

## Article

# The Assessment of Hydrothermal Potential in the Urban Area of Yichang City in China

Li Wang <sup>1,2</sup>, Wenqi Wang <sup>3</sup>, Yinglong Di <sup>1,2</sup>, Xiaohan Yang <sup>1,2</sup>, Fanghui Li <sup>1,2</sup>, Meng Xiang <sup>1,2</sup>, Jinbang Yuan <sup>1,2</sup>, Haitao Deng <sup>1,2</sup>, Lefeng Cheng <sup>3</sup> and Jin Luo <sup>3,\*</sup>

<sup>1</sup> Seventh Geological Brigade of Hubei Geological Bureau, Yichang 443100, China; 13707206707@163.com (L.W.); diyinglong@yeah.net (Y.D.); 15629367591@163.com (X.Y.); 13997694670@163.com (F.L.); 18671742076@163.com (M.X.); jet\_way@163.com (J.Y.); 15717200939@163.com (H.D.)

<sup>2</sup> Seventh Geological Brigade Expert Workstation of Hubei Geological Bureau, Yichang 443100, China

<sup>3</sup> Faculty of Engineering, China University of Geosciences (Wuhan), Wuhan 430074, China; wangwenqi0621@163.com (W.W.); 1202520662@cug.edu.cn (L.C.)

\* Correspondence: jinluo@cug.edu.cn

## Abstract

Groundwater recharge by faults is often ignored in current hydrothermal potential assessment approaches. This omission may cause a significant discrepancy between the estimated potential and the actual potential in areas adjacent to faults. To address this gap, this study proposes a novel approach for assessing hydrothermal potential that incorporates the influence of faults. This approach was applied to investigate the hydrothermal potential in the main urban area of Yichang, China. The data obtained from the traditional methods and the novel approach were evaluated through comparison with field pumping test data. The findings indicate that the estimates from both methods generally align with the actual potential in most areas. However, significant discrepancies emerge between the estimated and actual potential in zones proximate to faults. Specifically, the traditional method yielded an estimate 60–75% lower than the field measurements. In contrast, the novel approach reduced this deviation by 20%, demonstrating its superior accuracy in fault zones. This study demonstrates the superior performance of the proposed approach over traditional methods for characterizing the heterogeneous distribution of hydrothermal resources in fault-developed zones.

**Keywords:** hydrothermal geothermal resources; groundwater recharge conditions; dynamic assessment; refined assessment approach



Academic Editor: Krzysztof Skrzypkowski

Received: 18 December 2025

Revised: 10 February 2026

Accepted: 17 February 2026

Published: 2 March 2026

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## 1. Introduction

Geothermal resources can be classified into three categories according to their geological structural characteristics, heat transfer mechanisms, temperature ranges, and utilization methods: shallow geothermal energy, hydrothermal geothermal (underground hot water), and hot dry rock [1,2]. China's total hydrothermal geothermal resources are equivalent to 1.25 trillion tons of standard coal, with an annual extractable amount equivalent to 1.9 billion tons of standard coal—equivalent to 44% of the nation's energy consumption in 2015 [3]. The development potential of hydrothermal geothermal resources is substantial. As a critical component of geothermal development, resource evaluation provides robust technical support for the rational exploitation of these resources [4,5].

For evaluating the potential of hydrothermal geothermal resources, traditional evaluation methods typically employ the thermal reservoir method [6]. However, this method

directly estimates the water storage capacity of an aquifer, making it difficult to determine exploitable hot water resources. Exploitable hot water resources are precisely the most valuable resource quantity and serve as the primary indicator for formulating extraction plans [7]. When calculating the exploitable amount of geothermal fluid, the maximum allowable drawdown method is generally employed. This method estimates the extractable volume based on the maximum permissible drawdown value of the regional water level. For geothermal water, the maximum allowable drawdown value varies across different regions due to differences in geological conditions and extraction parameters. Yang used the geothermal evaluation of Dezhou City as a specific case study. By analyzing ground subsidence and deep underground geothermal water, he constructed a numerical model for the maximum allowable drawdown of geothermal water, thereby defining the maximum permissible drawdown range for similar regions [8]. Nevertheless, it is important to note that, as a static evaluation method, the maximum allowable drawdown approach does not incorporate the influence of groundwater recharge conditions during assessment. Consequently, in areas with significant groundwater recharge, the data derived from this method may exhibit considerable deviations. In contrast, numerical simulation methods, by establishing a thermo-hydrological–mechanical–chemical (THMC) multi-field coupled dynamic model, can comprehensively reflect the interactions among fluid migration, heat transfer, and artificial extraction in geothermal reservoirs [9–12]. This approach overcomes the limitations of the traditional maximum allowable drawdown method, which relies solely on static water level thresholds. Unlike the latter, which neglects groundwater recharge conditions, numerical simulation can dynamically predict the evolution of reservoir pressure, temperature fields, and thermal breakthrough risks during long-term extraction, thereby optimizing well network layout and reinjection strategies [10–15].

Yichang City is situated at the junction of the middle and upper reaches of the Yangtze River, serving as a vital gateway in southwestern Hubei Province. Renowned as the “Gateway to the Three Gorges” and the “Throat of Sichuan and Hubei,” it possesses significant potential for geothermal resource exploration and development. The previous studies have revealed abundant geothermal water resources near the main urban area of Yichang, accompanied by two major fault zones with substantial groundwater recharge [16]. These conditions provide a natural laboratory for studying the influence of groundwater recharge on the exploitation potential of geothermal resources.

## 2. Geological Background

### 2.1. Study Area and Geological Conditions

The study area is located near the central main urban area of Yichang City, Hubei Province, covering 2686 km<sup>2</sup>. The scope of the study area is shown in Figure 1, and the coordinates of the four corner points are listed in Table 1.

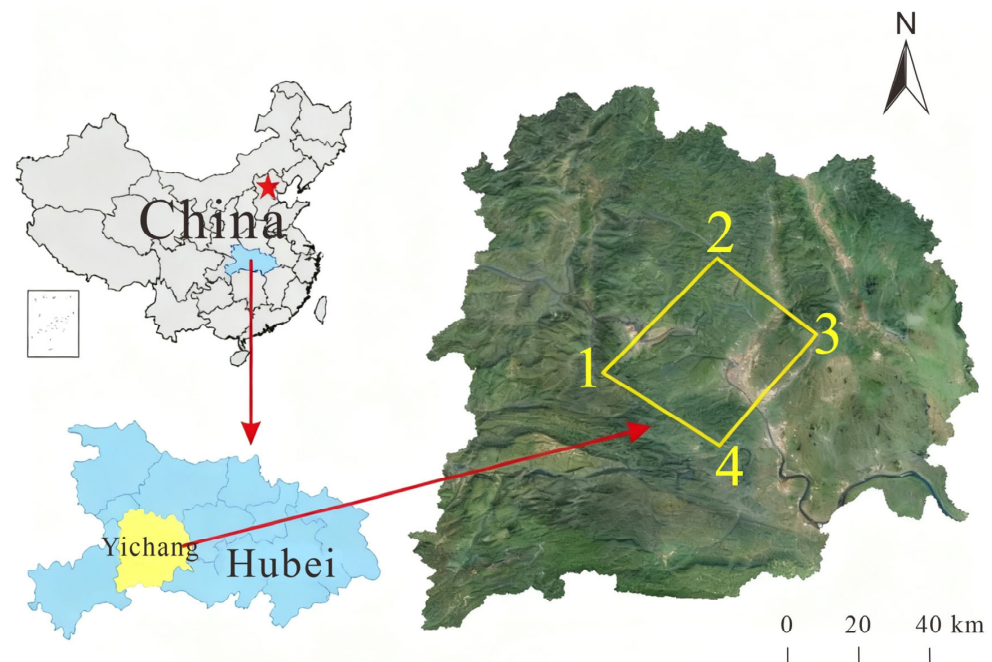
**Table 1.** Coordinates of inflection points in the study area.

| Inflection Point No. | Longitude | Latitude |
|----------------------|-----------|----------|
| 1                    | 110°52′   | 30°42′   |
| 2                    | 111°18′   | 31°06′   |
| 3                    | 111°41′   | 30°50′   |
| 4                    | 111°19′   | 30°27′   |

Situated in the transitional zone between the Huangling Uplift and the Jiangnan Depression, the study area is bounded by the Zigui Syncline to the northwest and extends toward the Jiangnan Plain in the southeast. Two major regional faults trend north–south across the area. The stratigraphic sequence in the region, from youngest to oldest, includes

the Cenozoic (Quaternary), Lower Paleozoic (Cretaceous, Carboniferous, Permian, Triassic, Silurian, Devonian, Ordovician, and Cambrian), and Upper Proterozoic (Sinian and Nanhua) formations. Two major faults are prominent within the study area:

(1) Wuduhe Fault

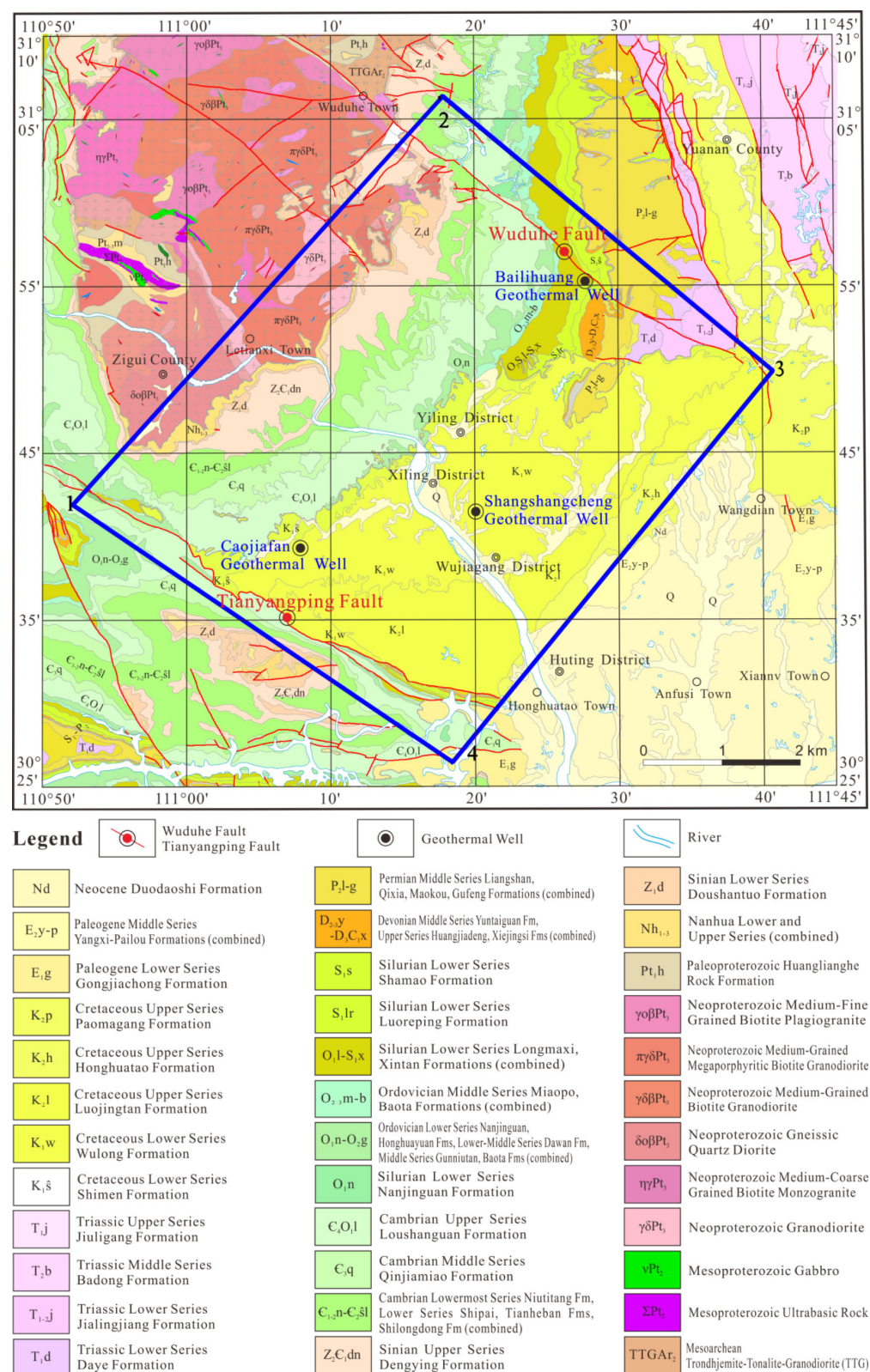


**Figure 1.** The geographical location of the study area.

This fault cuts across the Huangling crystalline basement, runs from Wuduhe to Dangyang, and is truncated by the Tongchenghe Fault in Hualinsi, Yuan'an. It then continues eastward into the Jiangnan Basin, joining the Shashi–Honghu concealed fault. It trends northwest and dips northeast, with a total length of about 160 km and a width of about 1 to 2 km. The fault zone contains a fractured rock belt up to 2 km wide, with dense breccia and cataclasite that form efficient water-conducting channels, significantly enhancing vertical recharge from surface water to deep aquifers. The fault plane dips at  $50\text{--}60^\circ$ , and the terrain is typically negative with prominent fault-triangle slopes, which further promote the infiltration and convergence of precipitation. In the concealed section within the Jiangnan Basin, it splits into two parallel faults, as revealed by magnetic and gravity gradients [17–19].

(2) Tianyangping Fault

This fault trends northwest and dips northeast. Eastward, it becomes buried beneath the Quaternary near Honghuatao Town and, according to aeromagnetic and seismic data, may extend further to Jianli City. It represents a major regional fault about 110 km long and 1 to 2 km wide. The western segment consists of two parallel master faults accompanied by several subsidiary fractures, forming a fault zone 1 to 2 km in width. In cross section, these faults constitute an imbricated thrust system, while the dense network of secondary fractures significantly enhances the permeability of the rock mass and forms a tree-like groundwater-conducting system. The modern Yangtze River and its meandering branches generally follow the same fault trend [17–19], allowing direct recharge of deep aquifers by surface water through the fault conduits. It is worth noting that previous studies on these two faults primarily focused on their thermal control and genesis mechanisms. In contrast, this study innovatively incorporates fault recharge mechanisms into a dynamic assessment framework, thereby extending their application to the assessment of hydrothermal exploitable potential. The geological setting of the study area is shown in Figure 2.



**Figure 2.** The geological setting of the study area.

## 2.2. Hydrogeological Conditions

In and around the urban area of Yichang, the Cretaceous formations generally have low aquifer capacity, acting as aquitards or semi-aquitards with a total thickness exceeding 1000 m, and are widely distributed around the city. The Silurian system, except for limited outcrops in the northern and northwestern areas, lies deeply buried at over 1000 m in

most of the area and also functions as a relative aquitard. The Ordovician, Cambrian, and Sinian carbonate strata, with a total thickness exceeding 1200 m, occur mainly in low and medium-low mountainous areas to the west and northwest of the urban area. These strata contain karst-fracture water with weak to moderate aquifer properties. The Lower Cambrian Shipai and Niutitang formations, with a total thickness of about 350 m, serve as the aquiclude between the Cambrian karst groundwater and the Dengying Formation karst-fracture aquifer.

### 2.3. Geothermal Conditions

#### (1) Caprock of the geothermal Reservoir

A thick and laterally continuous geothermal reservoir and its overlying caprock are essential conditions for the formation and preservation of deep geothermal water resources. According to geological data, the caprock in the study area consists of two major components. The first is the Lower to Middle Silurian strata that overlie the Ordovician. This sequence is widely distributed from the Yiling District in the west of the urban area to the Wujiagang District in the east, and it is characterized lithologically by argillaceous siltstone, sandy shale, and mudstone. These rocks exhibit relatively low permeability and low thermal conductivity. The second is the Upper Mesozoic Cretaceous stratum, which is extensively exposed in the area east of the Yiling District. It consists primarily of red fluvial-lacustrine deposits dominated by argillaceous siltstone, mudstone, and argillaceous fine sandstone, interbedded locally with conglomerate. These lithologies also display poor permeability.

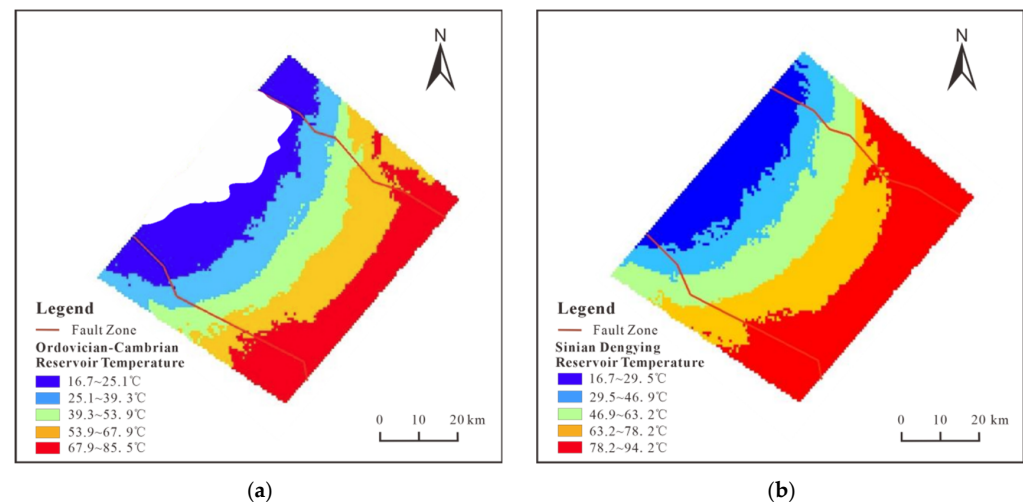
#### (2) The Geothermal Reservoir

According to drilling logs from the Shangshangcheng well, the Cambrian and Ordovician strata constitute the primary geothermal reservoir. This reservoir is located in the low-to-medium mountainous region to the west and northwest of the urban area of Yichang. The area is roughly bounded by the eastern branch of the Huangbo River, with the region to the west forming a zone of surface exposure. The total exposed area exceeds 750 square kilometers. In contrast, the eastern part of the reservoir dips gently toward the east and southeast and remains buried beneath overlying strata. The main geothermal reservoir units include the Ordovician Baota Formation through the Nanjinguan Formation, and the Cambrian Loushanguan Formation, the Qinjiamiao Formation, the Shilongdong Formation, and the Tianheban Formation. No distinct aquitards have been identified between these formations, and they can therefore be regarded as a single continuous geothermal reservoir. Drilling data from the DRJ2 well show that the top of the reservoir is buried at a depth of 1385 m, and the total thickness of the reservoir reaches 1620 m.

The drilling log from the Caojiayan wells shows that the dolomite of the Sinian Dengying Formation and the dolomite of the Doushantuo Formation constitute a second geothermal reservoir within the study area, with a combined thickness greater than 912.28 m. The drilling data indicate that the top of this reservoir is buried at a depth of 1490 m. This geothermal reservoir is mainly exposed outside the prospecting area on the northwest side, where it dips toward the southeast with a dip angle between 10 and 25 degrees. Field investigations reveal that karst features are well developed in the Sinian dolomite. Caverns, sinkholes, and springs of various sizes are observed at the surface, and both dissolution and structural fractures are abundant. These characteristics provide favorable conditions for the infiltration of meteoric water, the recharge of surface water, and the migration of groundwater.

#### (3) Temperature distribution of Geothermal Reservoir

The data obtained from borehole temperature measurements show that the geothermal gradient in the study area is approximately 1.8 °C/100 m. The spatial distribution of reservoir temperatures was calculated using the regional geothermal gradient and the burial depth of the two main reservoirs (Figure 3), with corresponding parameters listed in Table 2.



**Figure 3.** Temperature distributions of the geothermal reservoirs: (a) the Ordovician–Cambrian reservoir; (b) the Dengying Formation reservoir in the Sinian System.

**Table 2.** The determined geothermal reservoir temperatures.

| Reservoir                           | Minimum Temperature | Maximum Temperature | Average Thickness | Average Temperature |
|-------------------------------------|---------------------|---------------------|-------------------|---------------------|
|                                     | °C                  | °C                  | m                 | °C                  |
| Ordovician–Cambrian Reservoir       | 16.7                | 85.5                | 1400–1550         | 52.55               |
| Sinian Dengying Formation Reservoir | 16.7                | 94.2                | 600–650           | 64.19               |

### 3. Geothermal Potential Assessment

The evaluation of geothermal resources includes the total geothermal resource volume, the recoverable geothermal resource volume, the geothermal fluid storage capacity, and the recoverable geothermal fluid volume [20–24]. In this section, the recoverable heat density of geothermal resources in the study area is calculated using the maximum allowable drawdown method, which does not take recharge conditions into account, and the novel method, which incorporates recharge conditions. The spatial distribution characteristics of the recoverable heat density are also examined.

#### 3.1. The Maximum Allowable Drawdown Method

##### 3.1.1. Recoverable Geothermal Fluid Volume

In this study, the Ordovician–Cambrian reservoir and the Ediacaran Dengying Formation reservoir are selected as the geothermal reservoirs, and the resource volume is calculated based on the geothermal parameters of each reservoir. The recoverable geothermal fluid volume is estimated using the maximum allowable drawdown method. Under a specified production period, generally one hundred years, the maximum extraction rate is determined by ensuring that the sum of the water level decline at the center of the calculation area and the additional drawdown induced by a single production well does not exceed 100 m. This extraction rate represents the recoverable geothermal fluid volume for the calculation area. The expression is as follows [25]:

$$Q_{wk} = \frac{4\pi TS_1}{\ln(6.11\bar{t})} = \frac{4\pi TS_1}{\ln(\frac{6.11Tt}{\mu^* R_1^2})} \quad (1)$$

$$Q_{wd} = \frac{2\pi TS_2}{\ln \frac{0.473R_2}{r}} \quad (2)$$

where  $Q_{wk}$  is the recoverable geothermal fluid volume ( $\text{m}^3/\text{a}$ ),  $Q_{wd}$  is the single-well recoverable geothermal fluid volume ( $\text{m}^3/\text{a}$ ),  $S_1$  is the calculated drawdown of the water level at the center of the calculation area (m),  $S_2$  is the additional drawdown in the single-well water level (m),  $R_1$  is the mining radius (m),  $R_2$  is the single-well control radius (m),  $\mu^*$  is the elastic release coefficient of thermal reservoir aquifers,  $t$  is the mining period (a),  $T$  is the hydraulic conductivity ( $\text{m}^2/\text{a}$ ), and  $r$  is the radius of the geothermal well (m).

The total recoverable geothermal fluid volume  $Q_{wk}$  is calculated to be approximately  $3.9 \times 10^7 \text{ m}^3/\text{a}$ , and the recoverable geothermal fluid volume per single well  $Q_{wd}$  is approximately  $1.9 \times 10^5 \text{ m}^3/\text{a}$ .

### 3.1.2. Recoverable Geothermal Resource Density

The temperature distribution rasters of the two reservoirs in Figure 2 were substituted into Equation (3), and the annual recoverable geothermal resource of the study area was calculated using raster-based computation. The total area of the study region is  $2686 \text{ km}^2$ , which was divided into 26,374 units. Each unit corresponds to one raster cell with an area of  $0.102 \text{ km}^2$ .

The resource density for each grid cell was calculated based on its annual exploitable geothermal resource volume and area, using the following formula [26]:

$$Q_n = c\rho Q_{wk}(t_1 - t_0) \quad (3)$$

$$\rho_n = \frac{Q_n}{S} \quad (4)$$

where  $Q_n$  is the annual recoverable geothermal resources in the region ( $\text{kJ}/\text{a}$ ),  $c$  is the specific heat capacity of water ( $\text{J}/\text{kg } ^\circ\text{C}$ ),  $\rho$  is the water density ( $\text{kg}/\text{m}^3$ ),  $Q_{wk}$  is the annual recoverable geothermal fluid volume ( $\text{m}^3/\text{a}$ ),  $t_1$  is the reservoir temperature ( $^\circ\text{C}$ ),  $t_0$  is the annual mean surface temperature ( $^\circ\text{C}$ ),  $\rho_n$  is the annual recoverable geothermal heat density of the region ( $\text{kJ}/\text{km}^2 \cdot \text{a}$ ), and  $S$  is the area ( $\text{km}^2$ ).

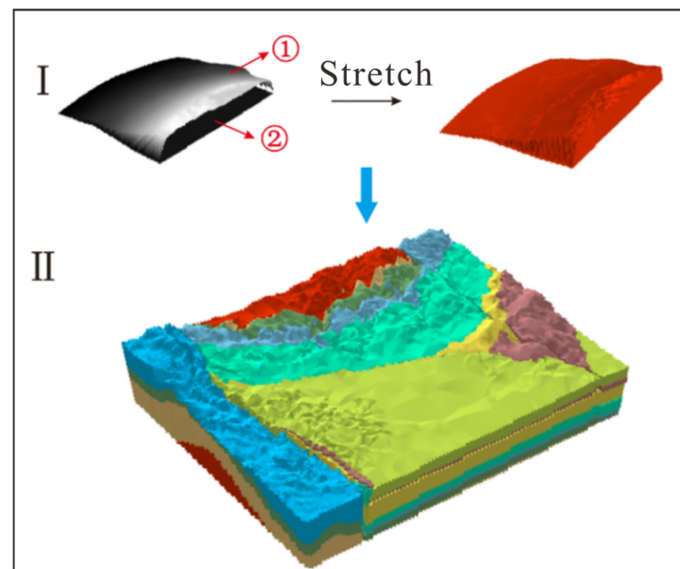
## 3.2. The Novel Method

Constructing a numerical model of the geothermal reservoir is one of the most effective methods for geothermal resource assessment, as it allows for the accurate representation of complex reservoir structures and enables continuous improvement of the evaluation accuracy through iterative fitting with monitoring data [27–33]. However, these are finite-element methods, which are computationally expensive in computing complex geological settings, e.g., faults. In this study, we developed a continuous–discrete method in which the discrete element is used to simulate the fault with very highly computing effectiveness. After the groundwater flow and recharge conditions of the reservoir were defined, various pumping scenarios at different well locations were simulated to analyze the influence of groundwater recharge on the recoverable geothermal fluid volume of a single well. This process facilitates the assessment of the recoverable geothermal resource density of the region. The specific steps are as follows:

### 3.2.1. Three-Dimensional Geological Model

Based on the collected geological data, including the surface elevation, borehole information, and fault structures, a three-dimensional geological model of the study area

was constructed. The main workflow involved three steps. First, multisource datasets were preprocessed and integrated. Second, discrete point data were converted into continuous stratigraphic and fault surfaces through spatial interpolation, followed by processing of their spatial intersections. Finally, a three-dimensional geological body was generated using a TIN-based modeling approach and validated against geological cross sections, resulting in a fully visualized three-dimensional model. The detailed workflow and model generation process are shown in Figure 4, a schematic diagram of the process of three-dimensional modeling surface-body generation.



**Figure 4.** A schematic diagram of the process of three-dimensional modeling surface-body generation.

### 3.2.2. Numerical Model

The simulation extent was defined according to the boundary of the working area, and the terrain of the study region was discretized and refined using the triangulation method. At the same time, the elevation file of the study area was imported into simulation software, and the elevation points were assigned to the model. The bottom boundary of the geological layers was set at  $-4000$  m, resulting in the creation of a three-dimensional model with elevation information as shown in Figure 5.

To visualize the stratigraphic information, geological parameters obtained from field measurements and laboratory tests, including basic physical parameters, thermal properties, and hydrogeological parameters, were assigned to the model. In this study, the hydraulic parameters such as hydraulic conductivity (m/s) were obtained by field pumping tests, while physical parameters including density and thermal conductivity were measured through laboratory tests. Several formations with similar characteristics were merged and simplified. Only the parameters that influence pumping capacity, namely porosity and permeability, are presented here. The specific data are listed in Table 3, and the parameter model is shown in Figure 6. The letters in the figure correspond to the following stratigraphic units: Cretaceous (K), Carboniferous (C), combined Triassic and Permian (T+P), combined Devonian and Silurian (D+S), combined Ordovician and Cambrian (O+E), and Sinian (Z).

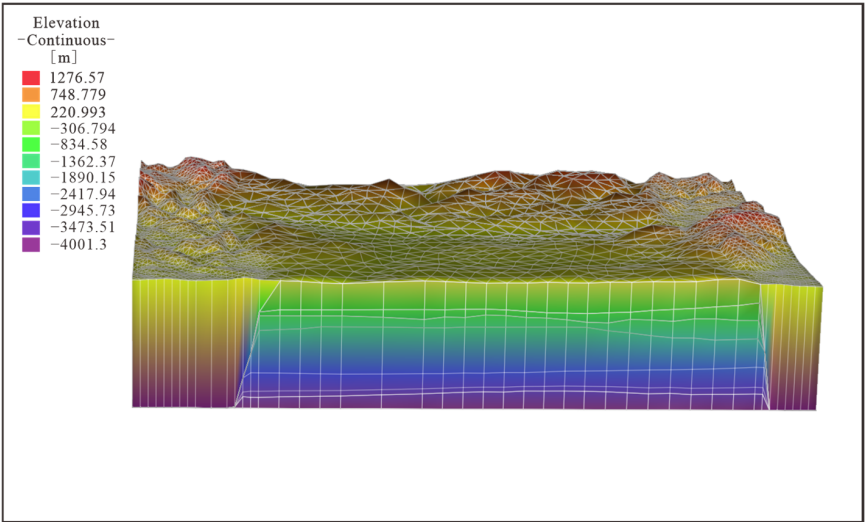
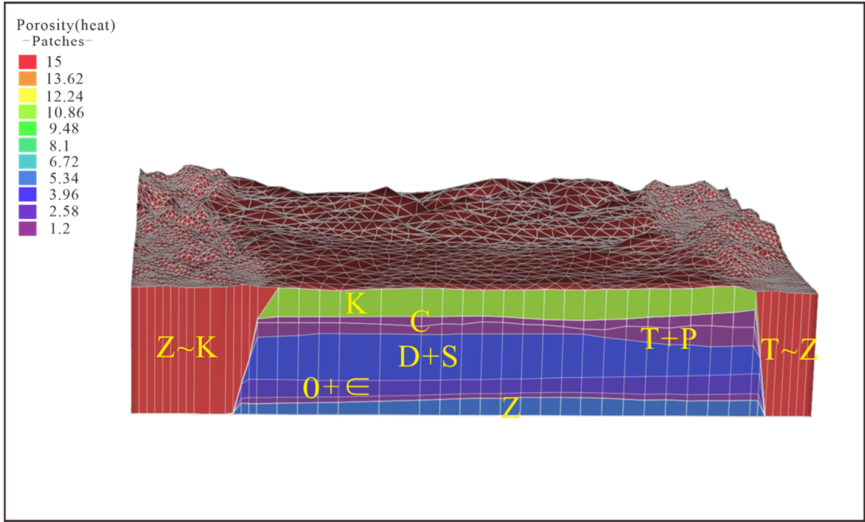
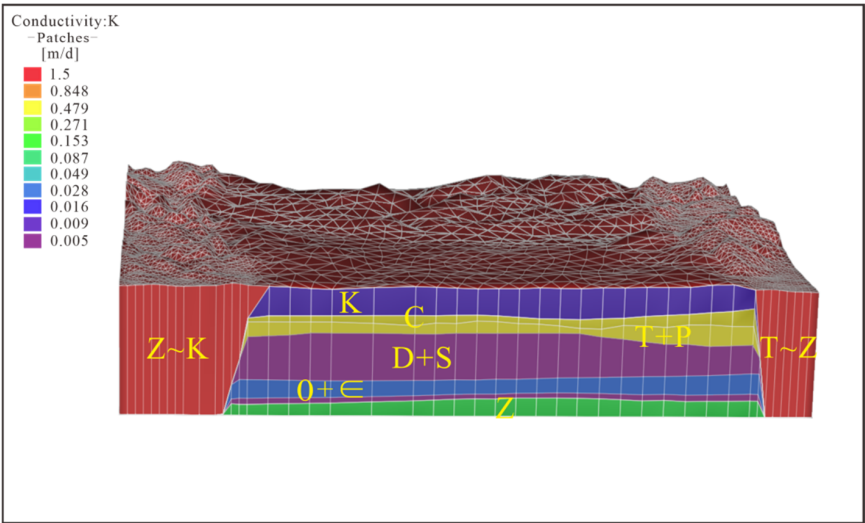


Figure 5. The three-dimensional numerical model of the study area.



(a) Porosity



(b) Permeability

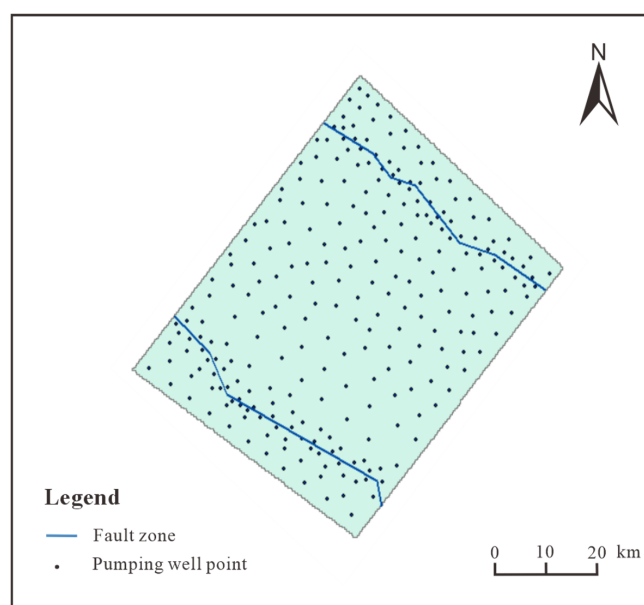
Figure 6. Parameter assignments in the numerical model.

**Table 3.** The parameter assignments for the numerical model.

| Model Formation                     | Porosity (%) | Permeability (m/d) |
|-------------------------------------|--------------|--------------------|
| Quaternary                          | 15           | 1.5                |
| Cretaceous                          | 11.5         | 0.01               |
| Triassic                            | 1.33         | 0.5                |
| Permian                             | 1.42         | 0.5                |
| Carboniferous                       | 4.28         | 0.005              |
| Devonian                            | 3.1          | 0.025              |
| Silurian                            | 1.74         | 0.005              |
| Ordovician–Cambrian reservoir       | 5.08         | 0.12               |
| Inter-reservoir aquifers            |              |                    |
| Sinian Dengying Formation reservoir |              |                    |

### 3.2.3. The Layout of Geothermal Wells

Geothermal wells were placed at various locations within the study area to simulate field pumping tests, and the recoverable geothermal fluid yield of each single well was recorded to calculate the recoverable heat density. To facilitate comparison with the static evaluation based on the maximum allowable drawdown method, the maximum drawdown for each well was set to 100 m. To improve the accuracy of the simulation data, well locations were arranged more densely in areas near the two faults. The arrangement of the well locations is shown in Figure 7.

**Figure 7.** The layout of geothermal well assignments in the potential assessment.

## 4. Results and Discussion

### 4.1. The Assessed Geothermal Potential

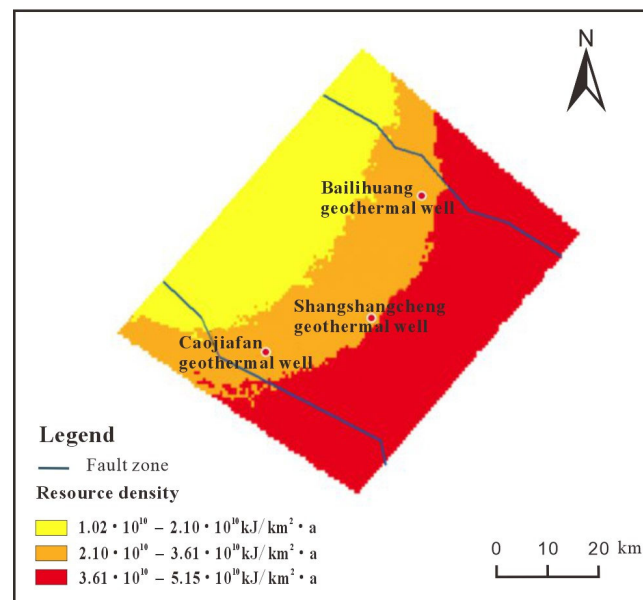
The geothermal resource potential of the study area was evaluated using the Jenks natural breaks classification method. This method determines the optimal classification thresholds based on the intrinsic distribution characteristics of the dataset, minimizing within-class variance and maximizing between-class variance, thereby enabling an objective identification of the spatial differentiation of potential zones. Consequently, the resource potential is classified into three levels—low-potential zones (yellow), medium-potential zones (orange), and high-potential zones (red)—where a higher level indicates greater resource development potential.

#### 4.1.1. Geothermal Potential Assessment by the Maximum Allowable Drawdown Method

The spatial distribution of the geothermal resource density in the reservoir is generally consistent with the temperature distribution, exhibiting an overall increasing trend from the northwest toward the southeast. As the burial depth increases, the temperature rises, and the corresponding recoverable energy density in those areas also increases. The geothermal resource densities of the three geothermal wells within the study area are as follows. The Shangshangcheng well has the highest value, approximately  $3.3 \times 10^{10}$  kJ/(km<sup>2</sup>·a). The Bailihuang well follows with approximately  $2.9 \times 10^{10}$  kJ/(km<sup>2</sup>·a), and the Caojiafan well is relatively lower at approximately  $2.6 \times 10^{10}$  kJ/(km<sup>2</sup>·a). The detailed data are presented in Table 4 and Figure 8.

**Table 4.** Recoverable resource density (maximum allowable drawdown method).

| Category         | Area (km <sup>2</sup> ) | Proportion (%) | Resource Density (kJ/km <sup>2</sup> ·a)       | Spatial Characteristics                                                                                           |
|------------------|-------------------------|----------------|------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|
| Low potential    | 721                     | 26.85          | $1.02 \times 10^{10} \sim 2.10 \times 10^{10}$ | Increases gradually from northwest to southeast, showing a strong positive correlation with reservoir temperature |
| Medium potential | 787.8                   | 29.33          | $2.10 \times 10^{10} \sim 3.61 \times 10^{10}$ |                                                                                                                   |
| High potential   | 1177                    | 43.82          | $3.61 \times 10^{10} \sim 5.15 \times 10^{10}$ |                                                                                                                   |



**Figure 8.** Recoverable geothermal resource density distribution (maximum allowable drawdown method).

#### 4.1.2. Geothermal Potential Assessment by the Novel Method

The spatial distribution of the annual recoverable geothermal fluid yield per single well, derived from the simulation data, is shown in Figure 9, with values ranging from  $1.8 \times 10^4$  to  $4.5 \times 10^4$  m<sup>3</sup>/a. High-yield zones are mainly concentrated near the two fault zones, followed by the northwestern part of the study area, while the southeastern region farther from the faults exhibits relatively low values. By further integrating reservoir temperature data and applying Equations (3) and (4), the annual recoverable geothermal resource density distribution of the reservoir was obtained, as shown in Figure 10. According to the classification criteria described in Section 4.1, the potential zones were categorized into low, medium, and high levels, with detailed data summarized in Table 5. The data indicate that the Caojiafan geothermal well has the highest annual recoverable resource density, approximately  $8.9 \times 10^{10}$  kJ/(km<sup>2</sup>·a). The Bailihuang well follows with approximately  $8.1 \times 10^{10}$  kJ/(km<sup>2</sup>·a), and the Shangshangcheng well shows the lowest value at approximately  $6.1 \times 10^{10}$  kJ/(km<sup>2</sup>·a).

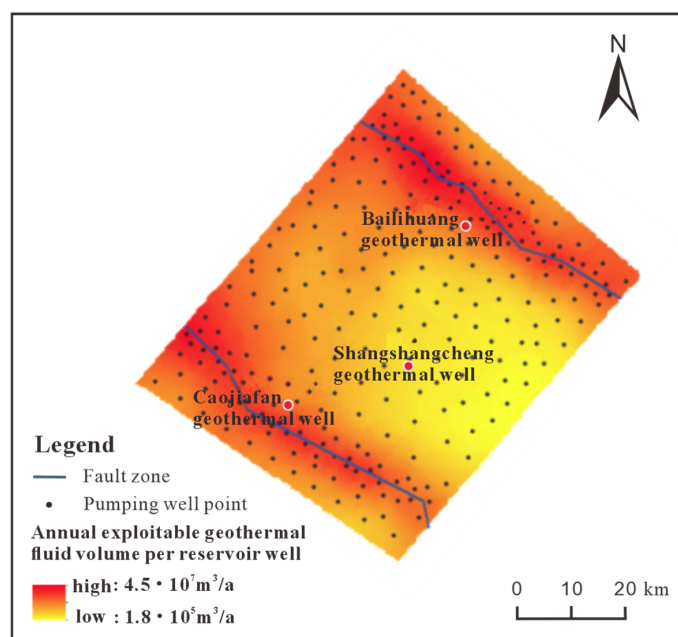


Figure 9. Annual recoverable geothermal fluid volume per well.

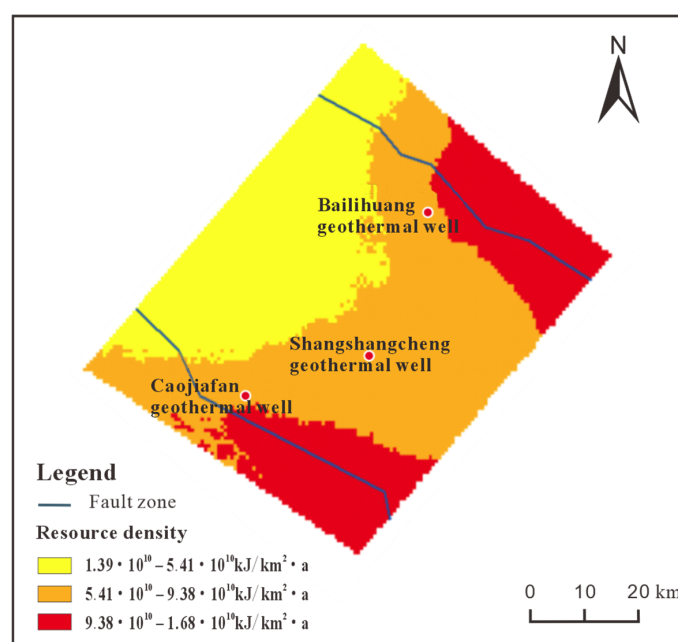


Figure 10. Recoverable geothermal resource density distribution (novel method).

Table 5. Recoverable resource density (novel method).

| Category         | Area (km <sup>2</sup> ) | Proportion (%) | Resource Density Range (kJ/km <sup>2</sup> ·a) | Spatial Characteristics                                                                                                                                                                    |
|------------------|-------------------------|----------------|------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Low potential    | 905                     | 34             | $1.39 \times 10^{10} \sim 5.41 \times 10^{10}$ | Increases gradually from northwest to southeast and exhibits belt-shaped high-value zones controlled by fault belts. Potential peaks where high-temperature areas overlap with the faults. |
| Medium potential | 1120                    | 42             | $5.41 \times 10^{10} \sim 9.38 \times 10^{10}$ |                                                                                                                                                                                            |
| High potential   | 659                     | 24             | $9.38 \times 10^{10} \sim 1.68 \times 10^{11}$ |                                                                                                                                                                                            |

#### 4.2. Comparative Analysis with Field Pumping Tests

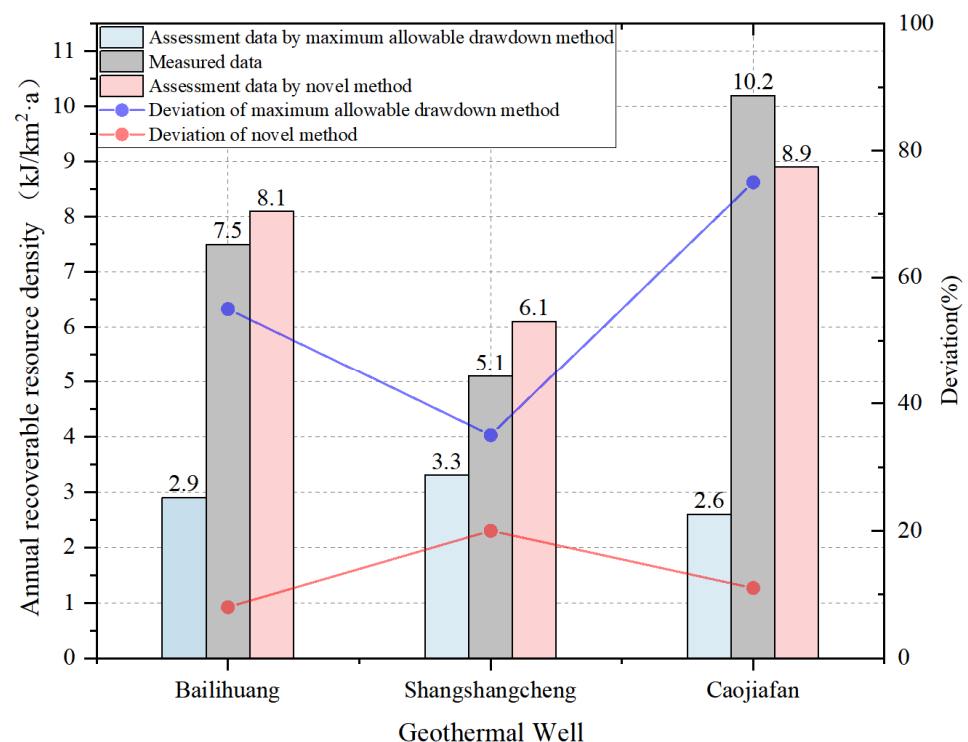
A relatively systematic and comprehensive dataset of geothermal geological exploration has been accumulated within the study area. The Bailihuang geothermal well (111°28'18" E, 30°56'03" N), the Shangshangcheng geothermal well (111°19'49" E, 30°41'18" N), and the Caojiafan geothermal well (111°8'13.6" E, 30°39'55" N) are located

in the eastern, central, and western parts of the study area, respectively. Based on detailed exploration data from these wells and field pumping tests obtained under conditions of long-term stable production, the measured annual recoverable yield of each well and its corresponding geothermal resource density were obtained (Table 6), along with comparative evaluation plots (Figure 11). These datasets were used to verify the accuracy of both the maximum allowable drawdown method and the novel method that incorporates groundwater recharge conditions.

**Table 6.** Comparative analysis of assessment data and measured data for the three geothermal wells.

| Geothermal Well                                               | Baili Huang                         | Shangshangcheng                     | Caojiafan                                         |
|---------------------------------------------------------------|-------------------------------------|-------------------------------------|---------------------------------------------------|
| Basic Parameters                                              |                                     |                                     |                                                   |
| Primary Reservoir                                             | Ordovician–Cambrian Carbonate Rocks | Ordovician–Cambrian Carbonate Rocks | Dengying and Doushantuo Formation Carbonate Rocks |
| Reservoir Thickness (m)                                       | 1831                                | 1565                                | 912                                               |
| Reservoir Temperature(°C)                                     | 66.8                                | 64.4                                | 50.1                                              |
| Measured Data (Field Pumping Test)                            |                                     |                                     |                                                   |
| Annual Recoverable Volume per Well (m <sup>3</sup> /a)        | $3.7 \times 10^5$                   | $2.6 \times 10^5$                   | $7.4 \times 10^5$                                 |
| Annual Recoverable Resource Density (kJ/(km <sup>2</sup> ·a)) | $7.5 \times 10^{10}$                | $5.1 \times 10^5$                   | $10.2 \times 10^{10}$                             |
| Assessment Data                                               |                                     |                                     |                                                   |
| Maximum Allowable Drawdown Method (kJ/km <sup>2</sup> ·a)     | $2.9 \times 10^{10}$                | $3.3 \times 10^{10}$                | $2.6 \times 10^{10}$                              |
| Novel Method (kJ/km <sup>2</sup> ·a)                          | $8.1 \times 10^{10}$                | $6.1 \times 10^{10}$                | $8.9 \times 10^{10}$                              |
| Deviation Rate                                                |                                     |                                     |                                                   |
| Maximum Allowable Drawdown Method                             | 61%                                 | 35%                                 | 75%                                               |
| Novel Method                                                  | 8%                                  | 20%                                 | 13%                                               |

Note: Deviation rate = |(evaluation density-actual measured density)| / actual measured density × 100%.



**Figure 11.** Comparison of estimated and measured recoverable resource densities.

The comparison of the assessment methods indicates that the geothermal potential obtained using the maximum allowable drawdown method is lower than the measured value for all three geothermal wells, with the deviations being particularly pronounced near the fault zones. For example, the Bailihuang geothermal well shows an underestimation of 61%, and the Caojiafan geothermal well shows an underestimation of 75%. The evaluation data produced by the novel method deviate from the measured values by less than 20% for all wells, demonstrating high accuracy even in areas near the fault zones.

#### 4.3. Discussion

(1) The fundamental limitation of the maximum allowable drawdown method lies in its neglect of recharge mechanisms. This method estimates the recoverable yield solely based on the prescribed maximum drawdown and static reservoir parameters, such as the transmissivity  $T$  and elastic storage coefficient  $\mu^*$ . Its core assumption is that the geothermal reservoir behaves as a closed or weakly recharged water body, where resource extraction relies primarily on the elastic release of water stored within the aquifer.

In the study area, especially in zones controlled by the Wuduhe Fault and the Tianyangping Fault, groundwater recharge is abundant and highly active. Fault zones function as efficient conduits for groundwater flow, broadening the sources of recharge and significantly accelerating recharge rates. As a result, during extraction, the geothermal reservoir receives continuous external recharge that far exceeds the amount contributed by elastic storage. Therefore, ignoring these recharge conditions inevitably leads to a systematic underestimation of the actual recoverable resource, with the discrepancy being particularly evident in areas near the fault zones.

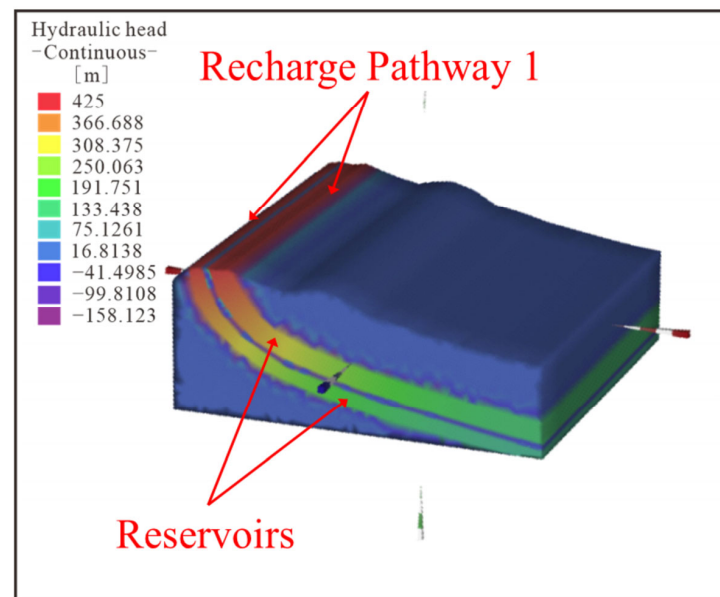
(2) The advantage of the novel method lies in its ability to quantify the recharge process. Based on regional geological investigation data and previous research findings, the novel method divides the recharge pathways of the study area into two types, as described below.

Recharge Pathway 1: The overlying Cretaceous and Silurian formations exhibit very low permeability, which severely restricts the vertical infiltration of surface water into the deep geothermal reservoir. Under these conditions, groundwater recharge primarily depends on direct infiltration of precipitation and surface water in the exposed areas of the Ordovician–Cambrian reservoir and the Sinian Dengying Formation (Figure 12).

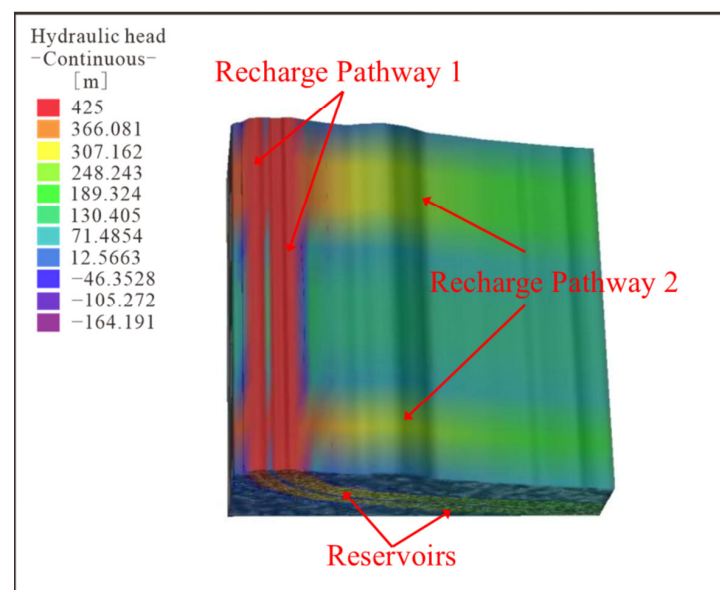
Recharge Pathway 2: The Wuduhe Fault and the Tianyangping Fault, both large regional deep faults within the study area, exert a significant influence on groundwater flow by functioning as major water-conducting structures. To accurately represent the contribution of these fault zones to reservoir recharge, high-permeability fault units (permeability coefficient set to 5 m/d) were assigned along both faults in the three-dimensional flow model to simulate their role as efficient hydraulic conduits. The fault zones substantially reshape the groundwater recharge mechanism. The dense fracture networks within them not only provide highly efficient vertical pathways for surface water to infiltrate through the fractured fault zones into the deep geothermal reservoir, forming an important additional recharge source, but also induce strong spatial heterogeneity in recharge rates. In the fault zones themselves and in areas where they overlap with reservoir outcrops, groundwater infiltration fluxes are significantly higher than those in surrounding regions, forming a “strong near, weak far” recharge intensity gradient (Figure 13).

Compared with the maximum allowable drawdown method, the novel method significantly improves the accuracy of the assessment by incorporating a three-dimensional geological model and a numerical model that explicitly represent key hydrogeological features of the study area, including the northwestern reservoir outcrop recharge zone, the high-permeability water-conducting fault zones, and the low-permeability caprocks. This

approach reproduces the dynamic process of deep groundwater circulation and heating along the fault zones. By successfully capturing both the substantial enhancement effect of groundwater recharge on the recoverable yield and the spatial heterogeneity of this effect, the refined method achieves a markedly higher level of evaluation accuracy.



**Figure 12.** Recharge through reservoir outcrops.



**Figure 13.** Groundwater seepage recharge in reservoirs (including fault zones).

## 5. Conclusions

This study addresses a key limitation in current assessments of medium to deep hydrothermal geothermal resources, namely the widespread neglect of groundwater recharge, particularly in tectonically active areas where major faults strongly influence groundwater flow. To overcome this limitation, a new evaluation method that explicitly incorporates groundwater seepage and recharge is proposed. By comparing the data from this method with those obtained from the traditional maximum allowable drawdown approach, and validating both against field pumping tests, the following major conclusions were reached:

- (1) The geothermal reservoir system in the study area consists of a clearly defined two-layer structure. The upper reservoir is composed of Ordovician–Cambrian carbonate rocks with a thickness of 1400 to 1550 m, whereas the lower reservoir is formed of dolomite of the Sinian Dengying Formation with a thickness greater than 912 m. The lower Cambrian units, including the Shipai Formation and the Niutitang Formation, exhibit very low permeability and therefore act as an aquitard separating the two reservoirs. Above these units, the Silurian and Cretaceous formations possess low permeability, considerable thickness, and stable distribution, together serving as the regional caprock.
- (2) The geothermal reservoirs are primarily recharged by meteoric water infiltrating in the northwest, where the reservoir aquifers crop out. Additional recharge occurs through direct infiltration of surface water along the Wuduohe–Honghu Fault and the Tianyangping Fault. The infiltrated water then migrates southeastward along these structural conduits and undergoes deep circulation. Through regional conductive heat transfer, reflected by a geothermal gradient of 1.8 °C per 100 m, and strengthened heat exchange within the fault zones, the circulating groundwater gradually evolves into the geothermal water system observed today.
- (3) Data obtained from the maximum allowable drawdown method indicate that the geothermal resource density increases progressively from the northwest toward the southeast, a pattern that closely corresponds to the spatial variation in reservoir temperature. In contrast, the novel method not only reproduces this overall trend but also reveals the dominant control exerted by major fault zones. The Wuduohe Fault and the Tianyangping Fault form distinct belt-shaped high-potential zones, and the geothermal potential reaches its maximum where high-temperature regions overlap with these fault-controlled pathways. Pumping tests conducted at the three geothermal wells further confirm the accuracy of both methods. Deviations between the novel method and the measured resource densities remain within 20%. In this respect, the novel method is significantly better than the maximum allowable drawdown method, which underestimates the actual values by 60% to 75%.
- (4) The novel method proposed in this study incorporates a three-dimensional geological model to quantitatively characterize the function of fault zones as highly efficient water-conducting pathways. This allows for a refined coupled simulation of dynamic groundwater recharge and the thermal response of the reservoir system. Furthermore, the method successfully delineates the belt-shaped high-potential geothermal zones concentrated along the Wuduohe Fault and the Tianyangping Fault with high spatial accuracy.

In summary, the traditional methods such as the maximum allowable drawdown approach are applicable only for preliminary and rapid estimations in areas where groundwater recharge is limited and geological structures are relatively stable. Their fundamental limitation lies in neglecting the influence of groundwater recharge on the evaluation of geothermal extraction potential. The evaluation framework developed in this study, which incorporates both the water-conducting properties of faults and groundwater recharge, provides an important methodological reference and practical tool for assessing geothermal resource potential and supporting efficient development in fault-controlled geothermal systems.

**Author Contributions:** Conceptualization, J.L.; methodology, M.X.; software, W.W.; validation, F.L. and J.Y.; formal analysis, W.W.; investigation, L.W., Y.D., X.Y., F.L., M.X., J.Y. and H.D.; resources, L.W., X.Y., F.L., M.X. and H.D.; data curation, Y.D.; writing—original draft preparation, W.W. and L.C.; supervision, L.W. and J.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by Three-Dimensional Geological Simulation and Development Research on the Genetic Conditions of Medium-Deep Hydrothermal Geothermal Resources in the Main Urban Area and Periphery of Yichang City grant number DQKJ2023-5. The APC was funded by Three-Dimensional Geological Simulation and Development Research on the Genetic Conditions of Medium-Deep Hydrothermal Geothermal Resources in the Main Urban Area and Periphery of Yichang City.

**Data Availability Statement:** Data is contained within the article.

**Acknowledgments:** This work was founded by the Seventh Geological Brigade of Hubei Geological Bureau for the joint project “Three-Dimensional Geological Simulation and Development Research on the Genetic Conditions of Medium-Deep Hydrothermal Geothermal Resources in the Main Urban Area and Periphery of Yichang City”(Authorized No. DQKJ2023-5).

**Conflicts of Interest:** The authors declare no conflict of interest.

## Nomenclature

|          |                                                                                              |
|----------|----------------------------------------------------------------------------------------------|
| THMC     | Thermal–hydrological–mechanical–chemical                                                     |
| $Q_{wk}$ | Annual exploitable volume of geothermal fluid ( $\text{m}^3/\text{a}$ )                      |
| $Q_{wd}$ | Annual exploitable volume of geothermal fluid per well ( $\text{m}^3/\text{a}$ )             |
| $Q_n$    | Annual exploitable geothermal resource of the region ( $\text{kJ}/\text{a}$ )                |
| $\rho_n$ | Annual exploitable energy density of the region ( $\text{kJ}/(\text{km}^2 \cdot \text{a})$ ) |
| $h_1$    | Drawdown at the center of the calculation area (m)                                           |
| $h_2$    | Additional drawdown per well (m)                                                             |
| $R_1$    | Radius of the exploitation area (m)                                                          |
| $R_2$    | Control radius of a single well (m)                                                          |
| $\mu^*$  | Elastic storage coefficient of the geothermal aquifer                                        |
| $t$      | Exploitation time (a)                                                                        |
| $T$      | Transmissivity ( $\text{m}^2/\text{a}$ )                                                     |
| $r$      | Radius of the geothermal well (m)                                                            |
| $c$      | Specific heat capacity of water ( $\text{kJ}/(\text{kg} \cdot ^\circ\text{C})$ )             |
| $\rho$   | Density of water ( $\text{kg}/\text{m}^3$ )                                                  |
| $t_1$    | Reservoir temperature ( $^\circ\text{C}$ )                                                   |
| $t_0$    | Annual average surface temperature ( $^\circ\text{C}$ )                                      |
| $S$      | Area of the region ( $\text{km}^2$ )                                                         |

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