

Research Article

Study on Storage Conditions and Suitability Zoning of Shallow Floor Energy in Nanchang City

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In the context of China's carbon summit strategy, as renewable clean energy, the development and utilization of shallow geothermal energy has broad prospects. Based on the analysis of the occurrence conditions of shallow geothermal energy in Nanchang City, the suitability zoning of the ground source heat pump project in Nanchang City is studied by using the analytic hierarchy process. The results show that Nanchang is very suitable for the construction of the ground source heat pump system. Among them, the suitable area of the groundwater ground source heat pump is 252.17 km², the basically suitable area is 133.64 km², and the unsuitable area is 124.29 km². The suitable area of the buried pipe ground source heat pump is 180.49 km², the basically suitable area is 320.82 km², and the unsuitable area is 8.79 km². The evaluation results can provide a basis for the development and utilization of shallow geothermal energy in Nanchang.

1. Introduction

Shallow geothermal energy refers to geothermal energy with value for development and utilization within a depth below the surface (generally 200 m) [1–5]. As green renewable energy, shallow geothermal energy has the advantages of large reserves, wide distribution, and convenient development and utilization [6–11]. In addition, shallow geothermal energy has obvious energy-saving benefits after being promoted and used [12, 13]. However, shallow geothermal energy as a resource is not inexhaustible, resource depletion by excessive mining. Therefore, the study of shallow geothermal energy suitability zoning is necessary to guide the development and utilization of shallow geothermal energy resources [14–16]. Fang and Wei [17] carried out geological, hydrogeological, geothermal drilling, and related experiments on 13 prefecture-level cities in Hunan Province. On this basis, they carried out the storage conditions, resources,

and suitability of shallow geothermal energy. Wang and others [18] investigated the storage conditions of shallow geothermal energy within the research area of Longkou City and carried out the suitability zoning study using the analytic hierarchy process and index method. Lu and others [19] added the influence of urban land use and space form into the suitability evaluation factors and evaluated the development potential of shallow geothermal energy in the Xicheng District of Beijing. Li [20] summarized the utilization situation of shallow geothermal energy in Jilin Province and pointed out the disadvantages of the suitability evaluation of the water source heat pump. In general, most cities in China have now carried out shallow geothermal energy suitability zoning research [21–26] to promote the rational development and utilization of the local shallow geothermal energy. However, Nanchang, the capital of Jiangxi Province, has progressed slowly in this regard. Therefore, in order to promote the rational development and utilization of shallow

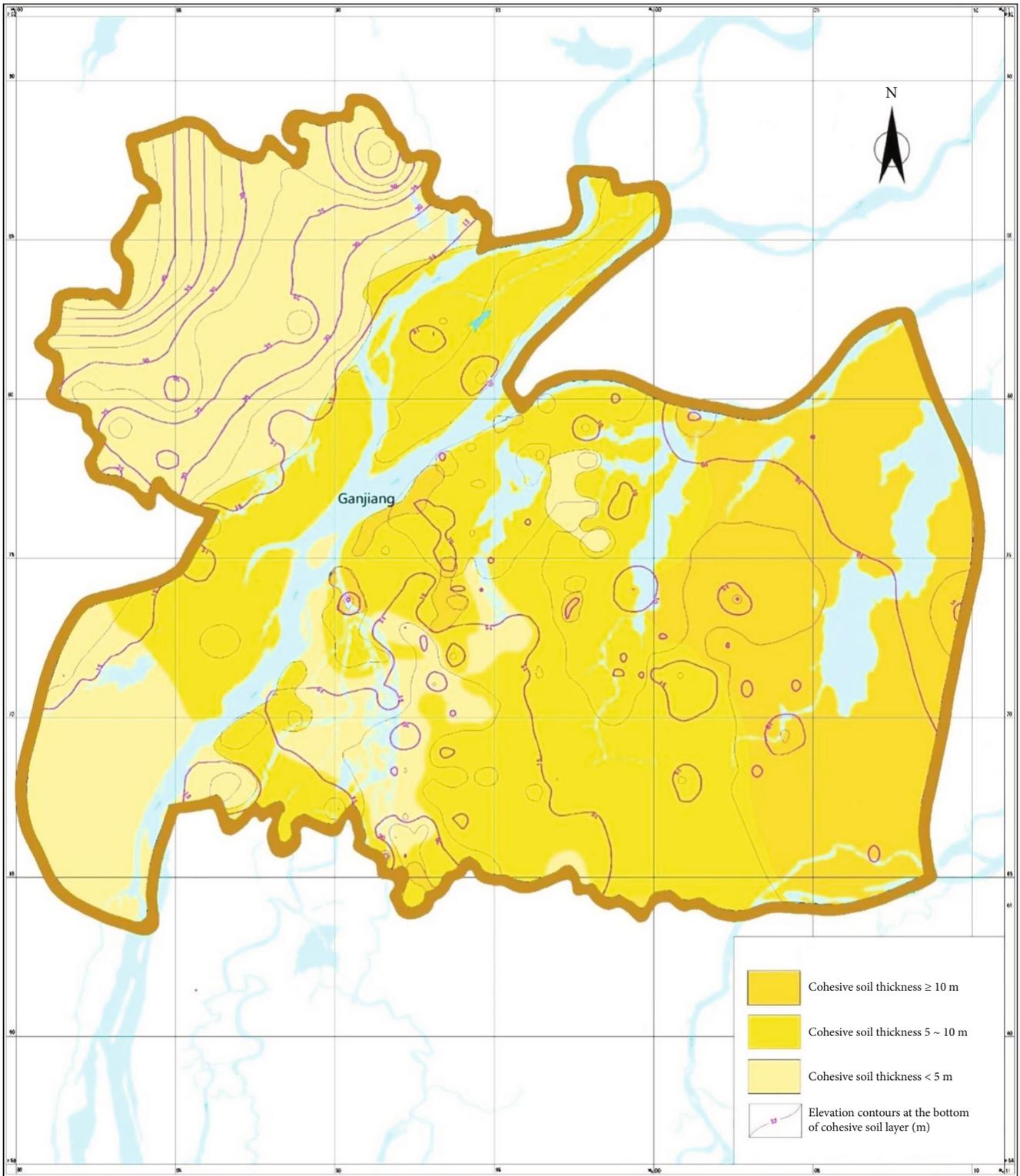


FIGURE 1: Zoning map of the overlying cohesive soil thickness.

geothermal energy in Nanchang City, it is particularly important to study the storage conditions and suitability zoning of shallow geothermal energy in Nanchang.

Based on the results of the project “investigation and evaluation of shallow geothermal energy in Nanchang,” this paper systematically expounds on the occurrence conditions of shal-

low geothermal energy in Nanchang and studies the suitability zoning of the Nanchang underground water source heat pump and ground-coupled heat pump in Nanchang City by using the analytic hierarchy process and GIS spatial analysis module, hoping to provide the basis for the rational development and protection of shallow geothermal energy in Nanchang.

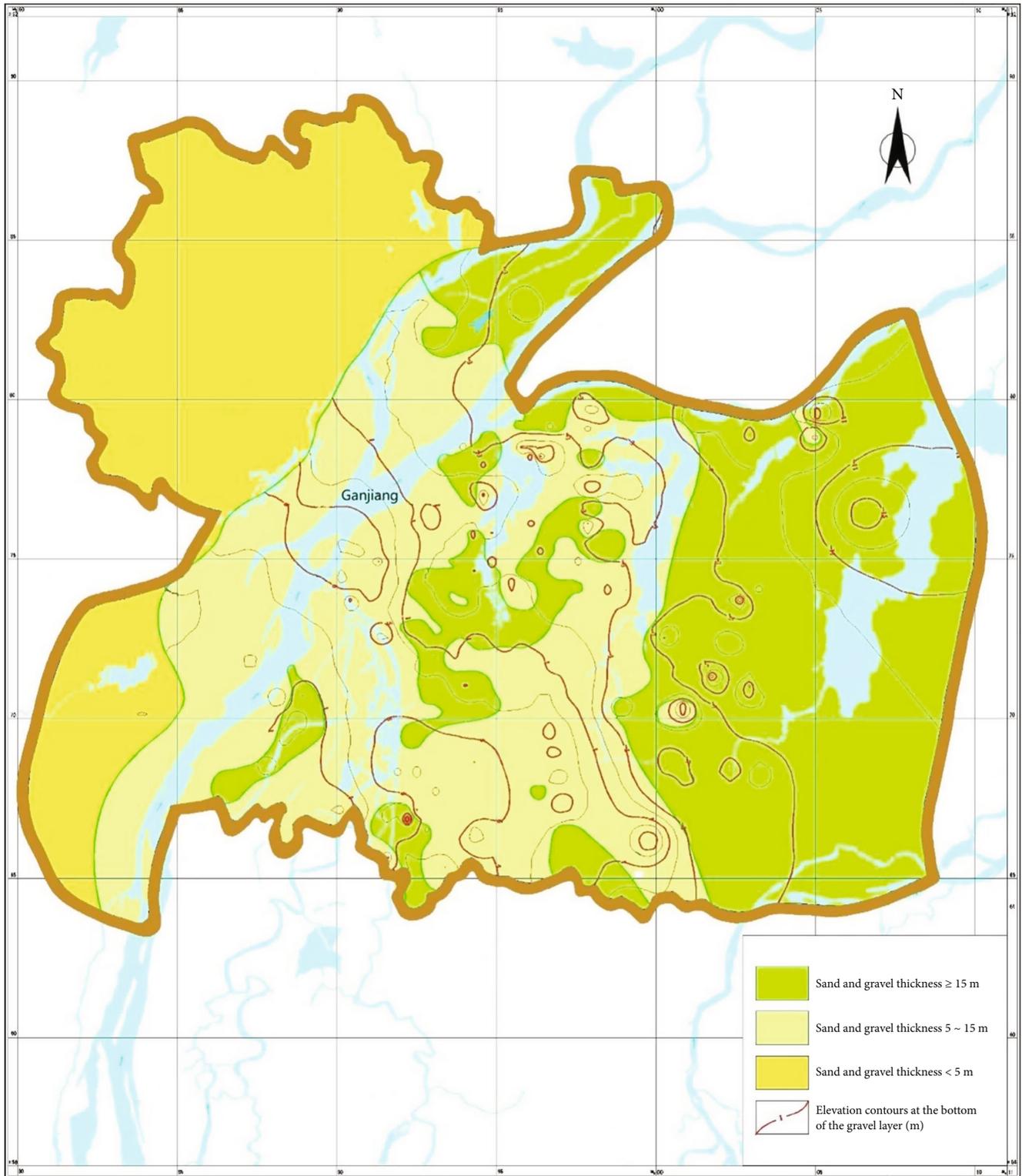


FIGURE 2: Zoning map of the Quaternary gravel layer thickness.

2. Shallow Geothermal Energy Supply and Storage Conditions

2.1. Overview of the Study Area. Nanchang City is located at $115^{\circ}46'43'' \sim 116^{\circ}05'07''$ NE and $28^{\circ}34'58'' \sim 28^{\circ}49'15''$ N,

with an area of 510.1 km^2 . The terrain is generally high in the northwest and low in the southeast. The climate belongs to the subtropical humid monsoon climate, with distinct four seasons and abundant rainfall. However, spring and autumn are short and summer and winter are long. It

TABLE 1: Comparison of different geotechnical thermal properties in the survey area.

Geotechnical name	Specific heat capacity (kJ/(kg·°C))	Thermal conductivity (W/(m·°C))	Thermal diffusion coefficient (10 ⁶ m ² /s)
Silty clay	1.452	1.435	0.502
Silty sand	1.142	1.481	0.665
Fine sand	1.176	1.655	0.739
Thick sand	0.654	1.783	1.517
Gravel sand	0.593	1.980	1.876
Calcareous mudstone	1.155	1.755	0.637
Sandstone	1.211	1.785	0.599
Phyllite	1.268	3.628	1.057

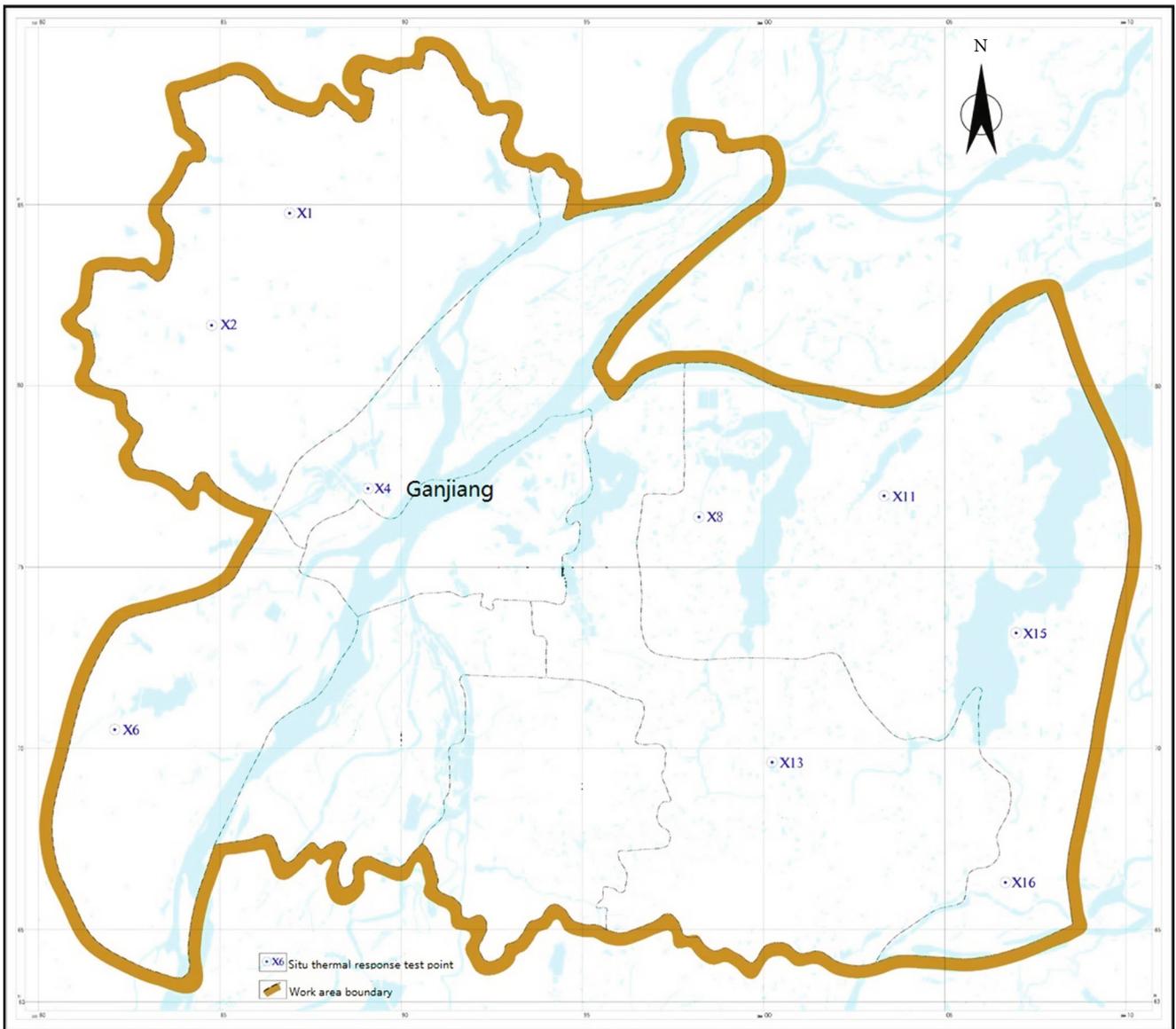


FIGURE 3: Distribution of the site thermal response test.

belongs to a typical hot summer and cold winter area. It is generally a refrigeration period from June to October, December to March of the following year. The heating and cooling cycle is long, large demand for cold and heat, and

geographical climate is very suitable for the development and utilization of shallow geothermal energy. The average annual air temperature is 17.75°C. Annual average precipitation is 1076.8~1991.8 mm; annual evaporation is

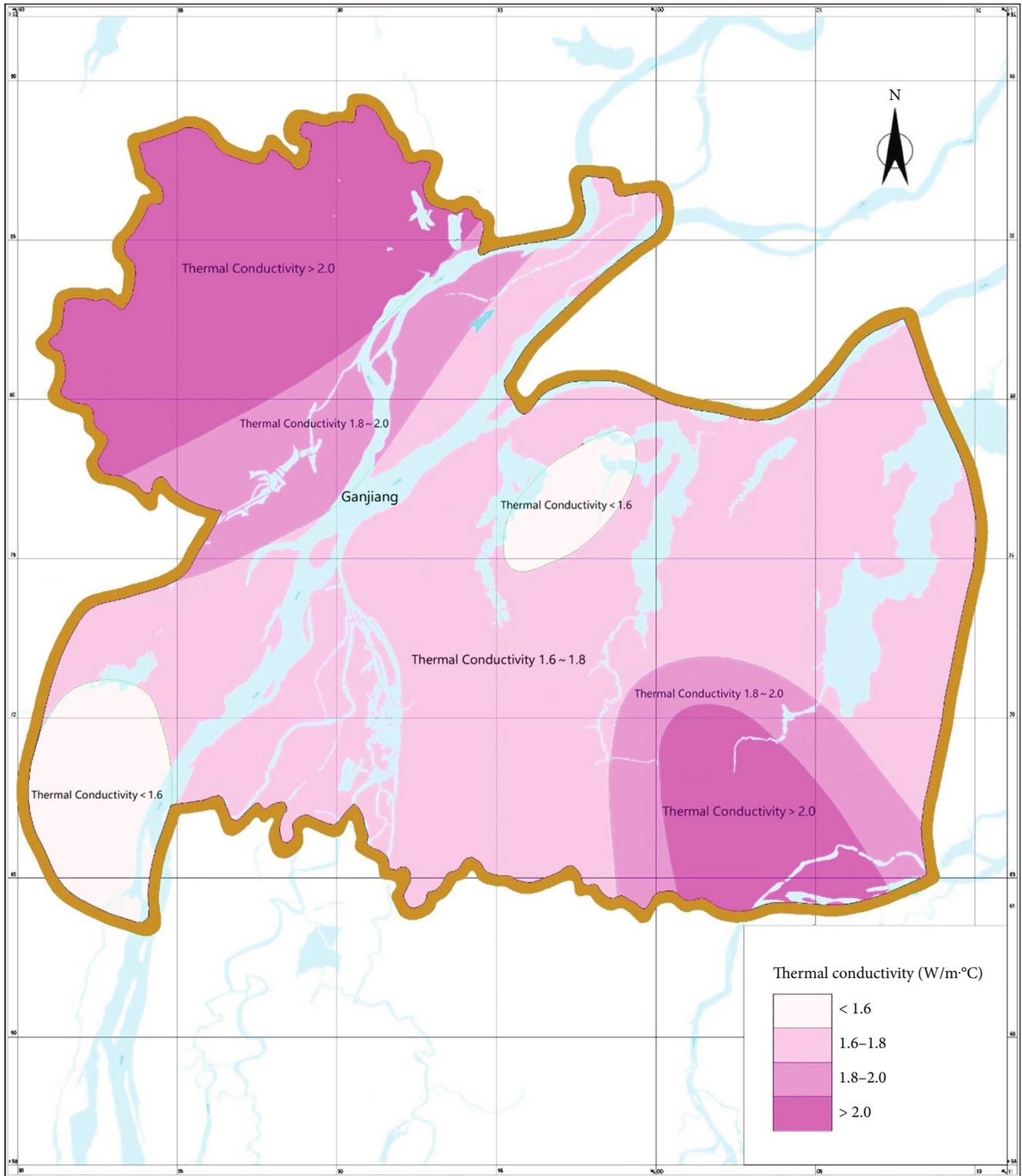


FIGURE 4: Plan distribution of thermal conductivity of rock and soil bodies.

1334.3~1823.7 mm. The water system in the research area is relatively developed, and the Ganjiang River and Fuhe River are the main rivers in the area.

2.2. Characteristics of the Shallow Geological Structure. According to the terrain, Nanchang is roughly the Xihe brick

factory-Jiaoqiao-Qianhu line and divided into the east and west. The upper part of the eastern alluvial plain area is the Quaternary soil layer, the thickness of the soil layer is 10~40 m, and the lower part is the red bed; the lower part of the western part of Gangbu District is mainly metamorphic rock. Figure 1 is the zoning map of the thickness of

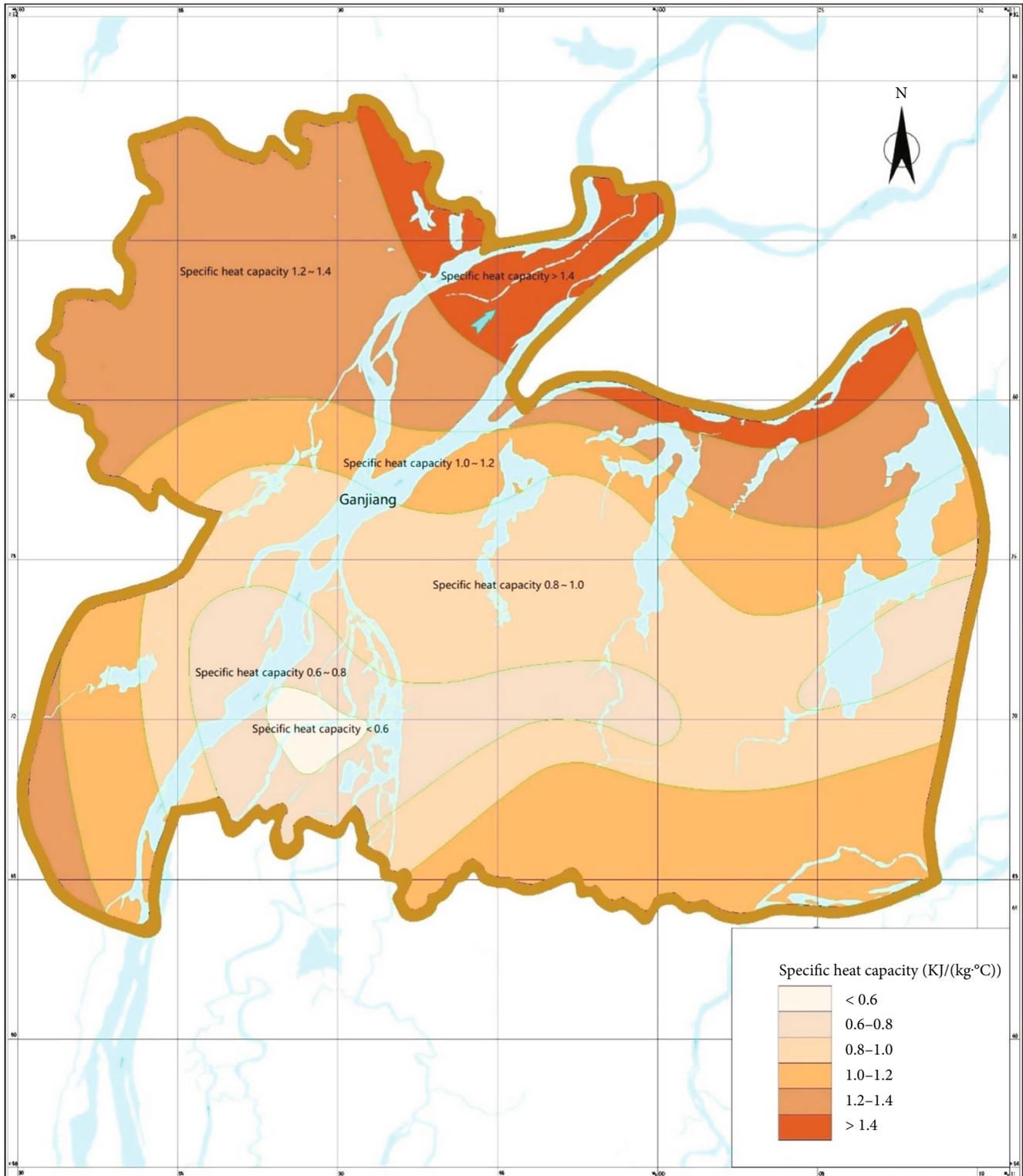


FIGURE 5: Plan distribution of specific heat capacity of rock and soil bodies.

the overlying cohesive soil layer in the study area, and Figure 2 is the zoning map of the thickness of the Quaternary sand gravel layer in the study area.

2.3. Hydrogeological Characteristics. According to the lithology combination of the aquifer group, groundwater storage

conditions, hydrological properties, and hydraulic characteristics, the working area can be divided into three groundwater types, loose rock pore fissure water, red bed pore fissure water, and bedrock fissure water, and loose rock pore aquifers, red layer pore fissure aquifer, metamorphic rock fissure aquifer, and magmatic rock fissure aquifer. Loose rock pore

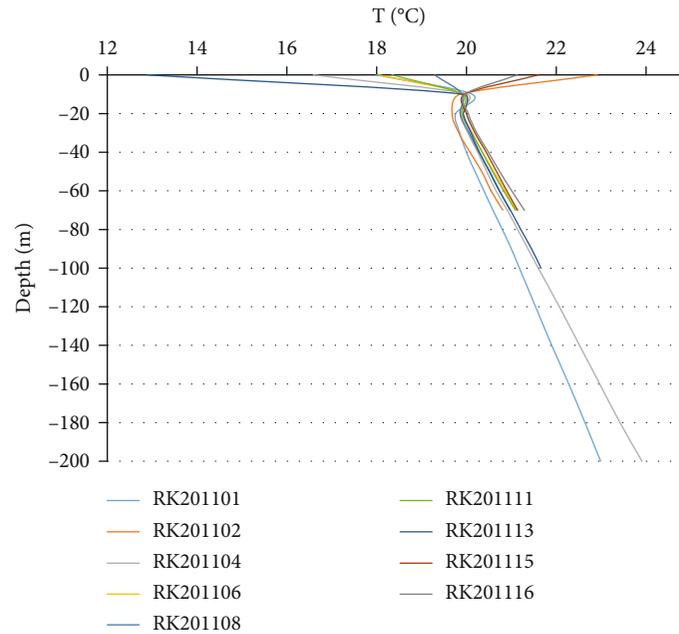


FIGURE 6: The average ground temperature of the monitoring hole changes with depth.

aquifers are widely distributed on both sides, Fuhe and Ganfu alluvial plain. The conversion inflow along and east of the Ganjiang River is $1000\sim 10000\text{ m}^3/\text{d}$, permeability coefficient is generally $10.34\sim 177.5\text{ m/d}$, and water content is mainly medium~extremely rich. The Ganjiang River and residual slope to the west of Ganjiang River are weak, and the water inflow is $\leq 1000\text{ m}^3/\text{d}$, and the permeability coefficient is $1.15\sim 5.15\text{ m/d}$; the red bed pore fissure aquifer is widely distributed under the Quaternary loose soil layer, exposed to Xiangtang in the south, Jiangxiang in the north, Shengmi Street in the west, and Maqiu in the east. The red bed aquifer is like the stratum, and the aquifer has good connectivity, generally $30\sim 60\text{ m}$; the metamorphic rock fissure aquifer is mainly distributed in the Xinjian-Muyu mountain area in the northwest of Nanchang City; the lithite is phyllite, phyllite slate, propylite, gneiss, etc.; the structural cracks are developed; and groundwater exists in the structural cracks. The average dry period runoff mode of groundwater is $1.424\text{ L/s}\cdot\text{km}^2$. The spring flow is generally $0.014\sim 0.039\text{ L/s}$, and the water inflow of a single well for the drilling and pumping test is less than $100\text{ m}^3/\text{d}$, and the permeability coefficient is less than 0.2 m/d , water-rich poor; the magmatic fissure aquifer is distributed in the Meiling area in the northwest of the working area, the lithology is inclined granite and gabbro-diabase, and the thickness of the aquifer is generally less than 30 m . The mode of runoff of groundwater is $3.23\sim 3.97\text{ L/s}\cdot\text{km}^2$. The spring flow is generally $0.14\sim 0.356\text{ L/s}$, and the water yield property is poor~medium.

2.4. Thermal Property Characteristics of the Rock and Soil Mass. On the basis of fully collecting the existing data, 16 boreholes were implemented, 164 geotechnical physical properties and 164 thermal properties, conducted indoor

and outdoor testing, and through comparative analysis of different lithology and different test methods, the thermal and physical characteristics of rock and soil bodies were systematically studied.

According to Table 1, the thermal conductivity change rules of the Quaternary loose sedimentary soil layer are as follows: silty clay < silty sand < fine sand < coarse sand < gravel sand; the thermal diffusion coefficient of the Quaternary loose sedimentary soil layer also shows a similar growth trend; the specific heat capacity of the Quaternary loose sedimentary soil layer shows a downward trend, and the larger the soil particles, the greater the thermal conductivity. The changes of the specific heat capacity, thermal conductivity, and thermal diffusion coefficient of bedrock are as follows: calcareous mudstone < sandstone < phyllite. The above changes show that the thermal release effect of coarse grain rock soil is good and has a poor thermal storage effect; on the contrary, the thermal release effect of the fine granular rock soil is poor and has a better thermal storage effect. The development and utilization of shallow geothermal energy resources requires the rock and soil layers to have good heat release performance, which is conducive to heat transfer.

In situ thermal response tests of 9 boreholes were carried out in the working area, and the plane distribution of test boreholes is shown in Figure 3. All the thermal response test holes in the study area have completed the high and low power tests for at least 48 hours, and there are obvious stable sections tending to the horizontal in the late stage of the test. After calculation, the comprehensive thermal conductivity of rock and soil in the study area is between 1.14 and $3.70\text{ W}/(\text{m}\cdot^\circ\text{C})$. On this basis, combined with the existing data, a plane distribution map of the thermal conductivity and specific heat capacity of the rock and soil in the study area (Figures 4 and 5) was made.

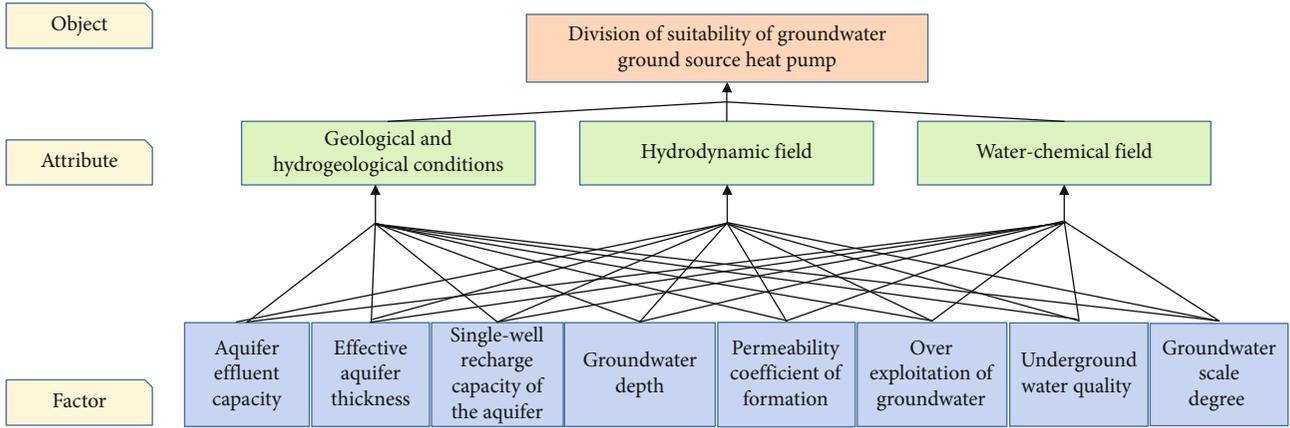


FIGURE 7: Structural diagram of the hierarchical analysis method of the underground water ground source heat pump.

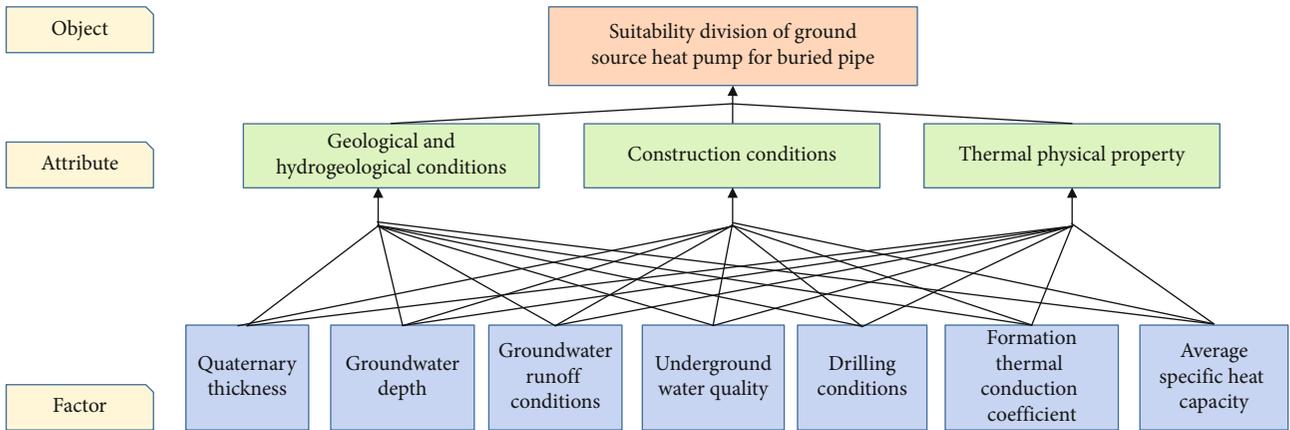


FIGURE 8: Structural diagram of the hierarchical analysis model of the ground source heat pump of the buried pipe.

TABLE 2: Weight of suitability of the groundwater ground source heat pump.

Evaluation elements	Weight
Aquifer effluent capacity	0.2806
Effective aquifer thickness	0.1824
Single-well recharge capacity of the aquifer	0.1534
Groundwater depth	0.0580
Permeability coefficient of formation	0.0468
Overexploitation of groundwater	0.0136
Underground water quality	0.1806
Groundwater scale degree	0.0846

TABLE 3: Weight table of the suitability of the ground source heat pump.

Evaluation elements	Weight
Quaternary thickness	0.0926
Groundwater depth	0.1039
Underground runoff conditions	0.0927
Underground water quality	0.0998
Drilling conditions	0.4567
Formation thermal conduction coefficient	0.0774
Average specific heat capacity	0.0769

2.5. *Characteristics of the Shallow Geothermal Field in Nanchang.* According to the drilling temperature measurement data, the vertical variation of ground temperature can be roughly divided into a temperature-variable zone, constant-temperature zone, and temperature-increasing zone [27]. Figure 6 shows the variation of ground temperature with depth in some monitoring holes. The burial depth of the constant-temperature zone in Nanchang is 10~24 m, which is closely related to the groundwater level; the burial depth of the constant-temperature zone is 30~50 m. The thickness of the constant-temperature zone in the working

area is 13~40 m. The thickness of the constant-temperature zone in the Changbei area is thicker, and in most other areas, it is about 20 m. The average temperature of the constant-temperature zone is 19.16~20.08°C, with an average of 19.62°C, which is 1.08~2.53°C higher than the average temperature in Nanchang, 1.87°C on average. The ground temperature in the temperature-increasing zone increases with the increase in depth. The ground temperature at a depth of 200 m is 22.3~28.10°C, and the average ground temperature is 25.47°C. The light (temperature less than 25°C and depth less than 200 m) ground temperature gradient is 1.82~5.40°C/100 m, average 3.41°C/100 m. The shallow

TABLE 4: Evaluation table of factors affecting the suitability of the ground source heat pump.

Element indicators	Grading level	Assignment of the value
Aquifer effluent capacity (m ³ /d)	<10	1
	10~100	3
	100~1000	5
	1000~5000	7
	≥5000	9
Effective aquifer thickness (m)	<10	1
	10~20	3
	20~40	5
	40~60	7
	≥60	9
Single-well recharge capacity of the aquifer (m ³ /d)	<50	1
	50~500	3
	500~1000	5
	1000~2000	7
	≥2000	9
Groundwater depth (m)	<5, 100~200	1
	5~10, 80~100	3
	10~15, 50~80	5
	15~20, 30~50	7
	20~30	9
Permeability coefficient of formation (m/d)	<5	1
	5~10	3
	10~20	5
	20~50	7
	≥50	9
Overexploitation of groundwater	Groundwater volume is abundant	9
	The groundwater volume is average	5
	Overdraft	1
Underground water quality	Class I water	9
	Class II water	7
	Class III water	5
	Class IV water	3
	Class V water	1
Groundwater scale degree	Very few	9
	Less often	7
	More than that	5
	A lot of it	1

geothermal gradient generally presents a trend that the southern region is larger and the northern region is smaller, and the new stratum is larger, and the old stratum is smaller. The ground temperature gradient distribution features an obvious strip. In the Chaoyang New Area and Luojia Area, the ground temperature gradient is large, 5.40°C/100 m, providing a channel for the lower heat source conduction, while the heat diffusion is relatively low and the heat gradient is slow; for the buried depth in Changbei, the thermal permeability is good, the temperature change is slow, and the

ground temperature gradient is small (pending further study).

3. Evaluation Method of Shallow Geothermal Energy Suitability

3.1. *Evaluation System Establishment.* The evaluation of the development suitability of shallow geothermal energy is a comprehensive analysis of resource storage conditions, distribution characteristics, development and utilization

TABLE 5: Evaluation table for suitability factors of the ground source heat pump.

Factor index	Classification	Assignment
Quaternary thickness (m)	20~40	5
	40~70, 0~20	7
	>70	9
Groundwater depth (m)	<5	1
	5~10	3
	10~15	5
	15~20	7
	≥20	9
Groundwater runoff conditions	Very good	9
	Good	7
	Commonly	5
	Difference	3
Groundwater quality	Class I and II water	9
	Class III water	6
	Class IV and V water	3
Drilling conditions	Good	9
	Commonly	5
	Difference	1
Thermal conductivity of formation (W/(m·°C))	<1.6	3
	1.6~1.8	5
	1.8~2.0	7
	≥2.0	9
Mean specific heat (kJ)/(kg·°C)	<0.8	1
	0.8~1.0	3
	1.0~1.2	5
	1.2~1.4	7
	≥1.4	9

TABLE 6: Suitability classification index of the groundwater source heat pump.

Index	0~5	5~7	7~9
Suitable type	Unsuitable area	Basically suitable area	Suitable area

conditions, and resource conditions, and the evaluation results are an important basis for guiding the development and utilization of shallow geothermal energy. The suitability evaluation factors include regional geology, hydrogeology, environmental geology, geotechnical and thermal properties, and development and utilization conditions. Among them, the geological and hydrogeological conditions, groundwater dynamic field, and hydrochemical field are the main factors for the suitability of the groundwater ground source heat pump; geological and hydrogeological conditions, stratum thermal property parameters, and construction conditions are the main factors for the evaluation of the buried pipe ground source heat pump [28].

Hierarchical analysis (AHP) is a systematic method to making decisions on more complex and fuzzy problems [29–35]. The environmental geological conditions in Nanchang are complex, and many factors affect resource devel-

opment. The hierarchical analysis method can better express the storage characteristics and development and utilization conditions of shallow geothermal energy. Through the comprehensive analysis of influencing factors, the suitability evaluation system of the groundwater ground source heat pump and buried pipe ground source heat pump was established, respectively (Figures 7 and 8). Among them, we have the application of the buried pipe ground source heat pump in Nanchang City, and from the perspective of saving land, this evaluation only considers the vertical buried pipe method. The evaluation system consists of 3 layers (from top to bottom: system target layer (O (Object)), attribute layer (A (Attribute)), and element index layer (F (Factor))).

3.2. *Determination of Element Weight.* According to the hierarchical analysis method (AHP), on the basis of the

TABLE 7: Suitability classification index of the buried pipe ground source heat pump.

Suitable type	0~5	5~6	6~9
Suitable type	Unsuitable area	Basically suitable area	Suitable area

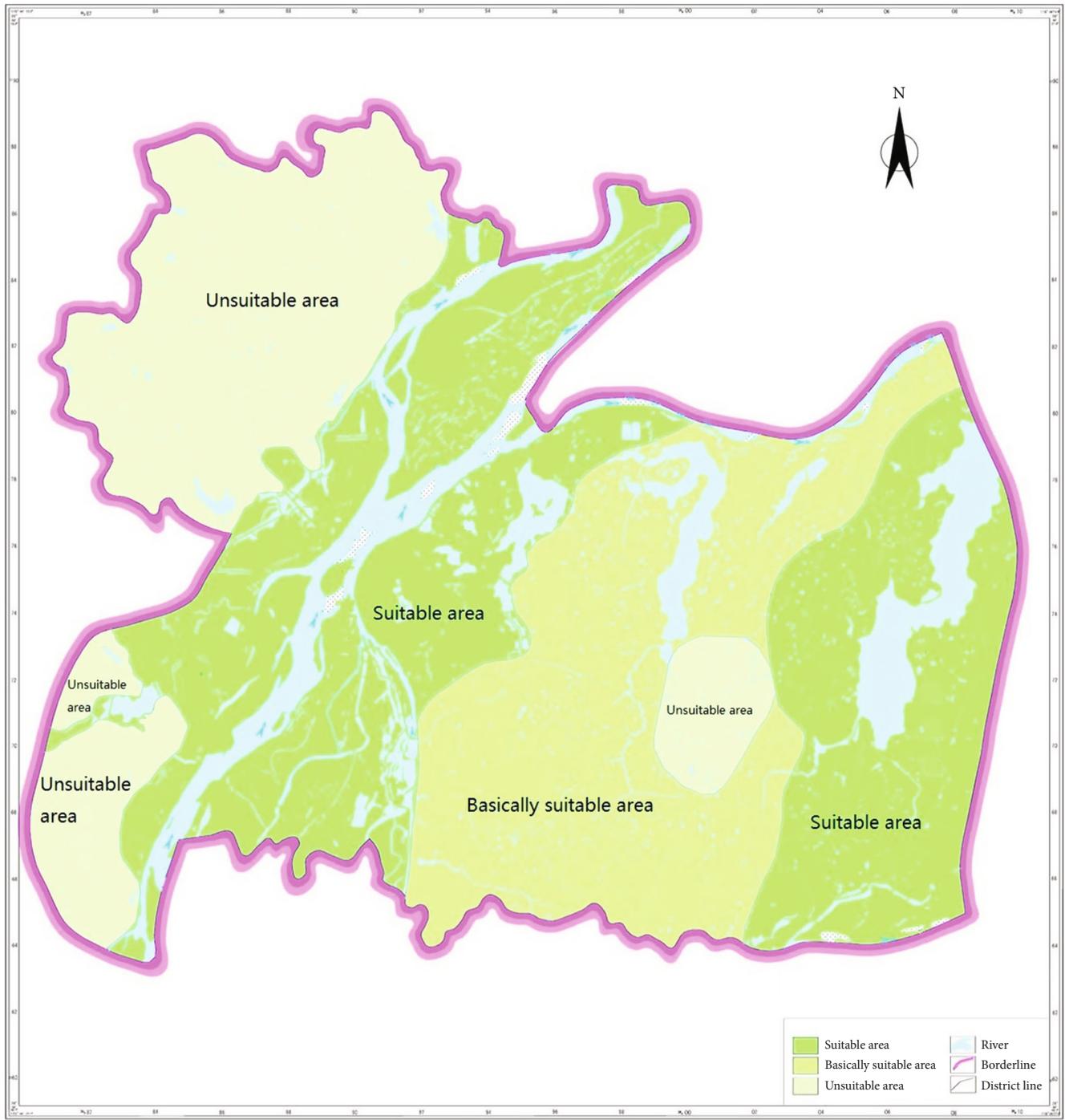
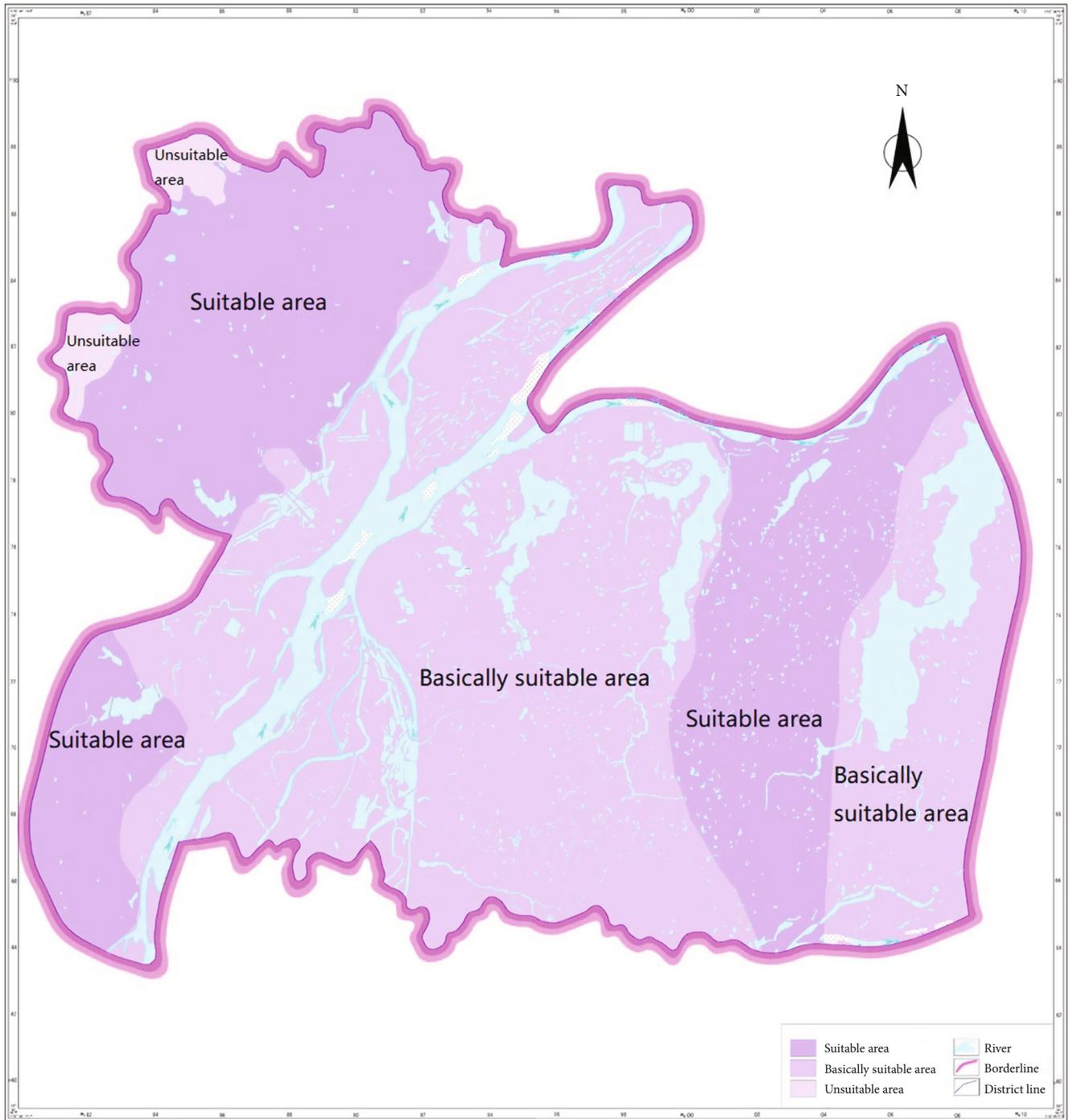


FIGURE 9: Suitability zoning map of the groundwater ground source heat pump.

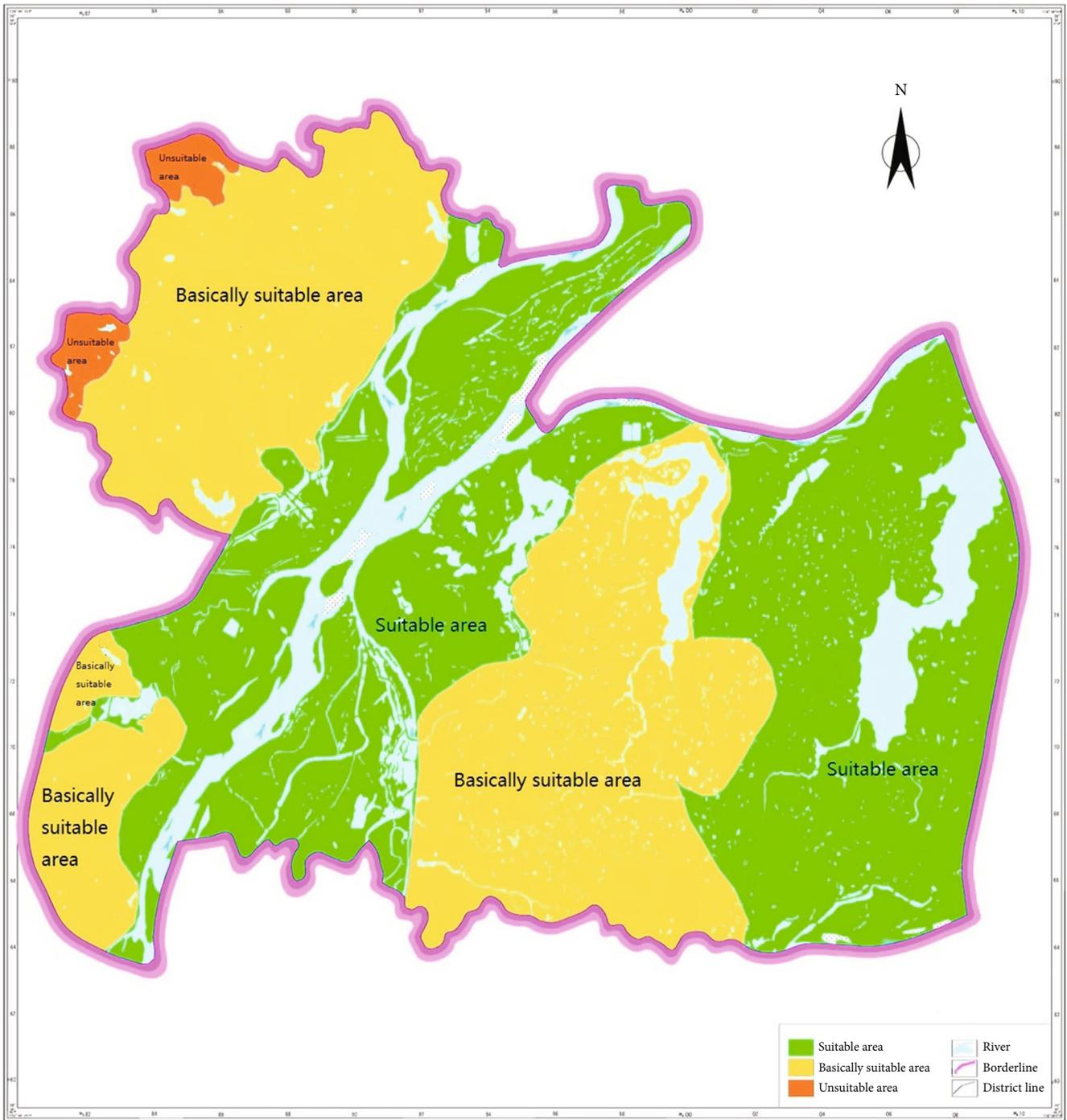


Scale 1:50000

FIGURE 10: Suitability zoning map of the buried pipe ground source heat pump.

TABLE 8: Comprehensive suitability classification table of the ground source heat pump system.

Groundwater	Suitable area	Buried pipe Basically suitable area	Unsuitable area
Suitable area	Suitable area	Suitable area	Basically suitable area
Basically suitable area	Suitable area	Basically suitable area	Basically suitable area
Unsuitable area	Basically suitable area	Basically suitable area	Unsuitable area



Scale 1:50000

FIGURE 11: Suitability zoning of shallow geothermal energy development and utilization.

hierarchical membership of the evaluation system, the 1~9 scale method is used to compare the relative importance of each factor in the attribute layer and element layer, respectively (the greater the importance of the greater influence on the appropriate area division), and build a comparison matrix. By calculation, check the consistency of the comparison matrix, modify the comparison matrix if necessary to achieve acceptable consistency, and finally determine the

weight of the elements in the element layer in the target layer (see Tables 2 and 3).

3.3. Element Index Layer Production and Index Extraction. In the GIS drawing software, make the drawings of each element index. Assign the various range values in each drawing (the higher the condition of the ground source heat pump). Then, the whole Nanchang City is divided into a grid of 5

km \times 5 km, overlaps the grid map with the already assigned map, and extracts the assignment to each layer through its spatial analysis function. Eventually, the assignment in the graph corresponds to the corresponding grid. Each influence element is assigned as follows [2, 23, 29] (Tables 4 and 5).

3.4. Comprehensive Evaluation. The comprehensive index method is used to multiply each attribute assignment on each grid point with its corresponding weight value and then summed, and the preliminary score on each grid point can be obtained. According to the distribution of this score, the scoring ranges of the groundwater and buried pipe ground source heat pumps in each suitable area are determined, respectively, which are shown in Tables 6 and 7.

4. Evaluation Results of the Suitability of Shallow Geothermal Energy

Each layer is superimposed by GIS spatial analysis, and the comprehensive evaluation zoning map is obtained by combining actual situations.

4.1. Suitability Division of the Groundwater Ground Source Heat Pump. According to Figure 9, the suitability zoning of the groundwater ground source heat pump in Nanchang City is divided into three categories. Among them, there are two suitable areas for the groundwater ground source heat pump (covering an area of 252.17 km², accounting for 49.4%), which are mainly distributed along Ganjiang River and Fuhe River and to the east of Yaohu Lake. The main aquifer is a single sand gravel layer with good water yield, strong recharge capacity, and superior hydrogeological conditions, which is very suitable for the development and utilization of groundwater ground source heat pump engineering. There is one basically suitable area (133.64 km², accounting for 26.2%), which is mainly distributed in the alluvial plain area to the east of Qingshan Lake and Xianghu Lake and the west of Yaohu Lake. The main aquifer is a single sand gravel layer with general water yield and medium recharge capacity. There are 4 unsuitable areas (124.29 km², accounting for 24.4%), which are mainly distributed in the center of Gangbu and Nangang funnel to the west of Ganjiang River. The Quaternary aquifer is generally poor in water, and the main aquifer is bedrock fissure water, with poor recharge capacity.

4.2. Suitability Zoning of the Buried Pipe Ground Source Heat Pump. According to Figure 10, the suitability zoning of the buried pipe ground source heat pump in Nanchang City is divided into three categories. Among them, there are three suitable areas for the buried pipe ground source heat pump (180.49 km², accounting for 35.4%), which are mainly distributed in the east of Aixi Lake, the west of Yaohu Lake, and the west of Ganjiang River. There are two basically suitable areas (320.82 km², accounting for 62.9%), which are mainly distributed in the east of Ganjiang River, the west of Aixi Lake, and the east of Yaohu Lake. There are two unsuitable areas (8.79 km², accounting for 1.7%), which are mainly distributed in the northwest edge of the hard metamorphic

rock area. Due to the large-scale drainage of the aquifer or hard lithology, it is difficult to drill, and the suitability of the buried pipe heat exchange system is poor.

4.3. Suitability Zoning of the Ground Source Heat Pump. The suitability zoning of the ground source heat pump system is the comprehensive zoning of groundwater suitability and ground pipe suitability. The zoning principle is as follows: suitability priority principle (see Table 8); that is, the suitability of different forms of the heat pump system is compared, and the comprehensive suitability is the better of the two. The comprehensive suitability zoning of the ground source heat pump system is shown in Figure 11.

According to Figure 11, the suitability zoning of the ground source heat pump in Nanchang City is divided into three categories. Among them, there are two suitable areas for GSHP (covering an area of 290.13 km², accounting for 56.9%), which are mainly distributed along Fuhe River of Ganjiang River, west of Qingshan Lake and Xianghu Lake and east of Aixi Lake. There are four basically suitable areas (211.18 km², accounting for 41.4%), which are mainly distributed in Gangbu to the west of Ganjiang River, east of Hongjiaozhou and Qingshan Lake, and west of Aixi Lake. There are two unsuitable areas (8.79 km², accounting for 1.7%), which are mainly distributed in the northwest edge of the hard metamorphic rock area. Due to the large-scale drainage of the aquifer or hard lithology, it is difficult to drill, and the suitability of the ground source heat pump heat exchange system is poor.

5. Conclusion

- (1) The shallow geothermal energy in Nanchang City has good storage conditions, and the resource reserves are large and widely distributed. The total area of the study area is 510.1 km². Among them, 98.3% of the area is suitable for the construction of ground source heat pump projects, and only 1.7% of the area is not suitable for the construction of ground source heat pump projects. Therefore, a large amount of shallow geothermal energy can be used to heat and cool buildings within the entire survey area of Nanchang City
- (2) According to the results of the suitability zoning of the groundwater ground source heat pump, the suitable area for the groundwater ground source heat pump is 252.17 km², the basically suitable area is 133.64 km², and the unsuitable area is 124.29 km²
- (3) According to the results of the suitability zoning of the buried pipe ground source heat pump, the suitable area for the buried pipe ground source heat pump is 180.49 km², the basically suitable area is 320.82 km², and the unsuitable area is 8.79 km²

Data Availability

The data support the results of this study and are reported in the tables.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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