Optimization of geothermal water exploitation in Xinji, Hebei Province, P. R. China

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Abstract: Geothermal with features of large reserves and non-pollution has been one of the most important energy. China has significant geothermal resources. There are rich hydrothermal resources in Xinji, which has been in development for 5 years. However, hot water continues to decrease because of extensive exploitation and utilization. We selected exploration area as study area, build a set of numerical models of Guantao formation on the basis of actual geological conditions. We get the distribution of hydraulic conductivity from 1.7 m/d to 1.9 m/d by parameter inversion using historical water level monitoring data, and simulation effect is good. We calculate the maximum permissible exploitation under the limitation of 200 m in depth in 50 years which is about 2.2 million m^3/a. The results will provide theoretic support for plan making of geothermal exploitation.

Keywords: Geothermal energy; Numerical simulation; Inverse calculation; Maximum permissible exploitation

Introduction

The geothermal is one of precious resources. As the international community pays much attention to climate changes, performs energy conservation and emission reduction, works hard to develop new energy and renewable energy, confronts an ever-dwindling supply of fossil resources and has considerable disagreements about the safety of nuclear power, the research and exploitation of geothermal resources have started a new round of vigorous growth (LIN Wen-jing *et al.* 2013; CHEN Mo-xiang *et al.* 1994). Geothermal power generation and direct use are main forms of geothermal resources exploitation. In most cases, the geothermal water is pumped directly from thermal reservoir for the purpose of power generation or bathing. However, the excessive exploitation may result in the decrease of water quantity in thermal reservoir. So the key is how to conduct the rational development and exploitation of geothermal water when the sustainable development and exploitation of thermal reservoir is maintained (ZHANG Jin-hua *et al.* 2013; LIAO Zhong-li *et al.* 2006).

Many methods, including genetic algorithm and ecological restraint, can be used to plan the development and exploitation of geothermal water (LIN Jin *et al.* 2007; WU Ming *et al.* 2015; WANG Hua-qi *et al.* 2014). Specifically, the numerical simulation method can use the actual monitoring data to forecast geothermal water in a quantitative manner so that a feasible plan will be prepared for the development and exploitation of geothermal water (GONG Hui-li, 1998; GANG Shen-ting *et al.* 2015; HUANG Dan *et al.* 2005). ZHENG Ting-ting *et al.* (2013) adopted GMS to optimize the groundwater exploitation plan at a given water diversion project in Heilongjiang province. WANG Li-ya (2014) created the numerical model for

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groundwater in the plain area of Beijing to simulate multiple groundwater exploitation plans and identify the best groundwater exploitation plan. ZHANG Fen-na (2014), who chose the geothermal fluid of Neogene Minghuazhen Formation of Qiaogu- Kanchaizhuang, Tianjin Binhai New Area, applied Visual MODFLOW software to conduct the numerical simulation of the geothermal fluid in Minghuazhen Formation, calculated the recoverable resources of the geothermal fluid and designed the exploitation plan.

This paper, which focuses on the intensive exploitation area of geothermal resources in Xinji as the study area, develops the numerical model of Guantao Formation within the study area, completes the inverse calculation of hydraulic conductivity when the data about historical water level are considered, and optimizes the maximum permissible exploitation under the permissible decrease rate of water level. The research findings will serve as the theoretical basis for our efforts to determine the geothermal water exploitation quantity within Guantao Formation in Xinji, thus providing references to the future researches on geothermal resources.

1 Overview of study area

Xinji's geotectonic locates at Sino-Korean paraplatform, North China depression and Linqing sink. The study area is located within the intensive exploitation zone of geothermal water in Xinji and covers a total area of 46 km^2. The strata within study area is Quaternary System, Minghuazhen Formation and Guantao Formation of Neogene System, and Paleogene system, beneath which are bedrocks. Guantao Formation within study area is the mainly exploitation stratum of geothermal water. The elevation of top board ranges from -1 337 m to -1 573 m, and the base board is -1 550 m to -1 852 m. And the reservoir has full confining bed. This paper mainly examines the thermal reservoir of Guantao Formation, without considering the effects of Minghuazhen Formation and bedrocks.

After two abandoned oil wells were transformed in 1999 to geothermal wells of Guantao Formation, there is a gradual increase in the number of geothermal wells in Xinji. Currently, there are more than 22 geothermal wells in Xinji, including fifteen geothermal exploitation wells with monitoring (Fig. 1), which have continuous water level observation records of Guantao Formation since 2010.

Based on the multiple-well pressure reduction test, the hydraulic conductivity K is 1.85 m/d. The storage coefficient is calculated through the empirical formula (QIU Mei-da *et al.* 1989), which is 2.76×10^{-4}.

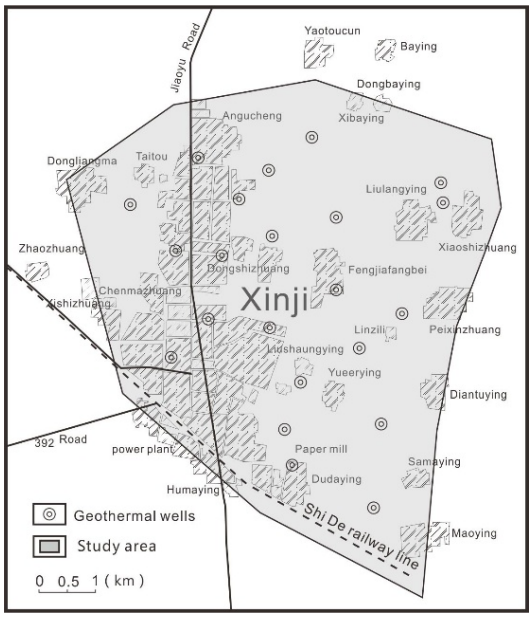

Fig. 1 Study area and distribution of geothermal wells

2 Conceptual model

Based on the distribution of existing hydrodynamics, this paper simulates and forecasts the dynamic distribution of water flow field under the permissible exploitation quantity. Therefore, the forward model is chosen to express the distribution of water flow field as time passes. This paper does not consider the effects of Minghuazhen reservoir and bedrocks, and treats the thermal reservoir of Guantao Formation as heterogeneous isotropic two-dimensional model. The top and bottom boundaries are the zero-flow border. Since the conditions outside of study area are unavailable, it is hard to generate complete hydrogeologic zones. According to the historical monitoring data, the boundary flow can be described as follows: For Zone 1, the boundary length is 14 km and the recharge quantity is

1 240 000 m^3/a; for Zone 2, the boundary length is 2 km and the recharge quantity is 180 000 m^3/a; for Zone 3, the boundary length is 3 km and the recharge quantity is 260 000 m^3/a; for Zone 4, the boundary length is 2.6 km and the recharge quantity is 210 000 m^3/a; for Zone 5, the boundary length is 2.4 km and the recharge quantity is 230 000 m^3/a (This paper uses the boundary recharge of the initial year as the constant boundary condition, and doesn't consider the recharge increase incurred by the fall in water level). There are 22 geothermal exploitation wells in the study area, and the exploitation quantity is determined according to historical exploitation data.

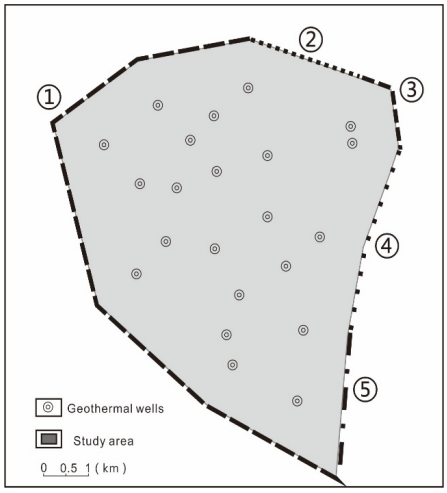

Fig. 2 Boundary conditions of study area

3 Mathematical model

Based on Darcy's law and mass conservation, the basic differential equation for two-dimensional groundwater movement (Panday *et al.* 2013) is detailed as follows:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)-w=S_s\frac{\partial h}{\partial t}$$

where, K_{xx}, the hydraulic conductivity along x, m/s; K_{yy}, the hydraulic conductivity along y, m/s; h–water head, m; w –source sink term, m^3/s; S_s–storage coefficient. The groundwater depth of Guantao Formation in 2010 is used as the initial condition of model: $H(x,y,t)|_{t=0}=H(x,y,t_0)$, where t_0–groundwater depth in 2010 (groundwater elevation have been changed to groundwater depth, Fig. 3). The boundary for the top and base is the zero-flow boundary. The lateral boundary condition is the constant flow boundary condition.

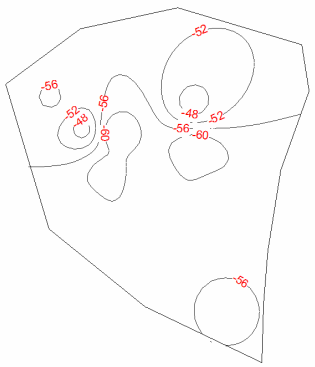

Fig. 3 Initial groundwater depth of study area

4 Model discretion

The rectangular mesh subdivision is used in this study. The study area can be subdivided into 51 rows and 44 columns. The length of sides is 0.2 km×0.2 km. There are 2 244 mesh units, including 1 206 valid units. Regardless of the effects of upper and lower strata, there is only one stratum in a vertical sense. The top and base elevation can be accepted by interpolation method according to the borehole data (Fig. 4).

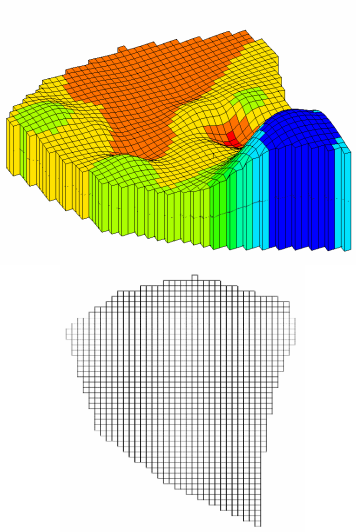

Fig. 4 Mesh subdivision of model

5 Model identification and verification

This paper uses GMS (ZHU Xiao-bin, 2003; ZHANG Xin *et al.* 2015; LI Yu *et al.* 2014)

software in the research process, and PEST toolkit for the inverse calculation of hydraulic conductivity and the model calibration and fitting.

There are fifteen monitoring wells within study area. From October 2010 to July 2015, there were fifteen identification and verification points. The hydraulic conductivity is 1.85 m/d, which served as the initial value of inverse calculation. The range of inverse calculation is 1.4–2.0 m/d. After calculation we got the distribution of hydraulic conductivity in study area (Fig. 5). The north-eastern and southern parts of the study area have the high hydraulic conductivity of 2.0 m/d; the hydraulic conductivity in the middle part of study area falls within the scope of 1.4–1.5 m/d; for the majority of study area, hydraulic conductivity is 1.7–1.9 m/d.

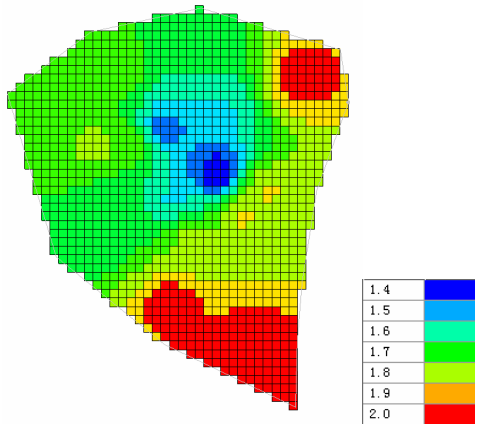

Fig. 5 Distribution of hydraulic conductivity

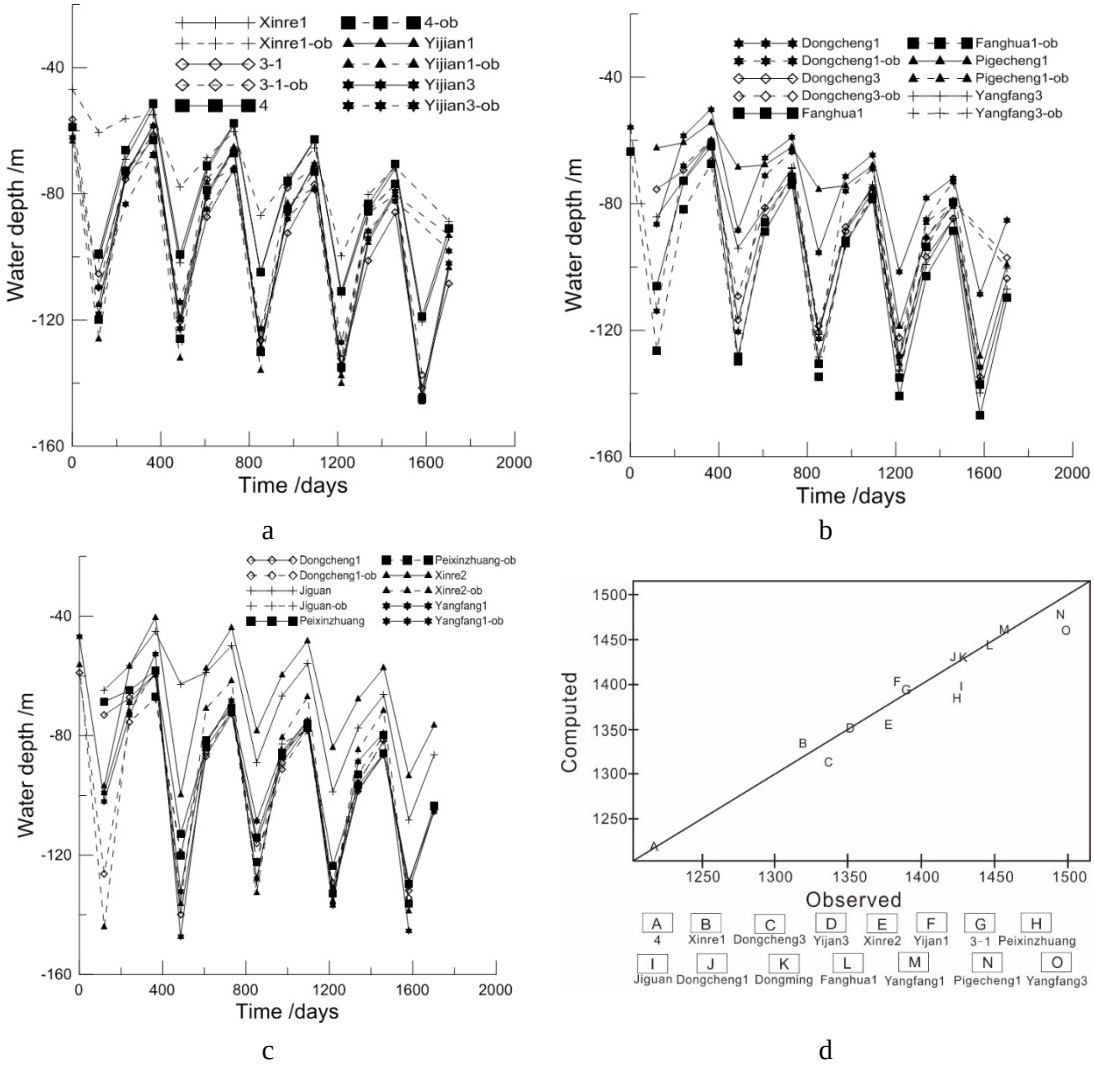

Fig. 6 Comparison of calculated water depth and monitoring values

Fig. 6 compares the calculation value and observation value of groundwater depth in each well. As indicated in the figure, the simulation effects of calculation value and observation value of groundwater depth in fifteen observation wells during the simulation period are quite satisfactory, so the results are believable (Fig. 6).

6 Evaluation of exploitation

This paper specifies the principle for determining the permissible annual decrease rate of static groundwater level, which is within 50 years exploitation period, the static groundwater depth in Guantao Formation does not exceed 200 m. The development of geothermal water in the intensive exploitation zone of Xinji started in 1999. In 2015, the groundwater depth averaged 93.1 m. So the permissible annual decrease rate of static groundwater level will be defined as 3.14 m/a.

If the present exploitation continues (Table 1, the total exploitation quantity is 2 922 864 m^3/a), the distribution of groundwater depth in November 2020 is described in Fig. 7. From the figure, we find that the exploitation of geothermal water will further drive down the groundwater level. At this time, the maximum groundwater depth comes close to 122 m, and the annual decrease rate of groundwater level is 5.5 m/a, which has exceeded the maximum permissible decrease rate of 3.14. Fig. 7 describes the distribution of groundwater level in November, 2049. At that time, the groundwater depth in study area will reach 282 m, and the annual decrease rate of groundwater level is 5.5 m/a, which is far above the maximum permissible groundwater depth. So we need to reduce the exploitation of the wells to meet the requirements for the maximum permissible groundwater depth.

Table 1 Exploration of wells

Well	Present exploitation (m^3/a)	Adjusted exploitation (m^3/a)	Groundwater level in 2049 (m)
Xinre 1	113 160	84 870	196.4129
3-1	143 700	107 775	194.9221
No. 4 well	132 600	99 450	193.3325
Yijian 1 well	148 800	111 600	193.6834
Yijian 3 well	187 896	140 922	195.5676
Yangfang 3 well	147 792	110 844	191.9241
Dongcheng 3 well	148 200	111 150	196.1383
Fanghua 1 well	179 160	134 369	195.740
Pigecheng 1 well	152 796	114 597	195.1251
Dongming well	136 500	102 375	194.5968
Jiguan well	136 500	102 375	195.4412
Peixinzhuang well	140 400	105 300	192.9015
Xinre 2 well	87 240	65 430	192.6554
Dongcheng 1 well	99 960	74 970	195.3324
Yangfang 1 well	99 000	74 250	194.8447
Dongcheng 4 well	140 400	105 300	196.017
Xinji High School well	188 160	141 120	196.1638
Guangboju well (Housing geothermal well No.1)	124 800	93 600	195.1774
Liulang well	151 200	113 400	195.5273
Tengyue well	72 000	54 000	193.7401
Xinre 6	63 000	47 250	196.3007
Meihua	129 600	97 200	194.0134
Total	2 922 864	2 192 148	-

Table 1 details the adjusted exploitation for each well and the forecasted groundwater depth in 2 049. All the wells have reduced the exploitation and their total exploitation is 2 192 147 m^3/a, about 75% of the present exploitation. In this case, the groundwater depth of each well averages 196 m, which meets the requirement for the maximum permissible groundwater depth.

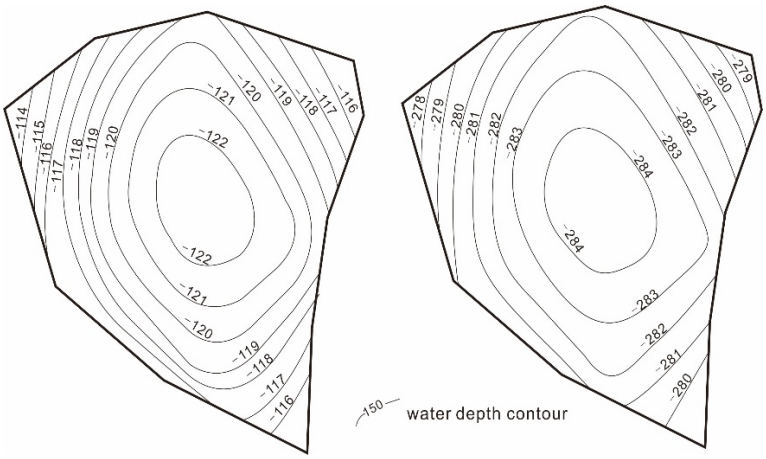

Fig. 7 Distribution of water depth

7 Conclusions

This paper, which focuses on the intensive exploitation area of geothermal resources in Xinji as the study area, develops numerical model of Guantao Formation, completes the inverse calculation of hydraulic conductivity with historical water level data, and optimizes the maximum permissible exploitation under the permissible decrease rate of water level. The research findings are described as follows:

(1) The hydraulic conductivity of thermal reservoir in Guantao Formation is in the range of 1.4–2.0 m/d. The northeastern and southern parts of the study area have the high hydraulic conductivity of 2.0 m/d; the hydraulic conductivity in the middle part of study area is within the scope of 1.4–1.5 m/d; for the majority of study area, hydraulic conductivity is 1.7–1.9 m/d.

(2) In this model, the simulation effects of fifteen identification and verification points in fifteen wells are quite satisfactory, and calculation value and observation value of groundwater depth show the same trend, so the results can be trusted.

(3) Within the fifty-year exploitation period, the maximum permissible exploitation of geothermal water in Guantao Formation is 2 192 147 m^3/a, about 75% of the present exploitation when the static geothermal groundwater depth in Guantao Formation does not exceed 200 m.

This study offers a chance to visually understand the migration characteristics of geothermal water in Guantao Formation when exploitation continues, and provides the theoretical basis for designing the development and exploitation plan of geothermal water after the maximum permissible exploitation is calculated, so some valuable references are made available for those regions with similar problems. What's more, because some data are unavailable, the model in this paper does not present the complete hydro-geologic units or consider the increased boundary recharge and the revolution of geothermal water temperature field as incurred by the water level decrease in study area. So future research is necessary to make improvements accordingly.

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