Research on Water-seeking Technical Methods and Analysis of Well Siting in Water-scarce Mountainous Areas

Yao Guo[1,2], Xinlin He[1,2]
[1]*Henan Academy of Geology, Zhengzhou, Henan, China*
[2]*Henan Research Center of Urban Geological Engineering Technology, Zhengzhou, Henan, China*

Abstract: The study area is located in the eastern part of an autonomous region in China and is a key town along the main route of National Highway 318, which connects the autonomous region with Sichuan Province. In recent years, water scarcity has become a critical factor constraining local economic development. To address this, this study employed hydrogeological surveys, geophysical exploration, and hydrogeological drilling to identify relatively water-enriched groundwater zones in the water-scarce mountainous areas. Methods such as high-density electrical resistivity and symmetric quadrupole induced polarization sounding were used for specialized investigation of the preliminarily delineated well construction distribution areas, providing a technical basis for effectively resolving drinking water difficulties for residents in the region.

Keywords: Water-Scarce Mountainous Area; Water Exploration Technology; Well Siting; Water Resources; Hydrogeological Survey

1. Introduction

The study area is situated in the eastern part of the Tibet Autonomous Region, specifically in Baima Town, which is located at an elevation of 3,260 m above sea level in the upstream region of the Nu River. The topography of the study area is primarily characterized by mountainous and valley landscapes. The mountainous terrain rises above 4,000 m, with relative elevation differences exceeding 1,000 m, and is often covered by perennial ice and snow, exhibiting glacial geomorphological features. The valley landscape is found in the central part of the study area, where rivers have carved deep channels, resulting in steep topographical gradients. Basu County serves as a crucial town connecting Tibet with the main route of National Highway 318 in Sichuan Province. In recent years, as development has progressed, the scarcity of water resources has emerged as a significant constraint on the economic development of the county.

2. Overview of Hydrogeological Conditions

Based on the conditions of groundwater occurrence and hydraulic characteristics, the groundwater in this area can be classified into two fundamental types: pore water in loose rock formations and fissure water in bedrock.

The bedrock distribution area is composed of intrusive rocks from the Mesozoic era. The study area is predominantly characterized by northwest-southeast trending faults and folds, with north-south oriented reverse and strike-slip faults being secondary. Along these faults, zones of compressional foliation, fractured influence zones, and densely fractured zones develop, controlling the formation and distribution of fissure water in the bedrock. In the Lengqu River valley region of the study area, Quaternary loose strata of limited thickness accumulate, influencing the formation and distribution of pore water. The majority of the study area consists of metamorphic rocks from the Mesozoic to Cenozoic eras, with multiple structural belts developed, which govern the formation and distribution of fissure water[1].

2.1 Pore Water in Loose Rock Formations

Pore water in loose rock formations is distributed along the riverbeds and channels on both banks of the Lengqu River in Basu County, as well as on various levels of terraces and at the foot of slopes. The aquifer in these loose rock formations is composed of sand, gravel, and clay layers from Quaternary alluvial deposits, as well as from flood deposits of sand, gravel, and clay. According to the results of this investigation, the clay layers are often cemented with gravel, filling the pores within the gravel and resulting in a scarcity of water in the Quaternary aquifer. In the western part of the study area, particularly around Shamu Village, the thickness of the Quaternary deposits can reach up to 49.75 m, while in the central area of Basu County, the thickness is approximately 16.5 m, and in the eastern region around Xiba Village, it measures about 18.0 m. The groundwater table is typically buried at depths of 2 to 10 m, with single well water yields in the regions of Badonggong and Basu County ranging from 10 to 100 m^3/d, while other areas yield less than 10 m^3/d, categorizing them as water-scarce zones[2].

2.2 Fissure Water in Bedrock

Based on the differences in lithology, the fissure water in the bedrock of the area can be further categorized into fissure water in metamorphic rocks and fissure water in igneous rocks, as detailed below:

Fissure water in metamorphic rocks is predominantly distributed throughout most of the study area. In regions of higher elevation, strata from the pre-Carboniferous, Carboniferous, Jurassic, and Upper Cretaceous periods are exposed. Although structural fissures are relatively well-developed, atmospheric precipitation and meltwater from snow rapidly infiltrate underground or flow through surface runoff to lower elevations. Only in localized structural water-blocking zones do springs emerge, indicating that these aquifer groups exhibit poor water yield potential. The study area features folds and secondary structures, with the lithology of the Neogene sandstones and the Lower Cretaceous Doni Formation consisting of sandstones and shales being notably fragmented. The fissures are well-developed, with significant variation in their orientations, allowing groundwater to be stored within weathered and structural fissures, concentrating along tectonic fracture zones. In low-lying terrains or specific structural locations, springs emerge, exhibiting moderate water yield potential[3]. Based on the water yield potential, lithology, and characteristics of the aquifers, the shallow groundwater in clastic rocks is classified as a water-scarce zone. According to flow measurements, the groundwater runoff modulus ranges from 0.015 to 0.07 $L/s \cdot km^2$.

Beneath the Quaternary cover, the fissure water in the bedrock is primarily composed of Jurassic sandstones or slates, characterized by good rock integrity but weak fissure development and poor water yield potential. The yield from single wells ranges from 1.10 to 3.63 $m^3/d \cdot m$, with groundwater permeability coefficients between 0.04 and 0.1 m/d. The water yield potential is relatively weak, providing only limited and dispersed water supply[4].

Fissure water in igneous rocks is found exclusively in the southwestern corner of the study area, where the aquifer is composed of intrusive rock bodies from the Yanshan and Himalayan orogenies. The primary rock types include quartz diorite, granodiorite, monzogranite, and porphyritic biotite granite. This aquifer is mainly characterized by fissure water in weathered zones, with spring flow rates ranging from 0.1 to 1.0 L/s and an underground runoff modulus of 0.09 $L/s \cdot km^2$.

3. Research on Water Exploration Technology in Water-Scarce Mountainous Areas

In the bedrock mountainous regions, zones with relatively high water yield potential are primarily located within tectonic fracture zones and the contact areas between intrusive rock bodies and surrounding rocks. These zones experience structural tension and pressure, as well as thermal and hydrothermal metamorphism, leading to fragmentation and the development of fissures within the strata. Following atmospheric precipitation infiltration, water accumulates within these fractured layers, forming relatively water-rich areas. The groundwater in mountainous regions predominantly originates from atmospheric precipitation. Due to the complex terrain characterized by hills and valleys, precipitation tends to converge in lower-lying areas, thus facilitating groundwater recharge in these relatively depressed regions[5]. The study area features extensive granite bodies and volcanic clastic rock formations, with significant surface weathering resulting in fragmented rock and well-developed fissures. Below the weathered surface lies relatively fresh rock, which maintains structural integrity and forms a water-blocking layer. After atmospheric precipitation infiltrates, it is impeded by the underlying fresh bedrock, leading to the formation of layers with high water yield potential within the weathered mantle, which are the primary targets for groundwater exploitation in mountainous areas. The discharge points for groundwater in these regions are predominantly located along the line of the river erosion base level. When the groundwater saturation line is exposed due to river erosion, springs typically emerge at the confluence of rivers at the foot of slopes. Therefore, considering the geological and geomorphological conditions within the study area, the main zones of groundwater accumulation in the bedrock mountainous regions are distributed as follows: 1) the contact zones between intrusive rock bodies and surrounding rocks; 2) fault fracture zones, particularly at the intersections of faults with varying orientations; and 3) the weathered layers of granite bodies[6].

According to the theory of zones with relatively high water yield potential in water-scarce mountainous areas, the initial step involves conducting hydrogeological surveys to identify target areas, primarily focusing on the contact zones between intrusive rock bodies and surrounding rocks, fault fracture zones, and the weathered layers of granite bodies as key investigation segments. In terms of geological surveys, particular attention is given to the lithology of strata on both sides of geological boundaries and fault lines, examining the development and closure of fissures and joints, as well as the orientation of fissures and the degree of fragmentation of the strata. From a hydrological perspective, the investigation in these areas primarily seeks to determine the presence of spring outlets, the existence of traditional wells, and the growth of hydrophilic vegetation. The appearance of these phenomena can preliminarily indicate a relative abundance of groundwater, allowing for the initial delineation of areas for well construction. Subsequently, geophysical exploration is employed to conduct specialized investigations within the preliminarily delineated well construction zones to verify the feasibility of drilling wells in these locations. This process further refines the determination of well locations, well depths, and the distribution of aquifers, thereby guiding the subsequent phases of well construction[7-8].

4. Case Analysis of Well Siting

In accordance with project requirements, two high-density electrical exploration lines were established within the area, along with four symmetrical four-electrode induced polarization depth profiling sections. The high-density electrical resistivity method was designed with an electrode spacing of 10 m and a profile length of 300 m. The symmetrical four-electrode induced polarization depth profiling was designed with point spacings of 100 to 200 m, targeting a maximum exploration depth of 120 m. Additionally, one induced polarization depth profiling point was designed in alignment with the drilling location, with an AB/2 spacing of 180 m and an exploration depth of 120 m.

Different electrode spacings correspond to varying exploration depths, which were derived from the analysis of interpretation models, model curves, and comparisons with drilling data. The empirical coefficient for the AB/2 electrode spacing and exploration depth in this area is approximately 2/3, with the coefficient decreasing as the electrode spacing increases[9]. To visually represent the electrical characteristics along each measurement profile and the geological conditions reflected therein, the following sections summarize the results based on the aforementioned curve analyses and quantitative interpretations:

4.1 Wangbi Village

Profile I—I′ was situated on the southern bank of the river in Wangbi Village, with ground elevations ranging from 3,460 to 3,480 m. The profile was oriented perpendicular to the river's course, at an angle of approximately 40°, as illustrated in Figure 1. The apparent resistivity values (ρ_S) at shallow depths exhibited a relatively regular variation. The ρ_S values formed high-resistivity closed and semi-closed loops, indicative of the electrical characteristics of surface gravel and pebbles, which was particularly pronounced between 50 to 270 m. In deeper sections, the ρ_S values gradually declined, reflecting the lower resistivity characteristics of the underlying strata. Based on the characteristics of the ρ_S profile, it was inferred that the shallow section consisted of gravelly soil or a pebble layer, underlain by clay shale. Overall, the profile indicated a gradual thinning of the pebble layer from south to north, with the burial depth of the clay shale becoming correspondingly shallower. The apparent resistivity values in the deeper sections generally showed higher values in the south and lower values in the north. The profile was immediately adjacent to the river in the northern part, where the water yield potential gradually increased from south to north. Therefore, the proposed well location was designated at the southern end of the profile, with a planned depth of 80 m and an expected single well yield of 10–15 t/h [10].

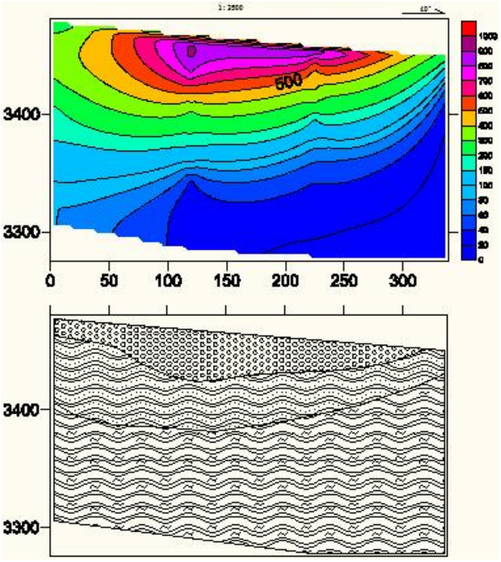

Figure 1. Apparent Resistivity Profile of Line I (Wangbi Village)

4.2 Badong New Village

Profile III—III′ was located to the west of Badong New Village, with ground elevations ranging from 3,398 to 3,439 m. The profile was oriented perpendicular to the river's course, at an angle of approximately 160°, as depicted in Figure 2. The apparent resistivity values (ρ_S) at shallow depths along the profile exhibited a relatively regular pattern. The ρ_S values manifested as high-resistivity closed and semi-closed loops, indicative of the electrical characteristics of surface sandy gravel and pebbles, a feature particularly pronounced between 0 to 260 m. In deeper sections, the ρ_S values showed a gradual decline, reflecting the lower resistivity characteristics of the underlying strata. Based on the characteristics of the ρ_S profile, it was inferred that the shallow section consisted of gravelly soil or pebble layers, underlain by clay shale. Overall, the profile indicated a gradual thinning of the pebble layer from south to north, with the burial depth of the underlying clay shale becoming correspondingly shallower. The apparent resistivity values in the deeper sections consistently showed a trend of higher values in the south and lower values in the north. The northern part of the profile was immediately adjacent to the river, where the water yield potential increased progressively from south to north. The proposed well location was designated at a horizontal position of 200 m along the profile, where the thickness of the surface sandy gravel and pebbles was greatest. The planned well depth was 80 m, with an expected single well yield of approximately 10 t/h.

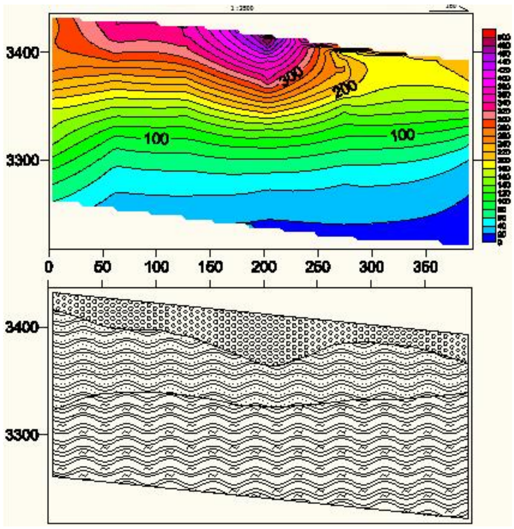

Figure 2. Apparent Resistivity Profile of Line III (Badong New Village)

4.3 Nairan Village

Profile V—V′ was located to the east of Nairan Village, with ground elevations ranging from 3,365 to 3,479 m. The apparent resistivity values at shallow depths along the profile exhibited a relatively regular variation. Specifically, within the horizontal distance range of 0–200 m, the surface exhibited relatively lower high-resistivity characteristics. Between 240–640 m, the shallow ρ_S values formed high-resistivity closed and semi-closed loops, reflecting the electrical properties of surface sandy gravel and pebble layers. In deeper sections, the ρ_S values gradually decreased, indicating the lower resistivity characteristics of the underlying strata. Based on the ρ_S profile characteristics, it was inferred that the shallow section consisted of gravelly soil or pebble layers, underlain by sandy and muddy slate. Overall, the profile suggested that the bedrock burial depth was relatively shallow within 0–200 m. Beyond 200 m, the surface gravel or pebble layer gradually thickened, and the bedrock burial depth progressively increased. The river channel was located near the 200-meter mark of the profile, where the water yield potential gradually decreased from south to north. The designed well was situated in the southern part of the profile, with a planned depth of 80 m and an estimated single well yield of approximately 10 t/h.

4.4 Xiba Village

Profile VI—VI′ was located to the west of Xiba Village, with ground elevations ranging from 3,191 to 3,209 m. The profile was oriented perpendicular to the river's course, at an angle of approximately 45°, as shown in Figure 3. The apparent resistivity values (ρs) at shallow depths along the profile exhibited relatively regular variations. The shallow ρs values formed high-resistivity closed and semi-closed loops, reflecting the electrical characteristics of surface sandy gravel and pebbles. In the mid-section, the ρs values showed relatively high resistivity, indicating the electrical properties of high-resistivity strata. In deeper sections, the ρs values gradually decreased, suggesting the lower resistivity characteristics of the underlying strata. Based on the resistivity profile characteristics, it was inferred that the surface layer consisted of 5–15 m of gravelly soil, underlain by sandy slate, with the deep strata composed of low-resistivity argillaceous slate. Overall, the profile indicated that the bedrock burial depth gradually decreased from south to north, and the thickness of the middle slate layer progressively thinned from south to north. The apparent resistivity values in the deeper sections generally exhibited higher values in the south and lower values in the north. The water yield potential progressively increased from south to north. The designed well was situated in the southern part of the profile, with a planned depth of 80 m and an expected single well yield of 10–15 t/h.

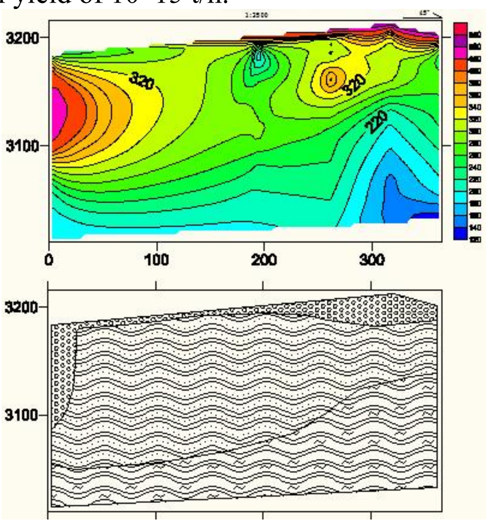

Figure 3. Apparent Resistivity Profile of Line VI (Xiba Village)

4.5 Shamu Village

According to the inversion results of the high-density electrical resistivity method survey, the shallow surface exhibited localized thin layers of silt and silty clay cover, underlain by a relatively high-resistivity layer at depths of 10–20 m, which was interpreted as a pebble layer. Below 20 m, the ρs values gradually decreased, reflecting the electrical characteristics of the underlying low-resistivity clay shale layer. Notably, in the profile sections between 0–90 m and 110–140 m, the mid-layer displayed a range of high ρs values and considerable depth, suggesting a relatively greater thickness of the pebble layer in these areas, as illustrated in Figure 4.

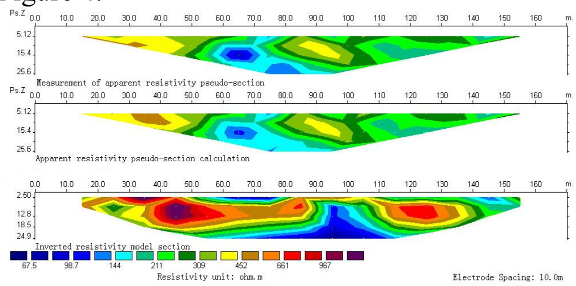

Figure 4. Apparent Resistivity Profile of Line II (Shamu Village)

4.6 Zhuba Village

The inversion results from the high-density electrical resistivity method survey indicated that the shallow surface, at depths of 1–10 m, exhibited low-resistivity closed or semi-closed loops, which were inferred to reflect the electrical characteristics of water-saturated gravelly soil. Beneath this layer, at depths of 40–50 m, a relatively high-resistivity layer was observed, which, in conjunction with drilling results, was inferred to be granite strata. Notably, around 240 m, a relatively low-resistivity zone appeared underlying the granite, reflecting the electrical characteristics of the clay shale underlying the granite, as depicted in Figure 5.

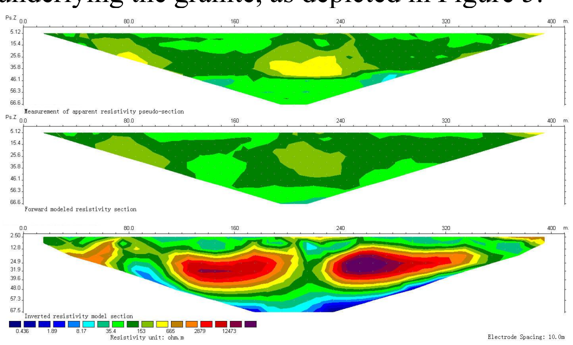

Figure 5. Apparent Resistivity Profile of Line IV (Zhuba Village)

5. Conclusion

In Basu County, extensive distributions of granite intrusions and metamorphic rock bodies are present, resulting in a scarcity of groundwater resources. In order to locate water in arid mountainous regions, it is essential to first identify potential aquifer zones based on the theory of zones with high water yield potential, with a particular focus on areas surrounding fault zones and fractured zones. Investigations should assess the development of strata fissures, the extent of fragmentation, the presence of spring outcrops, and the growth of hydrophilic vegetation. Additionally, integrating techniques such as induced polarization sounding and EH-4 geophysical surveys will aid in the final determination of well locations. Furthermore, when drilling for water in these water-scarce mountainous areas, it is advisable to employ advanced construction techniques, such as pneumatic percussion drilling, which offers a shorter construction time, higher efficiency, and eliminates the need for mud, making it well-suited for well construction in this region.

Acknowledgments

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