Science Academique
ISSN 2583-6889
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Pages: 61-78

Research Article

Suitability zoning for the development and utilization of shallow geothermal energy

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Citation: Zhenhua Z, Dongyi L, Weijia Y, Haijiao W, shuming Q, et al. (2024) Suitability zoning for the development and utilization of shallow geothermal energy. Sci Academique 5(1): 61-78

Received: 14 April, 2024; **Accepted:** 9 June, 2024; **Published:** 22 June, 2024

Abstract

Shallow geothermal energy is widely distributed and has significant reserves, thus making it a valuable clean energy source for development and utilization. However, research on the resource reserves and development methods of shallow geothermal energy in China is relatively weak, thereby restricting its development and utilization. To address this issue, this paper focuses on the built-up area, planning area, and new area of Liaocheng City, Shandong Province, as the research area and utilizes two mining methods: groundwater heat pump and buried pipe heat pump. The study comprehensively accounts for geological and hydrogeological conditions and applies the analytic hierarchy process to evaluate the suitability of resource development and utilization in the study area. The results indicate that shallow geothermal energy projects are suitable for the entire study area, with areas of good suitability accounting for 59.12% and areas of medium suitability accounting for 40.88%, while there are no areas of poor suitability. Additionally, the buried pipe heat pump system is suitable for about 94% of the entire area. These conclusions provide a reference for evaluating shallow geothermal energy resources, determining engineering heat transfer methods, and formulating development and utilization plans.

Keywords: Shallow geothermal energy; Analytic hierarchy process; Development and utilization; Comprehensive sub-areas

Introduction

Under the current technical and economic conditions, shallow geothermal energy, which is located at a certain depth range below the surface (generally from the constant temperature zone to a depth of 200 m) and has a temperature lower than 25 ℃, is a thermal energy resource in the earth's interior with development and utilization value [1]. Shallow geothermal energy is extensively hosted in underground rock-soil mass, groundwater, and gas. It is a kind of renewable, environmentally friendly energy and special mineral resource, and its utilization prospects are broad [2]. With the gradual maturity of heat pump technology, the development of shallow geothermal energy for heating, cooling, and hot water supply has become more and more common [3,4].

At present, domestic scholars' research on shallow geothermal energy mainly focuses on regional evaluation. According to the geological conditions and geothermal energy occurrence conditions, the analytic hierarchy process and comprehensive index method are used to analyze the study area and propose suitable methods for the region's development and utilization. Foreign scholars focus on establishing a localized suitability index evaluation framework [14,15]. For example, the European Geological Survey has a set of shallow geothermal energy management framework and governance model in urban areas [16]. Countries such as Iceland [17,18], Poland [19], Germany [20] have relatively localized evaluation frameworks.

The development and utilization of shallow geothermal energy are restricted by regional geology, hydrogeology, engineering geology, and environmental geology [21,22]. The scale and mode of development and utilization of shallow geothermal energy vary due to different geological conditions. Therefore, based on the reserves of shallow geothermal energy resources and other related conditions in the study area, this paper proposes development and utilization methods suitable for Liaocheng City.

Study area

The study area is located in the western part of Shandong Province. Its administrative division belongs to Liaocheng City. Specifically, the scope of study includes the built-up area, planning area, and new area (Figure 1). The boundaries of the study are: north to North Second Ring Road (S706), east to East Second Ring Road, south to South Outer Ring Road (S329), and west to the east of Deshang Expressway (S39). The area lies between the latitudes of 36°23′N and 36°32′N and the longitudes lies within 115°52′E and 116°05′E and its area is approximately 212 km^2.

The study area belongs to the strong water-rich section of the Liaocheng-Yucheng palaeochannel belt. The lithology of the aquifer in the study area is dominated by fine sand, followed by silt, with a thicker sand layer. The underground flow is slow, the recharge condition is good, the water abundance is better, and low salinity carbonate rock water is the main type of water, and the groundwater quality is good. Quaternary loose beds are distributed throughout the study area. The main fault in the area is the Liaokao fault. The fault runs along the line from Dengguantun to Shanguantun, which is NNE-trending and passes through the eastern part of the study area. The length of the fault in the area is about 16 km [23]. The western part of the fault is the stratigraphic area of northwestern Shandong, which mainly develops Paleogene, Neogene and Quaternary strata. The eastern part of the fault is the central and southern Shandong stratigraphic area, which mainly develops Ordovician, Carboniferous, Neogene, and Quaternary strata [24].

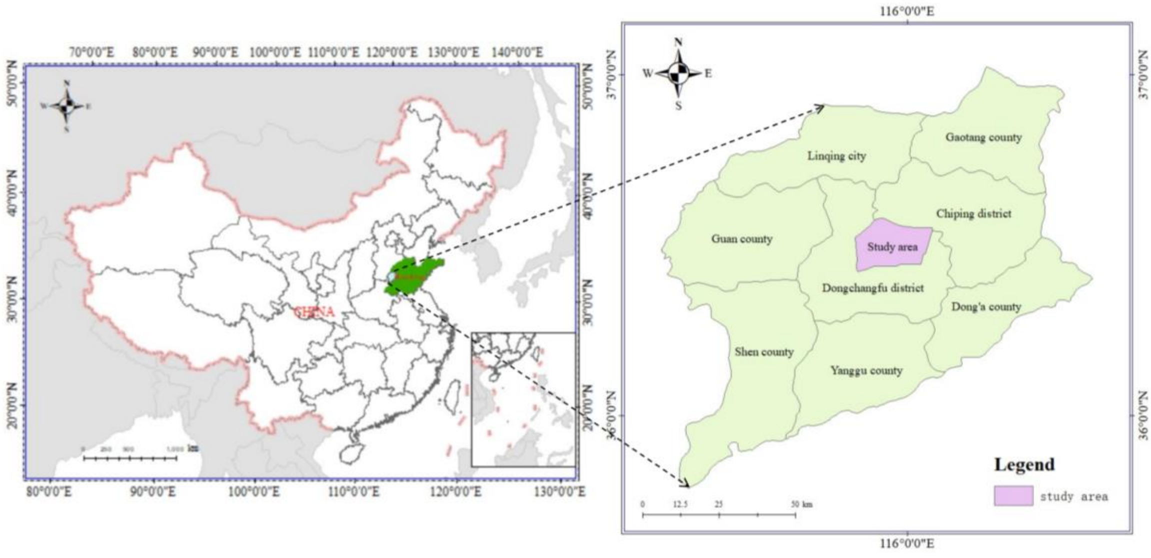

Figure 1: Geographical location map of the study area.

Analysis method

Dividing the type of study area: There are two ways to develop and utilize shallow geothermal energy resources in the study area: the groundwater heat pump system and the buried pipe heat pump system. In order to guide the rational development and utilization of shallow geothermal energy, this paper selects different reference factors to classify the suitability of the development and utilization of the two heat pump systems mentioned above. The suitability grades are divided into three categories: good suitability area, medium suitability area, and unsuitable area.

Division method: The division method uses the analytic hierarchy process (AHP) [26,27], which was proposed in the 1970s by American operations researcher T.L. Saaty et al. This is an effective method to make decisions about more complicated and ambiguous problems, as well as a combination of qualitative and quantitative, systematic, and hierarchical analysis method. This method quantifies the empirical judgments of decision makers. Therefore, it is more suitable for issues that are difficult to be completely quantitatively analyzed, especially in cases of complex structure of target factors and lack of necessary data [28]. This method is widely used in practice because it is simple, flexible, and practical.

The main steps of this method are as follows: First of all, establish a hierarchical structure model. The whole target problem is decomposed, with the suitability of shallow geothermal energy development and utilization taken as the target layer. Then, taking into account the various factors that influence this target, the target layer is decomposed into an attribute layer and a factor index layer. Secondly, construct a comparative judgment matrix. Through a two-by-two comparison of the various elements, combined with expert advice and relevant literature, a judgment matrix is established. Then, hierarchical single arrangement and consistency tests are carried out. Thirdly, hierarchical ordering. Using the normalization method, calculate the weight of each factor relative to the upper level and the overall target, and then determine the importance ranking weight of each factor. In the end, consistency tests and decisions are made.

Partitioning of shallow geothermal energy

Selecting evaluation index

According to the partitioning requirements of the Code for Evaluation of Shallow Geothermal Energy Survey DZ/T0225-2015, combined with the actual situation of the study area, the suitability partitioning of groundwater heat pumps mainly takes into account the geological and hydrogeological conditions, hydrodynamic fields and hydrochemical fields, temperature fields, and geological environment, among others [29].

Geological and hydrogeological conditions: The factors affecting the existing environment of shallow geothermal energy mainly consider the thickness, water-richness, and recharge capacity of the aquifer, as well as the thickness, structure, and water-rich characteristics of the aquitard, among others. The quality of water-richness reflects the enrichment degree of groundwater and the discharge capacity of the aquifer. It determines the amount of water available for the groundwater heat pump system and the amount of load that can offer cooling or heating. The recharge capacity is related to the sustainability of the heat pump system operation and the protection of groundwater resources.

Hydrodynamic fields: The hydrodynamic field includes groundwater depth and groundwater runoff conditions. The buried depth of groundwater determines the magnitude of natural recharge pressure, which is an important factor affecting recharge capacity. When the groundwater depth is shallow and the groundwater runoff conditions are good, the flow rate is high. This means that the cold and heat load released by the heat exchanger is quickly taken away by the groundwater, and the energy exchange between the groundwater and the rock and soil is fast. These conditions make it more suitable to develop shallow geothermal energy.

Hydrochemical characteristics: Hydrochemical characteristics include the corrosion potential of groundwater and its salinity. Only when the water quality meets the requirements for circulating water in groundwater heat pump units will it not cause significant corrosive harm to the equipment, pipelines, valves, and other materials of the unit. This helps avoid the production of significant chemical precipitation and ensures the long-term stable operation of the groundwater heat pump system [30].

Temperature fields: The temperature field mainly considers the groundwater temperature and the thermal influence radius. The heat exchange system has certain requirements for the temperature of the water source, as the water temperature directly affects the operational efficiency of the heat exchange system. Groundwater that does not meet the temperature requirements is not suitable as a water supply source for heat pump systems.

Geological environment: Land subsidence is the main geological environmental issue affecting the normal operation of groundwater heat pump systems in the study area [31]. Shallow groundwater is usually stored in aquifers consisting of loose, unconsolidated, or weakly consolidated Quaternary sediments. Groundwater source heat pumps often exploits groundwater in the sand layer sandwiched between cohesive soil layers, and cohesive soil is also sandwiched inside the sand layer. However, the compressibility of the cohesive soil layer is large, and the compression deformation is easy to occur when the groundwater level drops. If the thickness of the cohesive soil layer in the exploitation area is large and it is not recharged in time, it is possible to produce rock and soil deformation, leading to uneven land subsidence. However, independent groundwater source heat pumps do not generally induce significant land subsidence. But when the groundwater source heat pump is densely distributed, it may increase the risk of land subsidence if a combined funnel is formed. Therefore, attention should be paid to the spacing of extraction wells during exploitation to avoid causing ground subsidence.

Stratigraphic lithology and thermophysics: Different lithologies reflect specific generating environments. This not only determines their thermal-physical properties and the size of the single hole heat transfer, but also affects the difficulty of heat exchange hole construction and the initial investment of the project. The thermal conductivity of rock and soil reflects the speed of energy transfer and exchange, which directly determines the heat transfer capacity of the buried pipe heat exchanger.

The rest: The main factors considered are important water sources and other factors. Because the development and utilization of shallow geothermal energy involve the extraction and recharge of groundwater, attention should be paid to whether there are important water sources in the vicinity, in order to avoid impacts on water quality or quantity.

Constructing an evaluation system

The evaluation system of the groundwater heat pump system is shown in Figure 2.

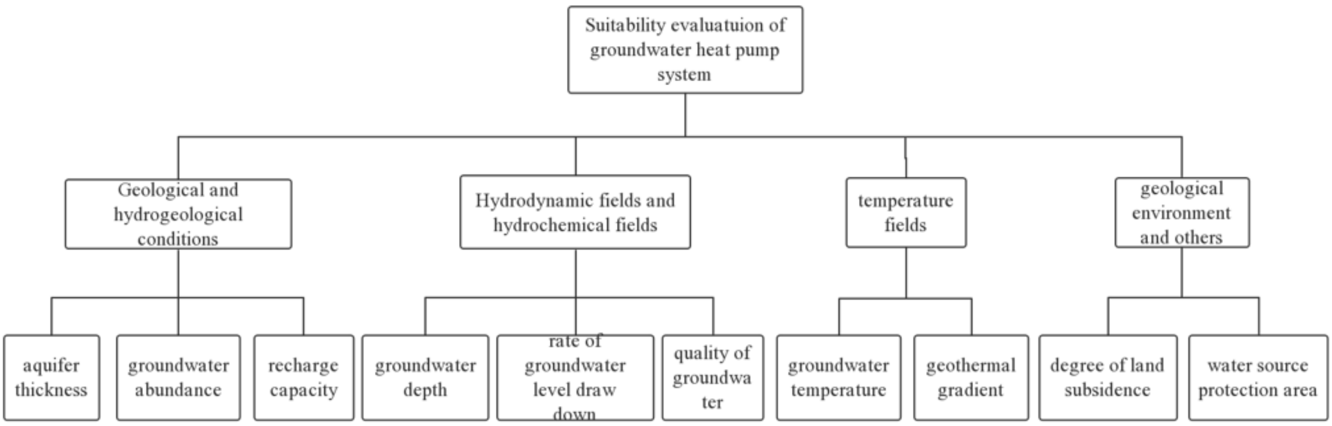

Figure 2: Structure diagram of suitability zoning evaluation of groundwater heat pump system.

The evaluation system of the buried pipe heat pump system is shown in Figure 3.

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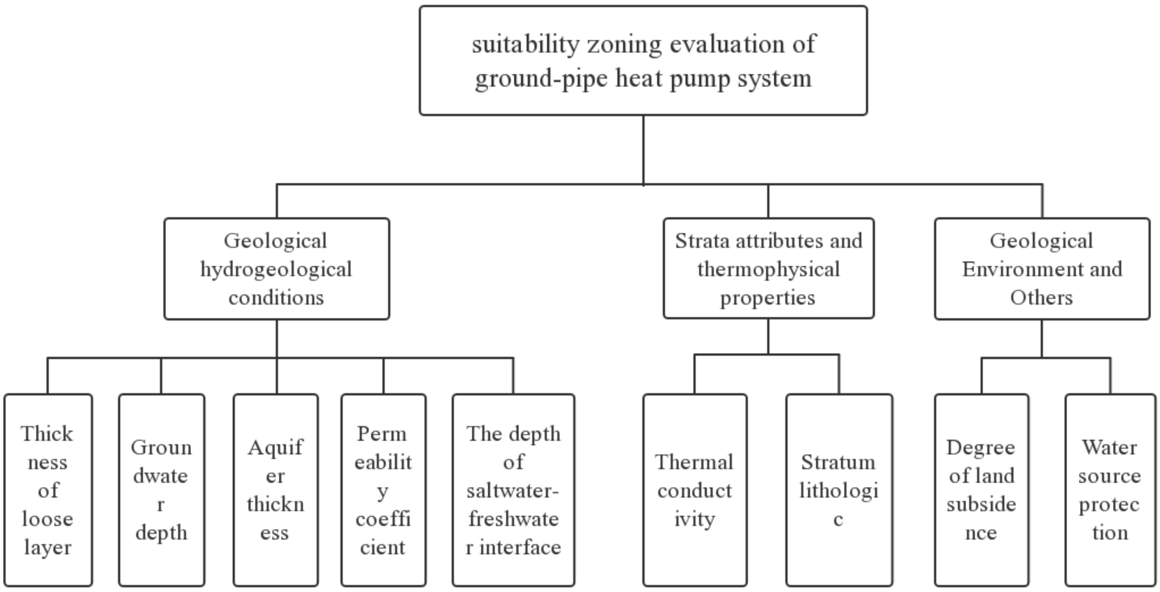

Figure 3: Structure diagram of suitability zoning evaluation of ground-pipe heat pump system.

Determining the weight of the impact factor

Among the influencing factors, the index factors that have the greatest influence on the suitability zoning of groundwater heat pumps are recharge capacity and groundwater dynamics. After comprehensive consideration, the weight of each factor in the evaluation of groundwater heat pump system is shown in Table 1.

Influence factors	weight	Influence factors	weight
Aquifer thickness	0.0746	Quality of groundwater	0.0977
Groundwater abundance	0.1701	Groundwater temperature	0.0928
Recharge capacity	0.1945	Geothermal gradient	0.0309
Groundwater depth	0.1537	Degree of land subsidence	0.0618
Descending rate of groundwater level	0.0619	Water source protection area	0.0618

Table 1: The final weight of each element in the total objective of the ground water heat pump system.

Considering the actual situation and expert opinions, the weight of each factor index factor in the evaluation of buried pipe heat pump system is shown in Table 2.

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Influence factors	weight	Influence factors	weight
Thickness of loose layer	0.2135	Stratum lithologic	0.1669
Groundwater depth	0.0887	Thermal conductivity	0.1669
Aquifer thickness	0.1133	Degree of land subsidence	0.0708
Permeability coefficient	0.0676	Water source protection	0.0708
The depth of saltwater-freshwater interface	0.0416		

Table 2: The final weight of each element in the total target of the ground-pipe heat pump system.

Making quantitative evaluation criterion

The grid generation is based on the 1:50,000 geographic base map, and the grid size is 500m × 500m. With the aid of GIS mapping software, the maps of each factor index are made, including the zoning map of single well unit water inflow, the zoning map of recharge capacity, the zoning map of aquifer thickness, the zoning map of groundwater depth, the zoning map of corrosion, and the zoning map of salinity. Comparison criteria are based on the suitability of building groundwater source heat pump systems and buried pipe heat pump systems. Each factor is assigned according to the factor classification; the more favorable to the application of the heat pump system, the higher the score awarded. The range of values is 1-9, so that all data are converted into dimensionless values between 1-9 that can be compared with each other. The assignment results of each factor are shown in Table 3 and Table 4. The grid subdivision diagram is superimposed with the assigned map, and then the assignment in each element map corresponds to the corresponding grid. Using the comprehensive evaluation index method, the attribute assignment on each grid point is multiplied by its corresponding weight value. Then, sum them up to get the initial score for each point.

The calculation formula of the comprehensive evaluation index method is shown in the formula (1).

$$R_k = \sum_{i=1}^{n} \alpha_i X_i \qquad (1)$$

where $R_k$is the comprehensive evaluation index, α_i is the weight of index elements, X_i is the attribute assignment of index elements, n is the number of index elements.

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Table 3: Evaluation index assignment table for suitability of groundwater heat pump system

Item	Classification of factors	Assignment	Explanation
Aquifer recharge capacity (%)	≤30	3	Comprehensive consideration of the proportion of mining and irrigation wells
	30~50	5	
	50~80	7	
	≥80	9	
Aquifer water capacity (m3/d·m)	≤120	3	Expressed in units of water inflow
	120~500	6	
	≥500	9	
Aquifer thickness (m)	≤10	3	
	10~30	6	
	≥30	9	
Descending rate of groundwater level (m/a)	≤0.5	9	
	0.5~1.5	6	
	≥1.5	2	
Groundwater depth (m)	≤5	2	
	5~10	5	
	10~15	7	
	≥15	9	
Corrosivity	Corrosive water	4	
	Semi-corrosive water	6	
	Noncorrosivity	9	
Mineralization (g/l)	≥1	6	
	1~0.5	8	
	≤0.5	9	

Table 4: Evaluation index assignment table for suitability of buried pipe heat exchange system.

Item	Grading	Assignment
Aquifer thickness (m)	≤10	2
	10~30	6
	≥30	9
Groundwater depth (m)	≤5	2
	5~10	4
	10~15	6
	≥15	9
Quaternary thickness (m)	≤60	3
	60~120	6
	≥120	9
Thermal conductivity (W/m·℃)	≤0.9	3
	0.9~1.5	6
	≥1.5	9

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Suitability zoning standards

According to the analytic hierarchy process, partition according to the actual score. The partitioning criteria are shown in Table 5.

Evaluation score	7~9	5~7	0~5
Adaptive partition	Good adaptability	Moderate adaptability	Inadaptability

Table 5: Zoning index for suitability evaluation of heat pump system.

Comprehensive zoning of shallow geothermal energy development and utilization

Suitability zoning of groundwater heat pump system

According to the calculation results of the above parameters, the development and utilization suitability of the groundwater heat pump system in the study area can be divided into two levels, namely, the medium suitability area and the unsuitable area. The specific division of the area is shown in Figure 4.

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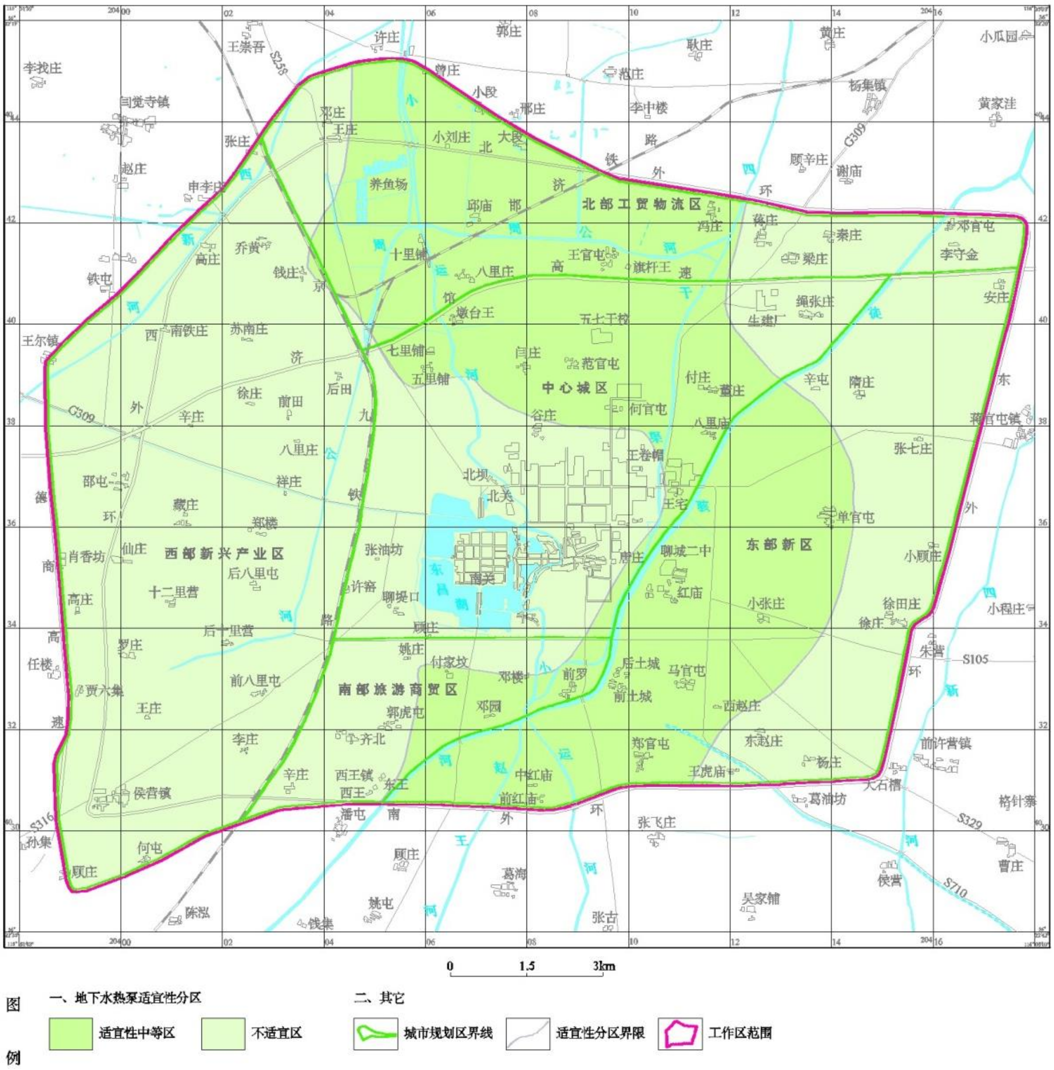

Figure 4: Suitability zoning map of groundwater heat pump system in the study area.

Medium suitability area: The medium suitability area is mainly distributed outside the central old city area, which is generally concave in shape, including Dengwang-Wulipu-Heguntun-Qianluo-Fujiafen-Dongwang-Qianhongmiao-Wanghumiao-Shanguntun-Fengzhuang-Zengzhuang within a line.

These areas cover an area of 79.39 km^2, accounting for 37.45% of the total area. The lithology of the aquifer is mainly fine sand and silt, and the water richness is good. The unit water inflow in the area is generally 120 m^3/d · m, the single well recharge capacity is generally greater than 50%, and it can reach about 90% near Zhaozhuang and Qiganwang in the north. The buried depth of water level in the area varies greatly. The buried depth is generally 5~11 m, and the annual variation of water level is about 1 m. The water quality in the area is mainly non-

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corrosive water, and the semi-corrosive water is scattered. The salinity is less than 1g/l in most areas and 1~2g/l in the southwest.

Unsuitable area: The remaining part of the study area is not suitable, including the water source area of Liaocheng power plant, the old city area, and the Dongchang Lake area. The total area of unsuitable area is 132.61 km^2, accounting for 62.55% of the total area. The lithology of the aquifer in the area is mainly fine sand and silt, and the water richness is good. The unit water inflow in the area is generally 80~120 $m^3/d \cdot m$, and the single well recharge capacity is generally 30~50 %. The buried depth of the water level varies greatly, and the buried depth is generally less than 7m. The water level near Dongchang Lake in the old city is about 3 m, and the annual variation of water level is less than 1~1.5 m. The water quality in the area is mainly non-corrosive water, with semi-corrosive water scattered. The salinity of most areas is greater than 1 g/l, and the northwest is greater than 3 g/l.

Suitability zoning of ground heat pump system

According to the calculation results of the above parameters, the suitability of the development and utilization of the ground source heat pump system in the study area can be divided into two levels, namely, the good suitability area and the medium suitability area. The specific division area is shown in Figure 5.

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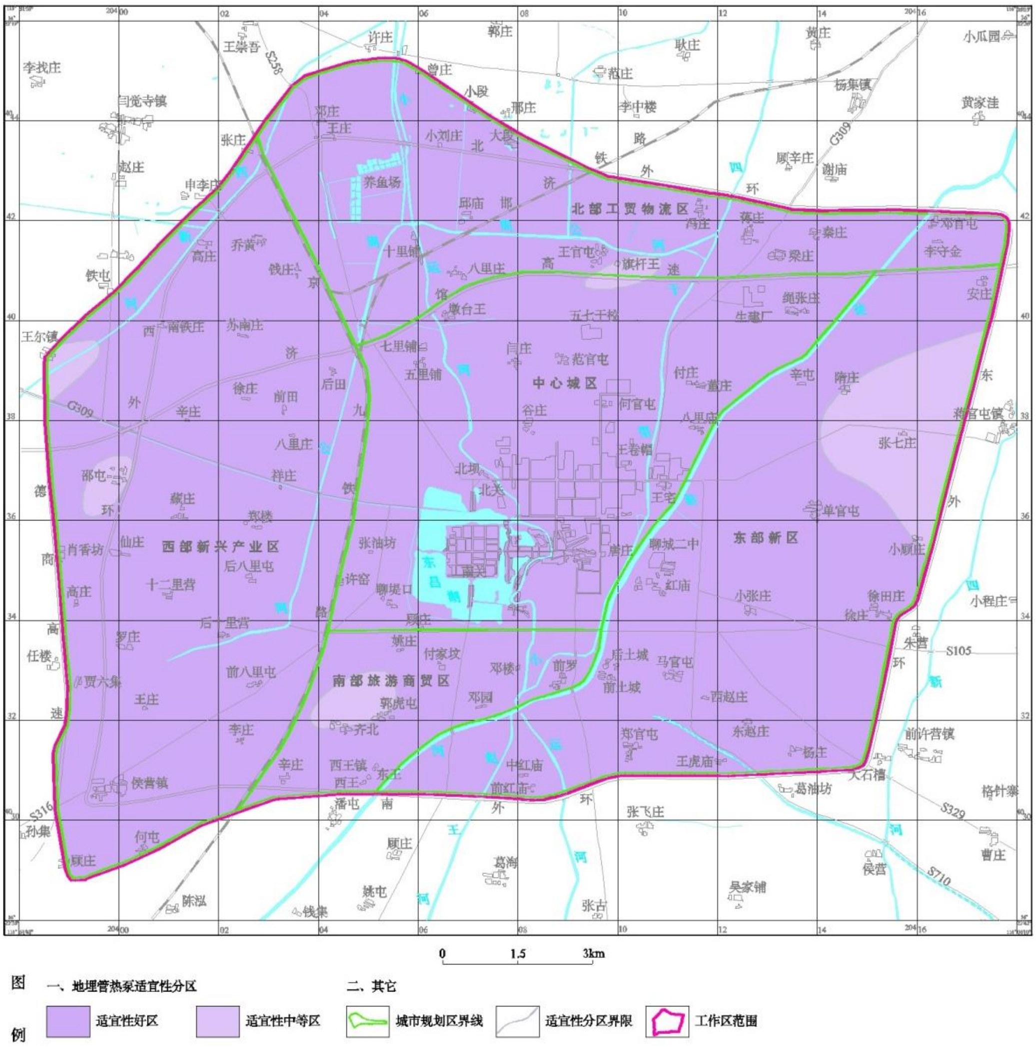

Figure 5: Suitability zoning map of ground heat pump system in the study area.

Good suitability area: It is distributed in most of the study area, with an area of 200.1 km^2, accounting for 94.39% of the total area of the region. The thickness of the Quaternary is generally greater than 120 m, and the lithology of the aquifer is fine sand and silt, with a thickness of about 30 m. Its thermal conductivity is generally 1.54~1.86 W/m·°C.

Medium suitability area: The distribution area of the suitability medium area is small, mainly distributed in Wanger Town, Shaotun in the west, Guohutun in the south, Jiangguantun in the east, and Qiganwang in the north. The area of moderate suitability is 11.9 km^2, accounting for about 5.61% of the total area of the region. The lithology in the area is mainly Quaternary loose rock stratum, and the aquifer lithology is fine sand and silt. The thickness of these strata is 10~20 m, and the thermal conductivity is generally 1.76~2.07 W/m·°C.

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Comprehensive zoning

According to the principle of suitability priority of groundwater heat pump systems and ground-pipe heat pump systems, the suitability of different forms of heat pump systems is compared in pairs, and then the more suitable utilization mode is selected (Table 6).

Groundwater heat pump system Ground-pipe heat pump system	Good suitability area	Medium suitability area	Unsuitable area
Good suitability area	Good suitability area	Good suitability area	Medium suitability area
Medium suitability area	Good suitability area	Medium suitability area	Medium suitability area
Unsuitable area	Medium suitability area	Medium suitability area	Unsuitable area

Table 6: Division of shallow geothermal energy suitability zone.

According to the above zoning principles, combined with the suitability zoning results of groundwater heat pumps and ground heat pumps, and following the principle of superior not inferior, the comprehensive suitability zoning of ground source heat pump systems in the study area is carried out (Figure 6).

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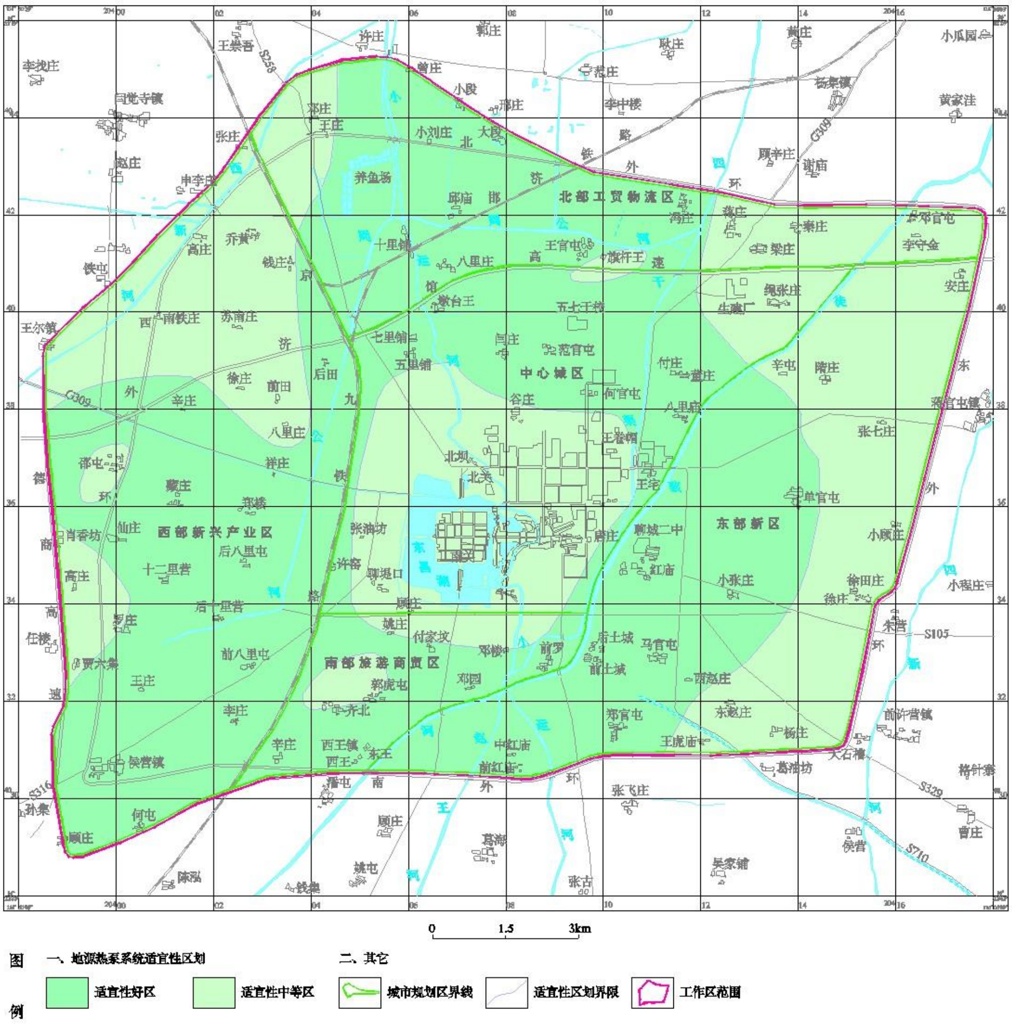

Figure 6: Comprehensive zoning map of suitability for development and utilization of shallow geothermal energy in the study area.

Good suitability area: The good suitability area is roughly circularly distributed around the central old city area, with an area of 125.33 km^2, accounting for 59.12% of the total area. The thickness of the Quaternary in this area is generally greater than 130 m, and the thickness of aquifer is about 30 m. The thermal conductivity in the area is greater than 1.5 W/m·°C, the unit water inflow is generally greater than 120 m^3/d·m, the recharge rate is about 50%, and the water level is buried at a depth of 5 to 9 m.

Medium suitability area: The medium suitability area is outside the good suitability area for the development and utilization of ground source heat pump. The distribution range is relatively scattered, with an area of about 86.67 km^2, accounting for 40.88% of the total area. The Quaternary loose layer in the area is 130~200 m, and the thickness of the aquifer is generally 10~30 m. Most of the thermal conductivity in the region is greater than 1.5 W/m·°C, only near Jiangguantun the thermal conductivity is less than 1.5 W/m·°C. The buried depth of water level in the area is 3~7 m, the unit water inflow is generally greater than 120 m^3/d·m, and the recharge rate is generally less than 50%.

Results and discussions

According to the evaluation results of the comprehensive consideration of multiple factors of shallow geothermal energy in the study area, the conclusions are as follows:

In the study area of Liaocheng City, the shallow geothermal energy resources are rich, and the thickness of the aquifer is substantial. The thermal conductivity in most areas is greater than 1.5 W/m·°C. The unit water inflow in the study area is large, and the recharge rate is high. It can be seen from the above that the study area has good conditions for development and utilization.

Generally speaking, the good suitability areas for development and utilization are mainly concentrated in the central urban area, with an area ratio of 59.12%. The area ratio of the medium suitability area is 40.88%, which is mainly distributed in the central urban area, the eastern new area and a few areas in the northwest of the study area. There is no unsuitable area in the study area. The ground heat pump system is recommended for the development and utilization of the whole research area.

The evaluation factors and evaluation methods used in the suitability zoning for the development and utilization of groundwater heat exchange and ground heat pump systems have certain limitations. Therefore, in the development and utilization of the project, the actual geological conditions of the engineering site should be fully considered, and the heat exchange system suitable for the geological conditions should be selected.

The development and utilization of shallow geothermal energy resources bring significant economic, social, and environmental benefits. However, it will also have a certain impact on the geological and ecological environment. To avoid repeating the mistakes of the past where destruction occurs first and treatment follows, the protection of the geological environment should be prioritized. It is recommended to carry out special research on the environmental impact of shallow geothermal energy development and utilization as soon as possible, focusing on the interrelationship between geological environmental problems such as land subsidence, groundwater funnel formation, and geothermal field imbalance and shallow geothermal energy development and utilization.

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