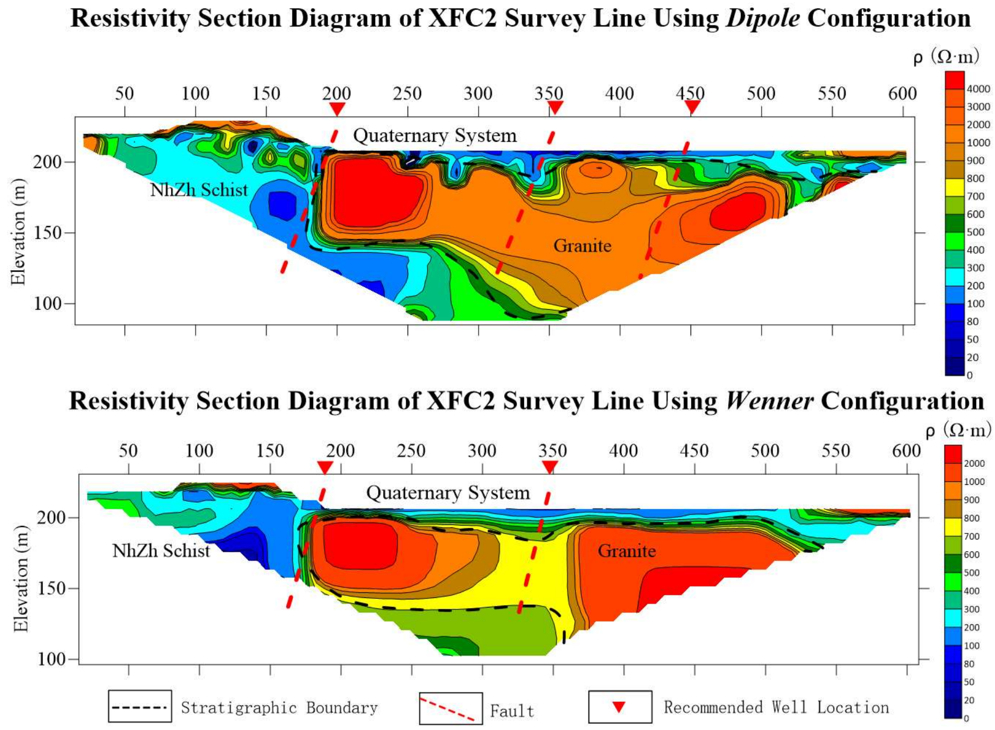

Figure 9. Inversion and Interpretation of High-Density Resistivity Survey for Survey Line XFC2

As shown in Figure 9, which presents the inversion profile of high-density resistivity for the XFC2 survey line, the starting end of the survey line is located in the metamorphic schist stratum of the Nanhua System, characterized by low resistivity. Starting from point 300, it enters the fine-grained dolerite-monzonitic granite area of the late Triassic period. There is a Quaternary cover layer with a thickness of approximately 10 meters on the surface. Based on the inversion results, geological data, and drilling information, three faults have been delineated in total.

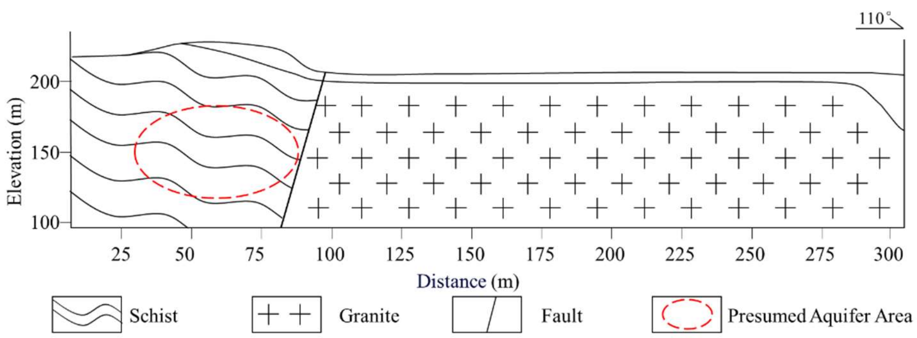

Figure 10. Geological Interpretation Profile of Survey Line XFC2 (point 0 to point 300)

Based on the comprehensive measurement results of the XFC2 survey line, a geological interpretation profile has been drawn. The section from 0 to 170 meters belongs to the metamorphic schist stratum of the Nanhua System. The schistose structure is prone to weathering, creating channels for the flow of groundwater and serving as a good aquifer. The section from 170 meters to 630 meters is composed of fine-grained dolerite-monzonitic granite of the late Triassic period, which is hard and dense, playing a role in water resistance. Therefore, the well location is selected at point 160.

3.3 Groundwater Searching Application in Shixing Village

The water network lines in Shixing Village run from northwest to southeast. Therefore, two survey lines were selected: one along the water network lines and the other along the main village road.

Figure 11. Location Map of Survey Points in Shixing Village

The SXC1 survey line is approximately oriented in the east-west direction, with a total length of 670 meters. The distance between survey points is 10 meters, resulting in a total of 68 survey points.The SXC2 survey line is approximately oriented in the north-south direction, with a total length of 750 meters. The distance between survey points is also 10 meters, totaling 76 survey points.

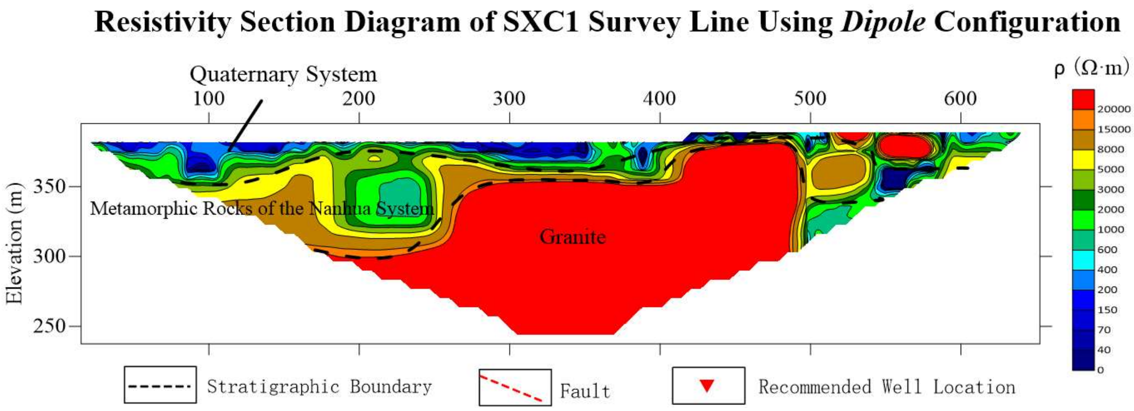

Figure 12. Inversion and Interpretation of High-Density Resistivity Survey for Survey Line SXC1

As shown in Figure 12, which presents the inversion profile of high-density resistivity for the SXC1 survey line, the burial depth of the bedrock along the line is relatively shallow, with a Quaternary cover layer thickness of approximately 10 meters. The layer with lower resistivity in the middle is quartz sandstone or glutenite of the Shabahuang Formation of the Nanhua System. Based on geological and gravity data, the red high-resistivity area at the bottom is inferred to be a concealed granite. Due to the shallow burial depth of the granite, it is not recommended to pre-plan well locations on this survey line.

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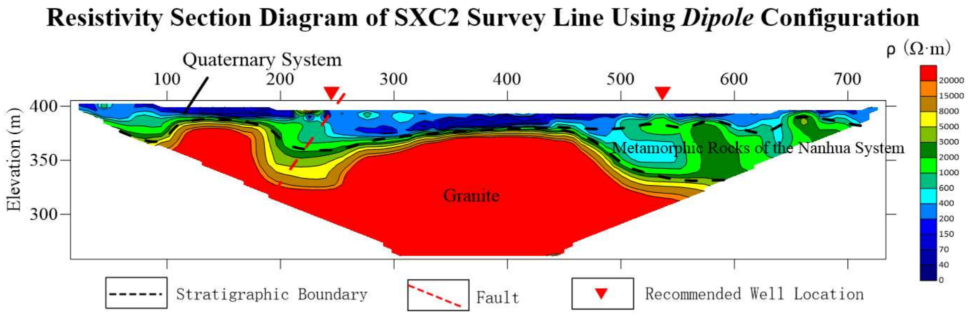

Figure 13. Inversion and Interpretation of High-Density Resistivity Survey for Survey Line SXC2

As shown in Figure 13, which presents the inversion profile of high-density resistivity for the SXC2 survey line, the burial depth of the bedrock along the line is relatively shallow, with a Quaternary cover layer thickness of approximately 12 meters. The layer with lower resistivity in the middle is quartz sandstone or glutenite of the Shabahuang Formation of the Nanhua System. Based on geological and gravity data, the red high-resistivity area at the bottom is inferred to be a concealed granite. A fault is also inferred at survey point 360. The preferred survey point for pre-planned well location is 620, located 520 meters from the southern end of the survey line. The second preferred survey point is 360, located 260 meters from the southern end of the survey line.

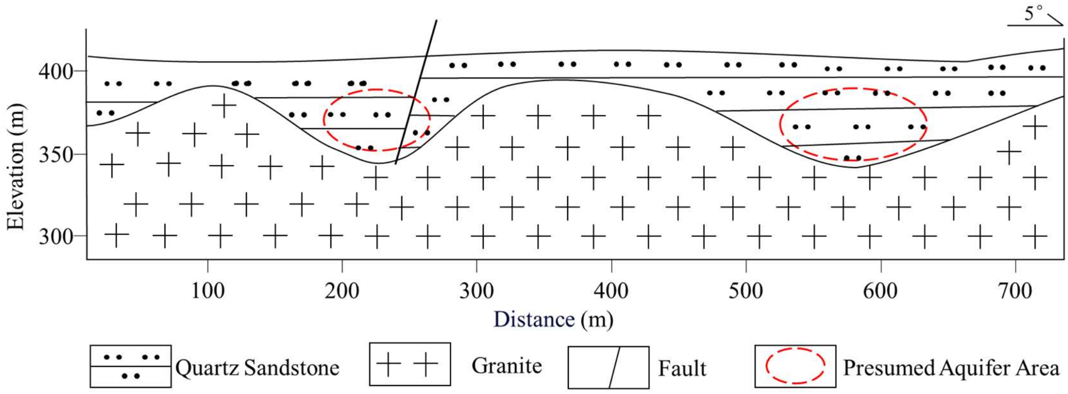

Figure 14. Geological Interpretation Profile of Survey Line SXC2

Based on the measurement results of the SXC2 survey line, a geological interpretation profile has been drawn. The upper layer consists of quartz sandstone strata of the Shabahuang Formation of the Nanhua System. Quartz sandstone is mainly composed of quartz grains, which have pores and cracks between them. These pores and cracks provide storage space for groundwater. The underlying bedrock in the region is a granite area, which is hard and dense, preventing further infiltration of groundwater and serving as a water-resistant layer. Finally, the well location has been selected at either point 230 or point 570.

4. Conclusion

This paper conducted a study on the application of combined DEM watershed feature extraction and high-density resistivity survey for groundwater exploration in the southern Jiangxi region. Field applications were carried out in Shixing Village and Xiefang Village in southern Jiangxi, and the selected well locations achieved good economic and social benefits. The following conclusions were drawn from this applied research:

(1) The construction of a multi-level water network in the study area was based on the spatial geographic data DEM collected in the early stage. The extraction of watershed features established a multi-level water network system in the southern Jiangxi region. The multi-level water network not

only quantitatively expresses the macroscopic geomorphic features within the region, but also provides critical data support for the layout of high-density resistivity survey lines.

(2) The combined technology of watershed feature extraction and geophysical exploration can overcome the complex conditions in mountainous areas and solve the difficult problem of selecting the best location for survey line deployment. It can provide accurate underground water resource information more quickly and help to explore reliable water source locations.

Acknowledgments

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