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RESERVOIR ASSESSMENT OF THE XIONGXIAN GEOTHERMAL FIELD, HEBEI PROVINCE, CHINA

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ABSTRACT

The Xiongxian geothermal reservoir is a low-temperature sedimentary sandstone and dolomite system. According to long-time pressure and temperature monitoring data, the reservoir temperature for the sandstone is in the range of 40-92°C and for the dolomite in the range of 60-118°C, which is suitable for space heating, swimming pools and greenhouses. No reliable evidence shows that the reservoir temperature has declined in the past few years. Because of increasing production since the 1980s, the water level has dropped continuously and the total drawdown has reached more than 40 m. Based on the available geological and geophysical information, a conceptual reservoir model was set up that explains the heat source, recharge zone, reservoir size, etc. Lumped parameter modelling is used for simulating pressure response data and predicting future water level variations. The simulation results indicate that the reservoir behaves as an open system with recharge water coming from an outer system or through the permeable faults around the Niutuozhen uplift. The prediction results show that by keeping a production rate of 70 l/s for the next 15 years, the water level will be relatively stable and finally reach equilibrium with the surrounding recharge system. In addition, several reinjection wells will be drilled in the next few years, which can slow the pressure drawdown and allow the withdrawal of more heat energy from the formations. The Monte Carlo volumetric method was used for estimating the thermal power potential of the Xiongxian geothermal system; the calculation results show that the recoverable thermal power has a potential between 48 and 300 MW_t for the next 100 years with 90% probability.

1. INTRODUCTION

The Xiongxian geothermal reservoir is part of the Niutuozhen uplift geothermal field, which is located in the centre of Hebei province, China, as shown in Figure 1. Geological investigations, as well as geochemical and reservoir engineering research, have been carried out in this area, and the results demonstrate that the geophysical and thermal conditions are fit for relative large scale exploitation. Based on available information, the Xiongxian geothermal system can be defined as a low-temperature sedimentary sandstone and dolomite reservoir, which consequently can be largely divided into three individual systems in accordance with the formations. Twenty-six wells were drilled in the reservoir up to 2004 with a total production of 226.5×10^4 m^3 (Liu et al., 2005). Additional five geothermal wells were drilled in 2007. Most of the geothermal water has been used for swimming pools, space heating and greenhouses, with great economic and environmental benefit.

FIGURE 1: Location of Xiongxian geothermal field, China

The main problem expected during exploitation is temperature and pressure decline during long-time production. Based on monitoring data, the water level decline in the Xiongxian geothermal field reached 40 m after production from 1970 to 2004 (Liu et al., 2005). For historical and economic reasons, reinjection wells have not been drilled in this field till now, but some specialists have suggested that the government drill reinjection wells to counteract the drawdown and extract more energy from the surrounding formations.

The main purpose of the work presented in this report is to estimate the production potential and pressure variations in the future. First, it is necessary to build a conceptual model to indicate the recharge conditions, heat source and other reservoir properties. Then simulation is done by a lumped parameter model to estimate reservoir properties and predict pressure changes. Finally, the volumetric method is used to estimate the thermal power potential for the next 50 years, and the results are compared with the results of the lumped parameter model.

2. BACKGROUND

2.1 Exploration history

The geological and petroleum department of Hebei province of China has carried out geological investigations in the Huabei plane since the 1950s, including gravity surveys, exploratory drilling and hydrological reconnaissance. In the early 1980s, the Niutuozhen uplift geothermal reservoir was discovered during petroleum exploration. Since then geological, tectonic, reservoir distribution and geochemical research has been carried out to make the initial assessment of the reservoir. Up to 1990, 13 geothermal wells had been drilled into the sandstone and dolomite reservoir, laying a solid foundation for further development. From 1990 to 2007, additional 18 geothermal wells were drilled in the Xiongxian geothermal field, obtaining more detailed geological and geophysical information on the reservoir.

2.2 Exploitation history

According to a resource assessment report (Liu et al., 2005) for the Xiongxian geothermal field, a total of twenty-six wells had been drilled in the field by November 2004. Most of them are distributed over the western part of Xiongxian County within the Niutuozhen uplift. Specifically, seven wells are scattered about the towns and county north of the city centre. Fourteen wells are located in the city centre and the final five wells are in the hot spring city of Baiyangdian. Detailed information is shown in Figure 2. Additional four geothermal wells were drilled in 2007.

The geothermal resource development in Xiongxian County started around 1970, but until the middle of the 1970s, both the production rate and the number of wells remained on a small-scale. The annual production was 8-12×10^4 m^3 for the initial developmental stage. Along with economic development

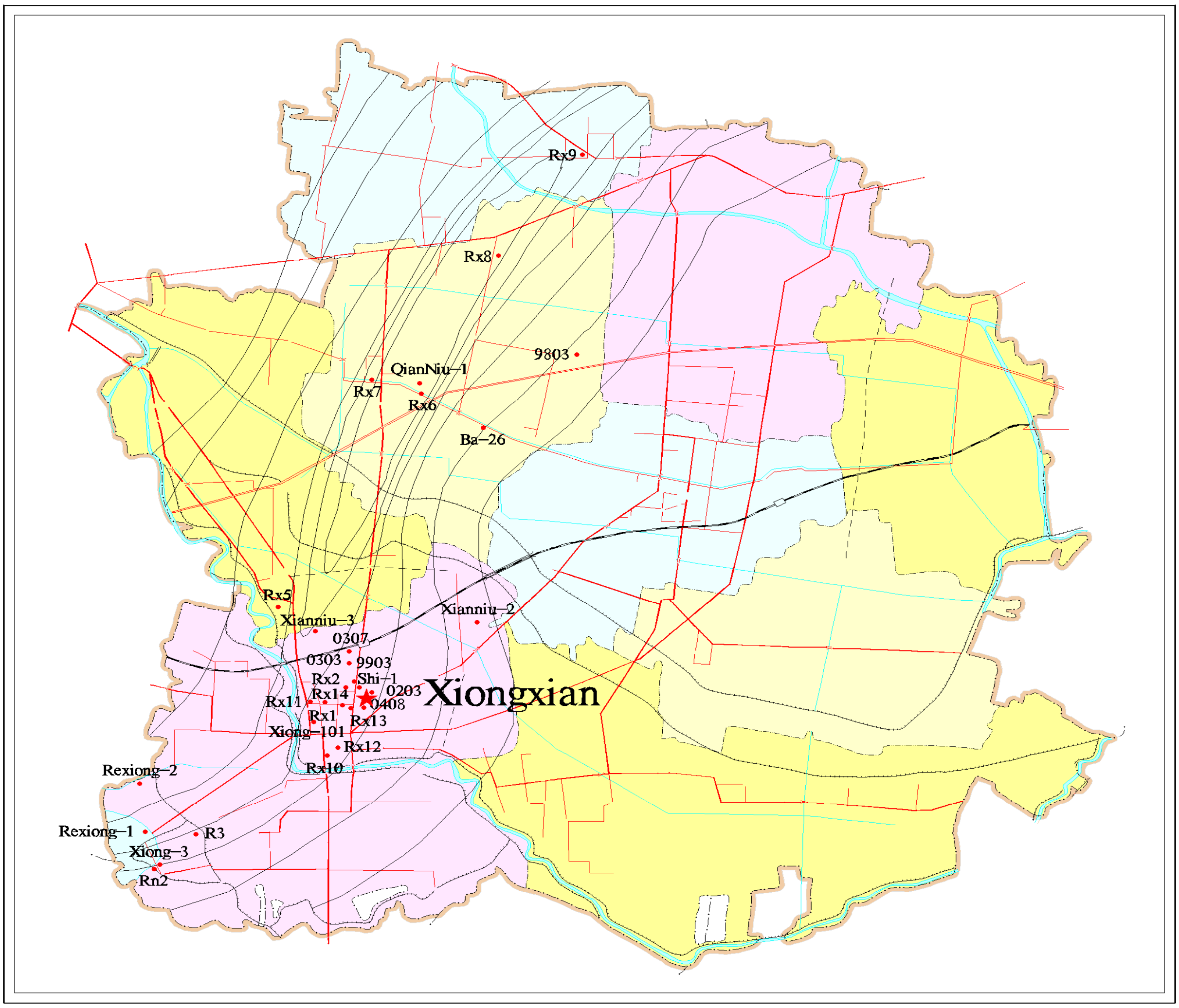


FIGURE 2: Distribution of geothermal wells in Xiongxian County

and technological progress, annual production increased to 31×10^4 m^3 in 1977. Because no additional geothermal wells were drilled during the 10 year period from the mid-1970s to the mid-1980s, geothermal exploitation did not develop rapidly. In the mid-1980s, several production wells were drilled in the field and annual production reached 54×10^4 m^3, which was 70% over the annual production of the previous 10 years. From 1993 to 2004, the annual production increased from 96×10^4 to 230×10^4 m^3. At the end of 2007, 31 wells had been drilled in the Xiongxian geothermal field with an annual production rate of 230×10^4 m^3, as shown in Table 1, and the total extraction of the past 30 years had reached 28×10^6 m^3. The combined annual production from 1973 to 2004 is shown in Table 2.

The available information on geothermal wells reflects that the pressure in the Tertiary and Jixian system is almost at the same level. The pressure differential between the two systems can hardly be discerned. There are many artesian wells in the Xiongxian geothermal field that had initial water levels of more than 10 m above the surface before the 1980s, for example: RW-1, located at the Xiongxian spring city. The initial water level could reach 14.63 m above the surface with a production rate of 65 m^3/h. The water level in artesian well RW-3 could reach 10.7 m above the surface with a production rate 80 m^3/h. Information on other artesian well is shown in Table 3. After the mid-1990s, the water levels dropped rapidly with the constant increase of the production rate. Now the water level has dropped about 40 m in the downtown area and 20 m near the northern part of the geothermal field.

TABLE 1: The total geothermal production in Xiongxian in 2004

Well number	**Production (10^4 m^3)**		
	Winter	**Summer**	**Total**
Rx1	10.6	1.4	12
Rx2	10.1	5.88	15.98
Rx5	10.8	1.4	12.2
Rx6, Rx8, Rx9, Rn2, Qianniu-1, 0203, 0307, 9803	--	--	Not in use
New-1, New-2, New-3, New-4, New-5	--	--	Unknown
Rx10	16.8	3.36	20.16
Rx11	12.6	6.72	19.3
Rx12	4.2	1	5.2
Rx13	11.5	3.36	14.86
Rx14	6.5	0	6.5
Rw1, Rw2, Rw3	30	15	45
Shi-1, 9903	33.6	7.2	40.8
0303	4.8	1.2	6.0
0408	8.6	4.3	12.9
Ba-26, Rx7, Xiong-3	10	5.6	15.6
Total	**170.1**	**56.4**	**226.5**

TABLE 2: The combined annual geothermal production from 1973 to 2004 in Xiongxian

Year	**Production (10^4 m^3)**	**Year**	**Production (10^4 m^3)**	**Year**	**Production (10^4 m^3)**	**Year**	**Production (10^4 m^3)**
1973	12	1981	31	1989	48.8	1997	183.5
1974	8	1982	31	1990	53.8	1998	192
1975	8	1983	31	1991	53.8	1999	192
1976	12	1984	31	1992	53.8	2000	192
1977	31	1985	30	1993	95.5	2001	190
1978	31	1986	31	1994	96.7	2002	210.4
1979	31	1987	49	1995	160.5	2003	220
1980	31	1988	49	1996	170.5	2004	226.5

TABLE 3: The water level in Xiongxian geothermal wells

Well no.	**Location**	**Drilled (year)**	**Init. water level (m above well head)**	**Init. prod. rate (m^3/h)**	**Depth to water level in 2005 (m)**
Rw1	Baiyangdian hot spring city	1992	+14.63	64.12	
Rw2	Baiyangdian hot spring city	1992	+10.9	22.604	
Rw3	Baiyangdian hot spring city	1993	+10.7	78.74	28.00
Rx1	Xiongxian middle school	1987	+10.77	43.92	
Rx5	Vocational middle school	1989	+2.71	64.11	29.80
Rx7	Daying town	1989	+9.64	36.96	46.82
Rx10	Xiongxian government	1990	+1	30	40.00
Rx13	Xiongxian hospital	1995			49.60

2.3 Geological information

Based on the lithology and drilling information, the Quaternary layer consists of alternating clay and sandstone and constitutes the caprock of the reservoir with an average thickness of 400 m. Though clay has a high porosity, the permeability is still very low (10^{-9} m/s, 10^{-1} mDarcy). According to the basic characteristics of the crustal temperature distribution in China (Wang et al., 1990), the measured clay thermal conductivity is 1.7-2.3 W/mK. Because thermal conductivity usually increases with depth and density for the Mesozoic and Cenozoic rocks, the thermal conductivity for the clay can be smaller than the surveyed value above. So neither the thermal conductivity nor the permeability are large enough to conduct heat from the deeper formation or form convection between the Quaternary and deeper formations. So we can deduce that the Quaternary forms a good caprock for the deeper sandstone and dolomite reservoir.

According to the rock properties and physical conditions in the reservoir, the Xiongxian geothermal system is composed of the Neogene, Paleogene and Jixian sub-systems. The Neogene system is a sandstone formation spread widely around Xiongxian County with a thickness of 500 to 1000 m. The thickness near the axis of the Niutuozhen uplift is much less than that of the outer stratum. This stratum consists of alternating sandstone and mudstone; the sandstone accounts for 38% of the whole Neogene layer.

The Paleogene system is mainly located in the Baxian graben, which is located at the SE-Niutuozhen uplift. The thickness of the Paleogene system reaches more than 5000 m, and the temperature gradient is lower than in the Neogene system. The Paleogene system can be divided into three groups. The Dongying group consists of alternating sandstone and mudstone and has a thickness between 1000 and 2000 m. The composition of the Shahejie group is complicated; it is composed of sandstone, dolomite, mudstone and shale. The depth of this group can reach more than 4000 m. The Kongdian group mainly consists of sandstone and mudstone and has a thickness of more than 1000 m. The detailed information is shown in Figure 3.

The Jixian system holds better thermal and tectonic conditions than the Tertiary system. Therefore most of the geothermal wells in this area have been drilled into these productive formations to extract the hot water more economically. The system can also be divided into several groups, and the Wumishan group is the most productive one; it is widespread around the Xiongxian geothermal

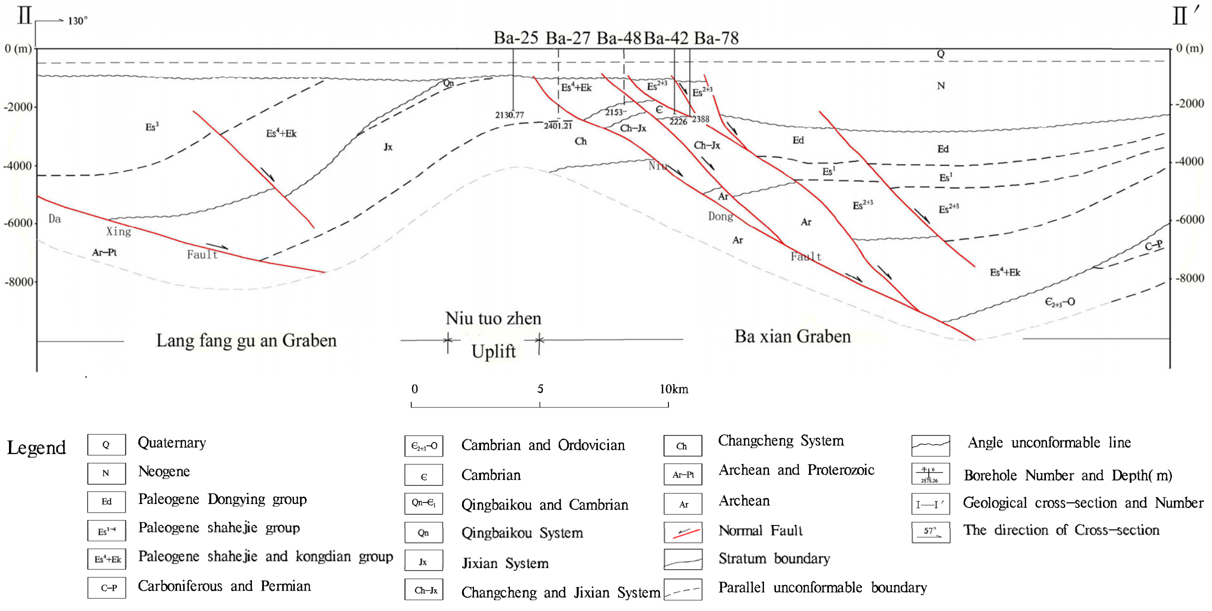


FIGURE 3: The II-II' geological cross-section through the Niutuozhen uplift (location shown in Figure 4)

system with a depth range of 950 to 1050 m. The thickness always becomes less in the axis of the Niutuozhen uplift. For example, the borehole exploration data from the Qianniu-1 well shows that the thickness close to the axis only reaches 528 m, while the formations becomes thicker on the lateral sides of the uplift, reaching 1100 m on the periphery of the Niutuozhen uplift. The formation in the Jixian reservoir largely consists of dolomite and alternating dolomite and flint belts. The simplified lithological structure in the Xiongxian geothermal system is shown in Table 4.

TABLE 4: Simplified lithological structure of the Xiongxian geothermal system

Stratum	Thickness (m)	Lithology
Quaternary	192 – 500	Clay, sandstone and sand-clay
Neogene	500 – 1000	Sandstone and mudstone
Paleogene	>5000	Mudstone, sandstone and shale
Ordovician	540 – 933	Limestone, dolomite and mudstone
Qingbaikou	350	Limestone and shale
Cambrian	353 – 780	Mudstone, limestone and dolomite
Jixian	1375 – 2950	Dolomite, mudstone and shale
Changcheng	>1000	Dolomite, shale and sandstone

2.4 Tectonics and lithology information

The boundary conditions of the Xiongxian geothermal system are controlled by the Niunan, Rongcheng, Xiongxianxi, Daxing and Niudong faults as shown in Figure 4. The profile I-I’ will be presented in the section on the conceptual reservoir model. The Niudong fault is situated east of Xiongxian County, at a 4 km distance from downtown. This fault controls the boundary conditions between the Niutuozhen uplift and the Baixian graben. The Niunan fault is located at the boundary between Xiongxian and Anxin Counties, controlling the southwest boundary of the Niutuozhen uplift. This fault crosses the eastern part of the Xushui fault, which is a normal fault. The Daxing fault is situated in the northwest part of Xiongxian County, and controls the sedimentation in the Niutuozhen uplift and the Gu’an graben. The

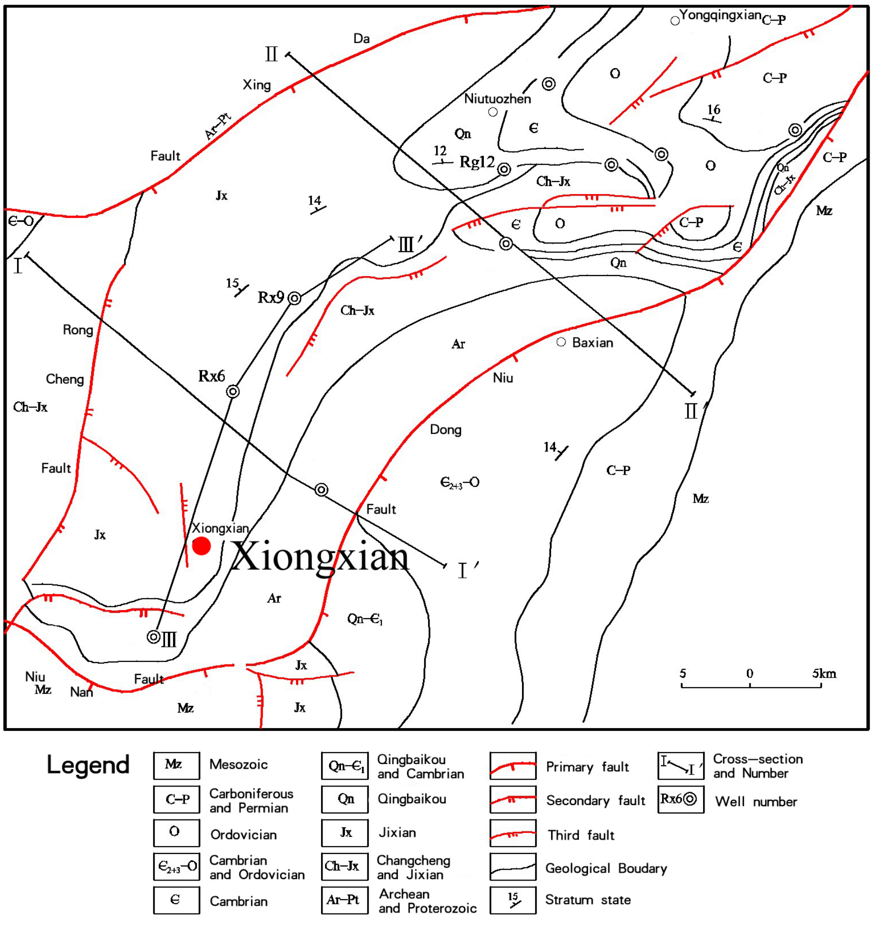


FIGURE 4: Geological map of the bedrock of the Xiongxian geothermal field

stratum sequence in the upper part of the fault is of Tertiary and Jixian system, and the lower part is Tertiary and Archean. The Rongcheng fault is the boundary between the Niutuozhen uplift and the Rongcheng graben, and this fault controls the Tertiary sedimentation in the area. Finally, the Xiongxianxi fault is located northwest of Xiongxian city centre, connecting to the Rongcheng fault on the western part. This fault does not control the Tertiary sedimentation, and some magma intrusions have formed along the fault.

Some evidence indicates that several segments of the Niudong and Rongcheng faults are responsible for convection of the hot water allowing it to reach the upper stratum. The thermal gradient can exceed 7°C/100 m near the southern part of the Niutuozhen uplift. As this value is much higher than in the periphery area, it indicates a regional water and heat convection existing between the strata. In the process of drilling well Qianniu-1 and Xiong-104, there were large quantities of drilling fluid loss in the limestone reservoir, which shows some fissures have formed in the limestone; another large solution crevice with a diameter of more than 20 m was found during the drilling in 2008. Though fissures are propitious for transferring water and heat to the upper stratum, it is not homogeneous in the horizontal direction and becomes feeble at depth. Another phenomenon is that the measured temperature around the bedrock surface, which is located at 1000-2000 m depth below the surface, doesn't appear to be homogeneous around the bedrock surface. So it is impossible to form strong convection through the faults in the whole reservoir. It can be concluded that the Xiongxian geothermal field is a conductive-dominated reservoir, with some regional convection near the faults.

In the Huabei plane, the Neogene system is largely dominated by a sandstone and gravel mixture. The rock properties of this formation present good sorting and porosity; here the stationary flow J. Dupuit formula was used to calculate the hydraulic conductivity of the formation, based on the fourteen well test data. The results show that the hydraulic conductivity is confined to a range of 0.13-0.65 m/d as shown in Table 5, denoting good conditions for future exploitation.

TABLE 5: The hydraulic conductivity in the Xiongxian geothermal reservoir

Well no.	**Formation**	**Depth (m)**	**Thickn. (m)**	**Drawdown (m)**	**Prod. rate (m^3/h)**	**Temperature (°C)**	**Hydraul. cond. (m/d)**
94-7	Jxw	1073	188	20.10	51.28	66.5	0.22
Rn-2	Nm	590	64	6.22	73.66	55-57	0.65
94-10	Jxw	1056	137	14.20	69.00	66.6	0.30
9717	Jxw	799	187	11.20	32.51	57	0.38
SHI-1	Jxw	1026	176	14.48	80.00	68.5	0.30
9903	Jxw	1014	12	10.00	42.47	68	0.42
0203	Jxw	1066	134	34.63	69.74	69	0.13
0303	Jxw	991	108	16.15	65.00	70	0.27
0307	Jxw	881	126	8.16	88.00	71	0.51
0408	Jxw	1034	216	9.25	63.00	69	0.45
Rw3	Jxw	1078	122	9.32	78.84	83.3	0.45
Rw2	Jxw	1013	111	7.20	16.05	77	0.57
Rw1	Jxw	971.8	258.38	11.00	57.21	83	0.38
9803	Ng	945.0	306.00	12.20	50.00	50.5	0.35

2.5 Dynamic temperature and pressure information

2.5.1 Dynamic pressure information

The pressure in the Xiongxian geothermal system has a significant seasonal variation as shown in Figure 5. The water level drops abruptly in winter due to the large quantity of exploitation, and in summer the water level rises by several metres. The annual water level variation is estimated to be in

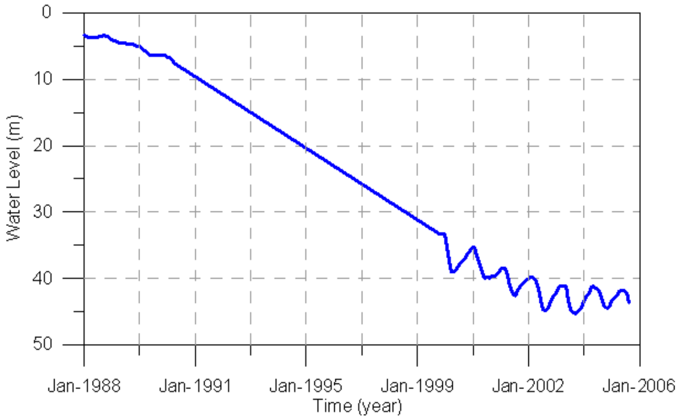


FIGURE 5: Reservoir pressure variations in Xiongxian County during 19 years from 1987

the range of 5-6 m. In the period of initial exploitation, the water levels usually reach 10 m above the surface, but with the increase in the production rate, the reservoir pressure has dropped at a constant rate every year. For example, the production history in Xiong-101 reflects that the water level dropped 2 m annually after 1988.

2.5.2 Dynamic temperature information

Dynamic information on temperature in the Xiongxian geothermal system has not been recorded accurately, but according to the wellhead testing report, the temperature in the geothermal wells has not changed drastically after large-scale exploitation started. In addition, the exploitation history during the past 20 years indicates that the temperature in most of the geothermal wells did not drop significantly.

According to the Niutuozhen geothermal resource assessment report (Liu et al., 2005), a constant temperature zone is located at 15-50 m depth underground with a temperature of 14.5°C on average. In the Cenozoic system, the temperature gradient can reach 13°C/100 m in the axis of the uplift, but falls gradually along the lateral sides. The lowest value is 2.3°C/100 m at the uplift boundaries. The thermal gradient in the Jixian system reaches 3.3°C/100 m, which is far lower than in the Cenozoic. The temperature gradient map for the Cenozoic system is shown in Figure 6.

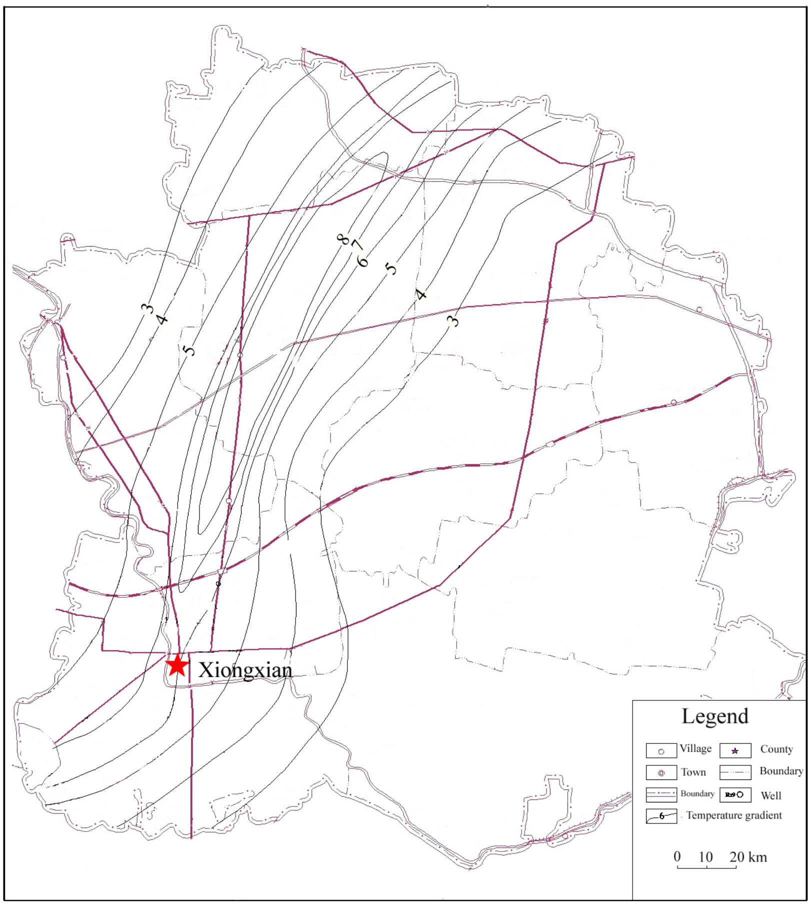


FIGURE 6: Temperature gradient map for the Cenozoic system of the Xiongxian geothermal field

The most important cause of the relatively high temperature and thermal gradient south of the uplift is the differences in the lithology conditions. Geochemical investigation has proven that the salinity can reach about 1.5-2.0 g/l in the bedrock around the southwest part of the Niutuozhen uplift, but gradually becomes higher from southwest to southeast and finally reaches 2.1-2.5 g/l in the Xiongxian County. According to the mathematical temperature simulation results in the Niutuozhen uplift (Chen, 1988), the measured thermal gradient in the south-west uplift is obviously lower than the simulation value. All the evidence above indicates that the southeast uplift is closer to the groundwater recharge zone than the other area in the uplift, and that the cold recharge water coming from the Taihang mountain flows from the west to the east, then encounters the hot water stored in the southwest part of the Niutuozhen uplift. So the temperature and thermal gradient become distinctly lower than simulated values would presume.

2.5.3 Dynamic water quality information

The chemical composition of the geothermal water over the past few years did not show many changes. Only Na+ concentration has slightly increased with the increasing production rate. The geochemical investigation data are shown in Table 6.

TABLE 6: Chemical composition of fluid from Xiongxian geothermal wells

Well no.	**Ba-26**		**0203**		**RW-3**	
Sampling date	1977.5	2005.11	2002.10	2005.11	1993.10	2005.11
K^+	56.0	56.0	817.4	62.8	901	66.2
Na^+	880	932		897		911
Ca^{2+}	32.1	32.1	62.1	56.7	66.1	54.1
Mg^{2+}	35.3	36.2	23.1	27.7	21.9	22.1
HCO_3^-	524.7	532	659	669	677.3	646
Cl^-	1294	1330	1021	1220	1134	1210
SO_4^{2-}		2.2	31.2	<0.2	38.4	<0.2
F^-	8.98	10.6	6.6	7.8	8.2	7.80
H_2SiO_3		54.8		55.5		71.1
TDS		2930	2300	2940	2500	2910
pH	6.85	7.52	7.2	7.47	7.24	7.09

2.6 Analysis of the well test data

Well tests have been carried out in six geothermal wells in Xiongxian in order to estimate the hydrological properties of the reservoir. This data has been used to simulate the relationship between water level and flow rate to correct for the friction and turbulent flow in the wells; the water level in the flowing well is then described by the following equation:

$$H = H_0 + B \times Q + C \times Q^2 \qquad (1)$$

where Q is the flow rate;
H_o is the water level in the well at zero flow (static well);
$B \times Q$ is the linear drawdown in the reservoir;
$C \times Q^2$ is the pressure loss caused by turbulent flow at the location of inflow into the well and in the well itself.

Then the simulation results, using the well test data, can be used for estimating the relationship between the water level and flow rate; the coefficients of each well are as follows:

Rn-2: $H = 8.2321 - 0.1735Q + 0.0019Q^2$
R1: $H = 7.8094 - 0.1718Q + 0.0039Q^2$
9803: $H = -0.6809 + 0.2556Q + 0.000039Q^2$
9717: $H = 3.9217 + 0.1062Q + 0.0036Q^2$
94-10: $H = 1.6819 + 0.1192Q + 0.0009Q^2$
9903: $H = 1.0881 + 0.1352Q + 0.0017Q^2$

The simulation results are shown in Figure 7. We can observe from the figure that the geothermal wells, which are located in different parts of the Xiongxian reservoir system, have basically the same shape. We can deduce that the recharge water from the outer system cannot maintain large scale production without reinjection. The Xiongxian government has prepared to drill several reinjection wells to deal with the problem of pressure drop.

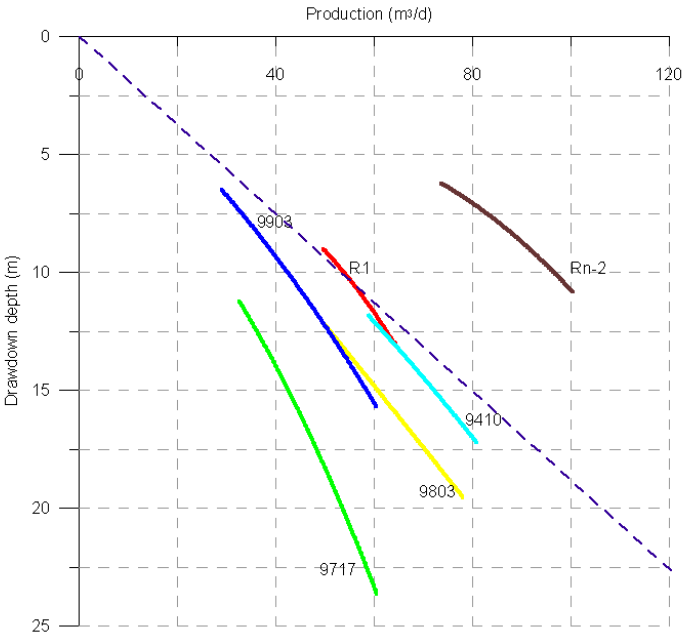


FIGURE 7: Simulation results of well test data in wells from the Xiongxian reservoir

3. MODELING THE XIONGXIAN GEOTHERMAL SYSTEM

3.1 Conceptual reservoir model

A conceptual reservoir model of the Xiongxian geothermal system incorporates all the available physical features that have been obtained through exploration drilling, geophysical surveys and other investigations. Temperature and pressure data are the essential data for constructing a good model. Then the model can provide information on the heat source mechanism, recharge conditions and other important information concerning the reservoir. The basic structure of the conceptual reservoir model of the Xiongxian geothermal system is shown in Figure 8. The details of the conceptual model are:

1. The Quaternary layer with an average thickness of 400 m constitutes the main caprock for the reservoir.
2. Based on the rock properties and physical conditions, the geothermal reservoir can be divided into three individual systems. The first reservoir is the Neogene system; it consists of alternating sandstone and mudstone layers and has an effective thickness of 225 m on average. The second reservoir is the Jixian system that is mainly composed of dolomite with an effective thickness

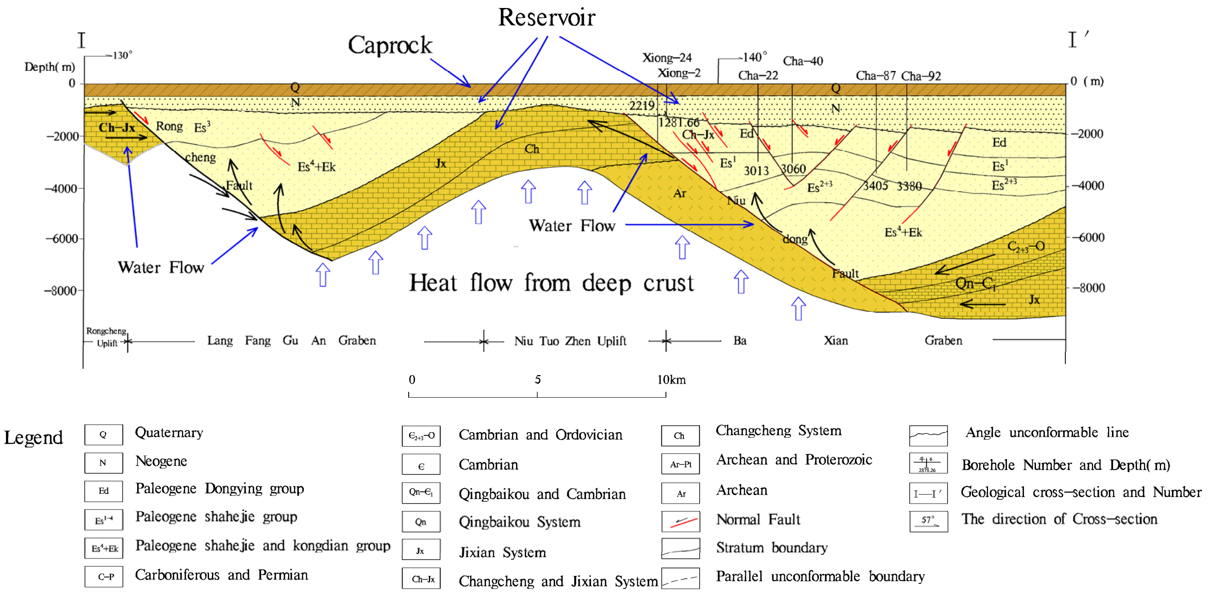


FIGURE 8: Conceptual reservoir model of the Xiongxian geothermal system

ranging from 285 to 315 m. The third reservoir is the Tertiary system with a total average thickness of 2500 m.

3. The Xiongxian reservoir system is a typical low-temperature sedimentary reservoir with a conduction-dominated heat flow, which largely comes from the deeper formation. The measured heat flux from the crust can reach about 72-110 mW/m^2 (Chen, 1988). The reservoir temperature at the top of the Tertiary is in the range of 25-60°C; at the bottom of it the temperature ranges from 40 to 92°C. The temperature at the bottom of the Jixian reservoir is in the range of 60-118°C. The temperature distribution at each depth is very similar to the temperature gradient map, shown in Figure 6.
4. Based on exploitation history information, Niudong, Rongcheng, Daxing and Niunan faults can be looked upon as permeable boundaries which have relatively high permeability. There is some evidence that shows that these faults contribute to the system recharge, as hot water can convect through these faults from the deeper formation to the shallow system.
5. The recharge water of the dolomite reservoir is believed to come from the faults surrounding the Niutuozhen uplift, but can also be of meteoric origin from the hills and mountains around the Huabei plane. Based on the model constructed by Bodvarsson for low-temperature systems in Iceland (Bodvarsson, 1982, 1983), the recharge can sink through an open fracture to a depth of a few kilometres inside the low-temperature geothermal field, where it takes up heat and ascends. In this model, the fracture is closed at depth but opens up and continuously migrates downward during the heat mining process by cooling and contraction of the adjacent rock (Axelsson et al., 2005a). This heat-source mechanism may also apply in the Xiongxian geothermal field.

3.2 Lumped parameter modelling

Lumped parameter models have been used widely to simulate geothermal reservoir pressure changes in Iceland for many years. They have also been constructed for some of the low-temperature fields in China, such as the Xi'an and Tianjin fields. Li (2003) and Yin (2002) have constructed such models by using the pressure and production monitoring data to predict future changes and estimate the properties of the reservoir. Axelsson (1989) has described an efficient method that tackles pressure change simulation with lumped parameter models as an inverse problem and can simulate such data very accurately, if the data quality is sufficient, even for very long data sets (several decades) (Axelsson et al., 2005b). The LUMPFIT program has been developed by employing iterative nonlinear inversion techniques to fit a corresponding solution to the pressure or water level data. The general lumped model, which consists of tanks and resistors, is shown in Figure 9. Tank and resistor represent capacitor with capacitance *κ* and conductor with conductance *σ,* respectively.

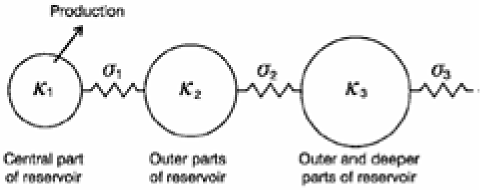


FIGURE 9: An open three-tank lumped parameter model

The capacitance of each tank expresses the response to a load of liquid mass *m* with pressure increase $p=m/\kappa$. This parameter then reflects the storage mechanism and is controlled by the liquid/formation compressibility or the surface mobility. Equation 2 defines the capacitance when the capacitor is dominated by liquid/formation compressibility:

$$\kappa = V\rho C_t \tag{2}$$

where V is the reservoir volume (m^3);
ρ is the liquid density (kg/m^3); and
C_t is the total compressibility of the liquid-saturated formation (Pa^{-1}).

The compressibility of the liquid-saturated formation C_t can be calculated by Equation 3:

$$C_t = \varphi C_w + (1-\varphi) C_r \tag{3}$$

where φ is the formation porosity;
C_w is the compressibility of water (Pa^{-1}); and
C_r is the compressibility of the rock (Pa^{-1}).

However, the capacitance can also be controlled by the mobility of the free surface as shown in Equation 4:

$$\kappa = A\varphi/g \tag{4}$$

where A is the surface area (km^2); and
g is the acceleration of gravity (m/s^2).

The conductance σ depends on the geometry and structures in the reservoir system, which reflects the permeability and other properties of the reservoir:

$$\sigma_i = 2\pi k_i \frac{h}{\ln(\frac{r_{i+1}}{r_i})\nu} \tag{5}$$

where k is the permeability (m^2);
h is the thickness of the reservoir (m);
ν is the kinematic viscosity of the fluid(m^2/s); and
r is the radius of the tanks (m).

In the models, coefficients A_j, L_j and B are functions of the capacitance coefficient κ_j and the conductance coefficient σ_j. The pressure response p of a general open lumped model with N tanks, to a constant production Q since t=0, can then be described by Equation 6:

$$p(t) = -\sum_{j=1}^{N} Q\frac{A_j}{L_j}\left[1-e^{-L_j t}\right] \tag{6}$$

And the pressure response p for a general closed model with N tanks can be described by Equation 7:

$$p(t) = -\sum_{j=1}^{N-1} Q\frac{A_j}{L_j}\left[1-e^{-L_j t}\right] + QBt \tag{7}$$

The two-tank open and the two-tank closed models were used to simulate the water level data individually; the results of the two-tank open model are shown in Figure 10. The parameters of these two models are presented in Table 7 for comparison. Based on the geological and geophysical investigation data from the past few years, the two-tank open model is regarded as the most appropriate model for the Xiongxian geothermal system. Consequently, we can use the parameters of the two individual models to estimate the reservoir properties, respectively, i.e. permeability, and reservoir volume and area, and then to investigate whether the results of the open

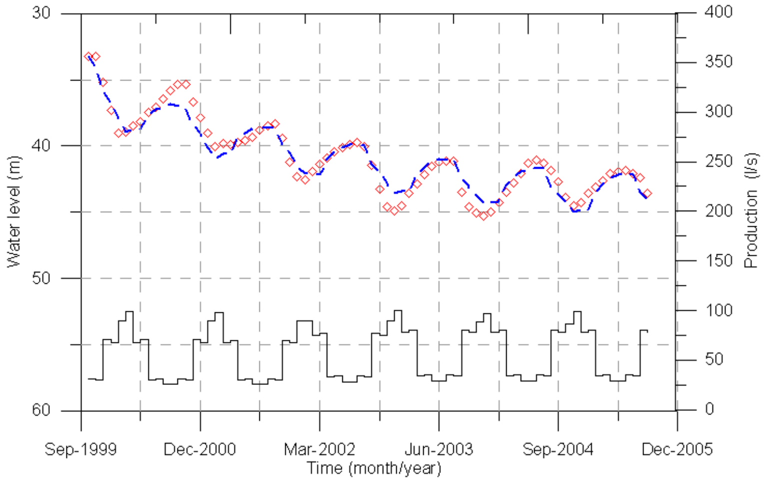


FIGURE 10: Simulation result for the Xiongxian system using a two-tank open lumped parameter model

model is in agreement with the reservoir properties revealed by geological investigations.

The surface area for the two-tank open model is as large as 860 km^2 and the permeability values are about 56 mD, which indicates good fluid transport conditions between the inner and outer tanks. It also reveals that the inner tank has good recharge conditions.

In order to assess the production potential and pressure variations in the future, we use both the open and the closed model to predict the pressure changes for three different production scenarios; these were selected by increasing the annual production from 70 l/s, the annual production in 2005, to 95 l/s, on average. The prediction period chosen was between 2006 and 2020.

TABLE 7: The simulation parameters for the two-tank closed and two-tank open lumped models for the Xiongxian geothermal system

Parameter	**Two-tank closed model**	**Two-tank open model**
A1	.0366	.0395
L1	.4692	.8613
A2		.0047
L2		.0319
B	.0015	.0000
κ_1 (ms^2)	7039.61	6074.19
κ_2 (ms^2)	162240	55573.7
σ_{12} (10^{-4} ms)	.0012	.00178
σ_{23} (10^{-4} ms)		.00075
Reservoir volume (km^3)		
Tank 1 (km^3)	196	169
Tank 2 (km^3)	4510	1550
Reservoir area (km^2)		
Tank 1 (km^2)	98	84.5
Tank 2 (km^2)	2255	775
Permeability (mD)	22.39	55.42
Coefficient of determination	**87.25%**	**92.69%**

Based on the prediction results shown in Figure 11, the open model indicates that the reservoir can sustain a production rate of 70 l/s until 2021 with an average additional drawdown of less than 4 m; this shows that the withdrawal from the inner reservoir can keep equilibrium with recharge coming from the outer area, according to the open model. It also indicates that the surrounding recharge area can supply sufficient water to maintain a nearly stable pressure. The closed model predicts that the pressure will drop relatively abruptly with a drawdown of more than 15 m. Increasing the annual production to 80 l/s, the open model indicates that the recharge water is still enough to sustain a withdrawal with an average additional drawdown of about 10 m. The closed model shows that the drawdown in this case could reach more than 22 m. When increasing the production to 95 l/s, the average additional water level drawdown for the open model becomes about 12 m and for the closed model more than 25 m.

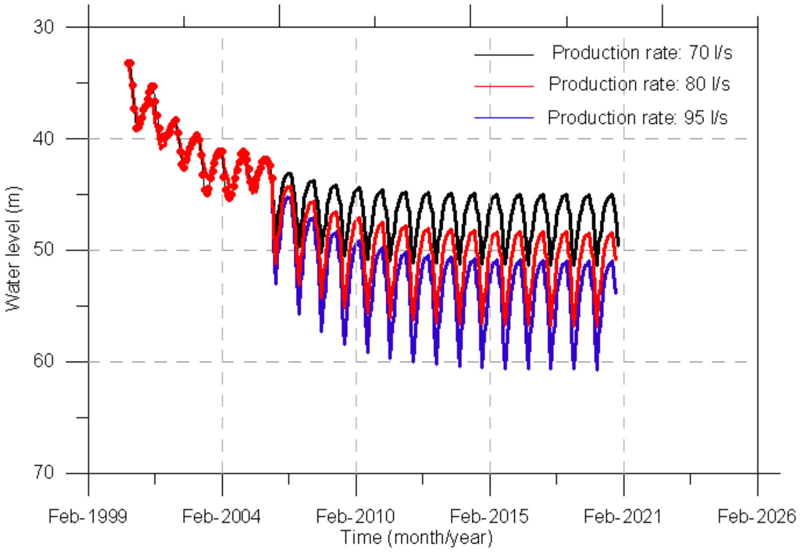


FIGURE 11: Prediction of an open model for the Xiongxian system for the next 15 years for three production scenarios

According to plans for future geothermal development in the Xiongxian geothermal field, several reinjection wells will be drilled around the field. The reinjection water can counteract the drawdown due to increased production. Therefore, the first scenario with a production rate of 70 *l/s* is the most likely scenario for future development in Xiongxian geothermal field. Because all the geothermal

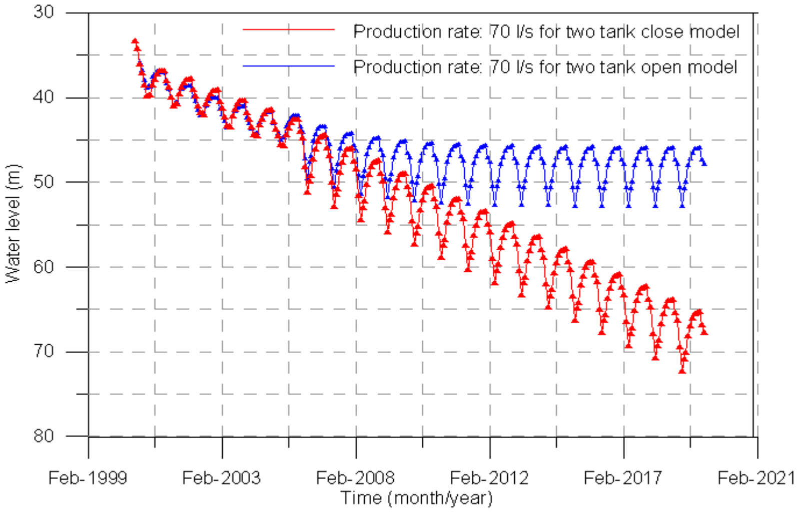


FIGURE 12: Comparison between predictions of the closed and open models for 70 l/s production in Xiongxian

wells drilled into the sandstone are used for swimming and bathing, it is hard to collect the return water for injection. In addition, the problems of clogging in the sandstone have not yet been resolved, so all the reinjection wells are drilled into the dolomite reservoir. Reinjection experiments and tracer tests will be carried out within few months. The prediction results for 70 l/s net production are shown in Figure 12, comparing the closed and open models. The most likely drawdown lies between the two curves.

4. GEOTHERMAL RESOURCE ASSESSMENT WITH THE VOLUMETRIC METHOD

The objective of using the volumetric method is estimating the total heat content and fluid quantity in the Xiongxian geothermal field. The most important factor of such an assessment is, as the name suggests, an assessment of the volume of the geothermal system in question (Hjartarson et al., 2008). The whole reservoir system is composed of the rock matrix and fluid, so we should calculate the usable heat energy contained in both the formation and the water. This method neglects the pressure dynamic response to production and the geometric structure inside the reservoir. Therefore, the energy content can be estimated easily without detailed information on the reservoir.

The variables used in the volumetric method are often shrouded in uncertainty and therefore it is necessary to define a probability distribution for these variables (Hjartarson et al., 2008). Estimating the volume of the reservoir is the first and the most important task for the subsequent calculations. For simplicity, the Xiongxian geothermal field is defined as a box with surface area A and thickness ΔZ. It is also assumed, in order to facilitate the calculation, that the heat capacity and temperature are horizontally homogenous, only changing with depth. The heat content then can be calculated by using Equation 8.

$$Q = A\int_{Z0}^{Z1} c(z)[T(z) - T_0]dz \tag{8}$$

where A is the surface area (km^2);
Q is the heat energy (J);
Z_0 and Z_1 are the upper and lower depth limits of the reservoir system (m);
$c(z)$ is the heat capacity of the reservoir system changing with depth (kJ/kg°C);
T_0 is the cut-off temperature for the planned utilization (°C); and
$T(z)$ is the temperature changing with the depth (°C).

The other important factor for the calculation is the temperature curve. According to the reservoir conditions in the Xiongxian geothermal field, we can define the temperature curve as a linear curve increasing with depth.

We also define a recovery factor R that represents the ratio of accessible energy that can be technically recovered, and then the recoverable energy is given according by the following equation:

$$Q_H = RQ \tag{9}$$

where Q_H is the recoverable heat energy (J); and
R is the recovery factor.

The heat capacity in each sub-volume can be taken as homogenous for the whole system for simplicity:

$$C = S_R(1\text{-}\varphi)\rho_R + S_W\varphi\rho_W \tag{10}$$

where C is the heat capacity for the reservoir system (kJ/kg°C);
S_R and S_W are the specific heat of the rock and water (kJ/kg°C);
φ is the rock porosity; and
ρ_R and ρ_W are the density of the rock and water (kg/m^3).

The reservoir system in the Xiongxian geothermal field can be divided into three individual blocks based on the formations and geological structure as shown in Figure 13. The first block is the Neogene system with the sandstone formation overlaying the Jixian system. The total area of this block is about 400 km^2. The second block is the Jixian system with the dolomite formation overlain by the Neogene system; this is the most important reservoir system in this field. The area covered by the block is about 400 km^2. The third is the Tertiary system with a sandstone formation situated in the grabens surrounded by the Niutuozhen uplift. It includes both the Neogene and Paleogene systems. Some of the parameters used are listed in Table 8. Then we calculate the heat energy in each sub-block according to the geological and tectonic information. For each block the calculation results are shown in Table 9.

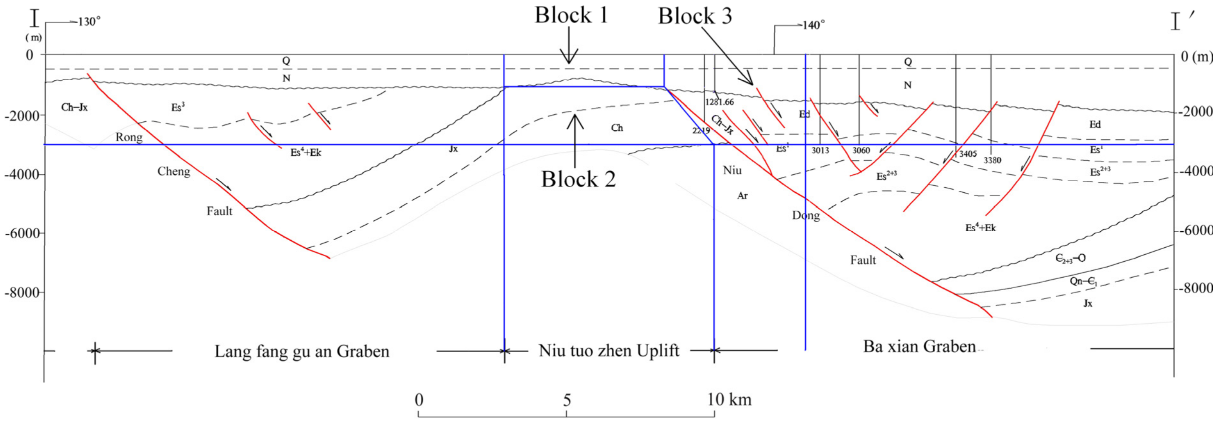


FIGURE 13: The three individual blocks used for volumetric assessment of the Xiongxian system

TABLE 8: The reservoir properties of the Xiongxian geothermal reservoir

Parameter	**Value**
Rock density in the Tertiary system (kg/m^3)	2600
Rock density in the Jixian system (kg/m^3)	2700
Rock heat capacity of the sandstone and dolomite (kJ/kg°C)	0.92
Water heat capacity (kJ/kg°C)	4.18
Rock porosity in sandstone (%)	7.9
Rock porosity in matrix (%)	0.37

TABLE 9: The assessment results for the three individual blocks in the Xiongxian geothermal field

Reservoir	Block 1	Block 2	Block 3
Heat in water (10^{17} J)	240	58	7.9
Water (10^9 m^3)	130	31	2.96
Heat in total (10^{19} J)	15.1	3.08	12

Another calculation was carried out for the reservoir confined by the Xiongxian administrative boundary. The three individual blocks for the whole reservoir were used as before, but the areas and other relevant parameters were changed for this estimation. The calculation process was the same and the results are shown in Table 10.

TABLE 10: The assessment results for the reservoir confined by the Xiongxian administrative boundary

Reservoir	Block 1	Block 2	Block 3
Heat in water (10^{17} J)	102	33.5	4.9
Water (10^9 m^3)	54	18	1.85
Heat in total (10^{19} J)	7.82	1.76	8.15

4.1 The Monte Carlo method

For reasons of intrinsic uncertainty of the reservoir parameters of the Xiongxian geothermal field, it is necessary to define the probability distributions for the essential variables. For example, according to the geological and geophysical information, the average temperature in the tertiary system is about 60-80°C, so this parameter can have a range of possible values for the volumetric calculation. These variables can be assumed to comply with triangle or square probability distribution functions. Then taking a random value of each variable from its probable range, one possible result of heat content is calculated. By repeating this process a sufficient amount of times, the combined results form the production potential probability distribution. Based on the geological structure and stratum sequence, the whole reservoir is divided into three individual systems as before. The first part is the Neogene system, which holds a relatively high temperature gradient compared to the deeper Jixian system. The Jixian system is the second block covered by the Neogene system, with different rock properties and hydrogeological conditions. The third block is the Tertiary system, which surrounds the Niutuozhen uplift and has a relatively low temperature gradient, awaiting further investigation and exploration.

The thermal power in the Neogene system (first block) is calculated by taking the recovery factor between 0.1 and 1% (other parameters are listed in Table 11). The recoverable thermal power that can be exploited has a potential between 2.6 and 38 MW_t for the next 100 years with a 90% probability (see Figure 14). The mean potential power reaches 16 MW_t. The cumulative distribution indicates that the model has predicted with 90% probability that the thermal power is more than 7 MW_t for the next 100 years. The most important reason for the large variance of the results is the inner uncertainty of the reservoir properties, i.e. temperatures, porosity, density and recovery factor; all the parameters above are very hard to estimate for each sub-volume of the reservoir.

The frequency distribution and cumulative distribution for the potential of the Jixian system, the second block in the reservoir, were also calculated. The parameters for the calculation are listed in Table 12 and the results are shown in Figure 15. It can be estimated that the recoverable thermal power that can be exploited has a potential of between 33 and 170 MW_t for 100 years with a 90% probability. The width of each column in Figure 15 represents 7 MW; the mean value of the thermal potential is 95 MW_t. The cumulative distribution shows that the model predicts with 90% probability that the thermal power can reach at least 46 MW_t for the next 100 years.

TABLE 11: The estimated values and probability distribution for Monte Carlo volumetric assessment of the first block

Parameter	Distribution	Min.	Best guess	Max.
Possible surface area (km^2)	Triangular	400	440	500
Upper depth (m)	Triangular	200	300	450
Lower depth (m)	Triangular	800	1000	1500
Porosity (%)	Triangular	12	12.3	12.6
Rock density (kg/m^3)	Triangular	2550	2600	2650
Cut-off temperature (°C)	Constant		45	
Water density (kg/m^3)	Triangular	970	979	990
Specific heat capacity of rock (kJ/kg°C)	Triangular	0.9	0.92	0.94
Specific heat capacity of the fluid (kJ/kg°C)	Constant		4.18	
Production time (year)	Constant		30/50/100	
Linear temperature gradient (°C/km)	Triangular	50	75	90
Accessibility (%)	Triangular	50	55	60
Recovery factor (%)	Triangular	0.1	0.4	1

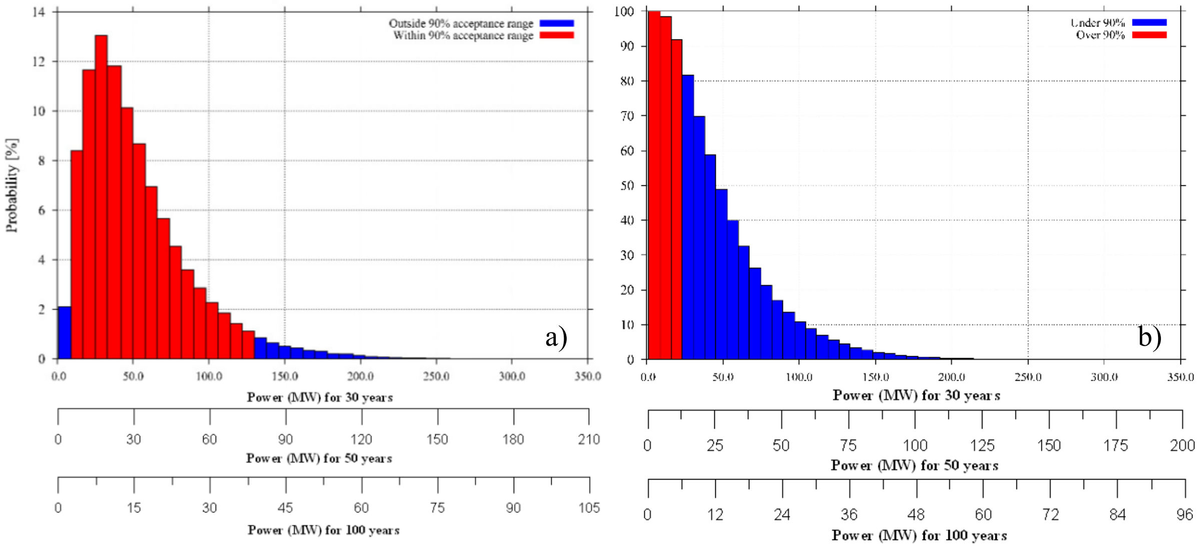


FIGURE 14: a) Probability and b) cumulative probability distributions for the estimated thermal power potential of the first block in the Xiongxian geothermal field

TABLE 12: The estimated values and probability distribution for Monte Carlo volumetric assessment of the second block

Parameter	Distribution	Min	Best guess	Max
Possible surface area (km^2)	Triangular	370	400	430
Upper depth (m)	Triangular	800	1000	1300
Lower depth (m)	Triangular	2000	2500	3000
Porosity (%)	Triangular	0.3	0.37	0.45
Rock density (kg/m^3)	Triangular	2650	2700	2750
Cut-off temperature (°C)	Constant		45	
Water density (kg/m^3)	Triangular	970	979	990
Specific heat capacity of rock (kJ/kg°C)	Triangular	0.9	0.92	0.94
Specific heat capacity of the fluid (kJ/kg°C)	Constant		4.18	
Production time (year)	Constant		30/50/100	
Linear temperature gradient (°C/km)	Triangular	30	32.8	36
Accessibility (%)	Triangular	50	55	60
Recovery factor (%)	Triangular	0.1	0.4	1

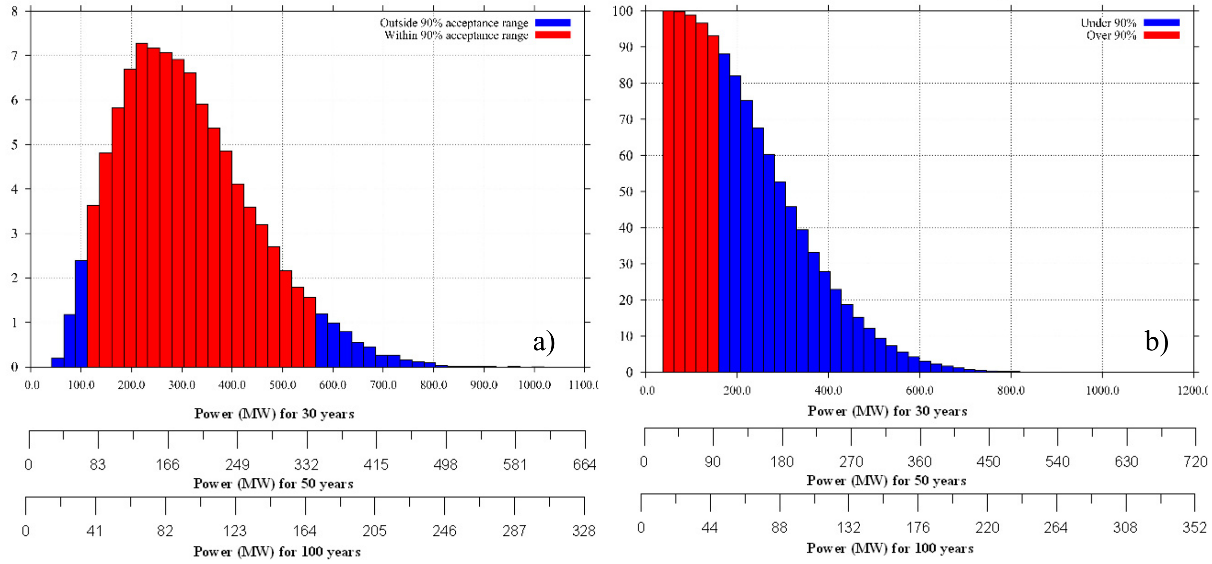


FIGURE 15: a) Probability and b) cumulative probability distributions for the estimated thermal power potential of the second block in the Xiongxian geothermal field

Finally, the thermal power in the Tertiary system (third block) was calculated by taking the recovery factor between 0.1 and 1% (the other parameters are listed in Table 13). Then the recoverable thermal power is estimated to be between 13 and 93 MW_t over the next 100 years with a probability of 90% (see Figure 16). The mean potential power reaches 48 MW_t and the cumulative distribution shows that the model has predicted with 90% probability that the thermal power is more than 23 MW_t for the next 100 years.

TABLE 13: The estimated values and probability distribution for Monte Carlo volumetric assessment of the third block

Parameter	Distribution	Min	Best guess	Max
Possible surface area (km^2)	Triangular	400	500	550
Upper depth (m)	Triangular	200	300	450
Lower depth (m)	Triangular	2000	2500	3000
Porosity (%)	Constant	4.6	8	12.3
Rock density (kg/m^3)	Triangular	2550	2600	2650
Cut-off Temperature (°C)	Constant		45	
Water density (kg/m^3)	Triangular	970	979	990
Specific heat capacity of rock (kJ/kg°C)	Triangular	0.9	0.92	0.94
Specific heat capacity of the fluid (kJ/kg°C)	Constant		4.18	
Production time (year)	Constant		30/50/100	
Linear temperature gradient (°C/km)	Triangular	30	35	40
Accessibility (%)	Triangular	50	55	60
Recovery factor (%)	Constant	0.1	0.4	1

The recovery factor is the most sensitive parameter in the calculation with the power depending linearly on it. The value differs greatly between different geothermal fields and the difference can be several orders of magnitude. This problem will be discussed in the next section.

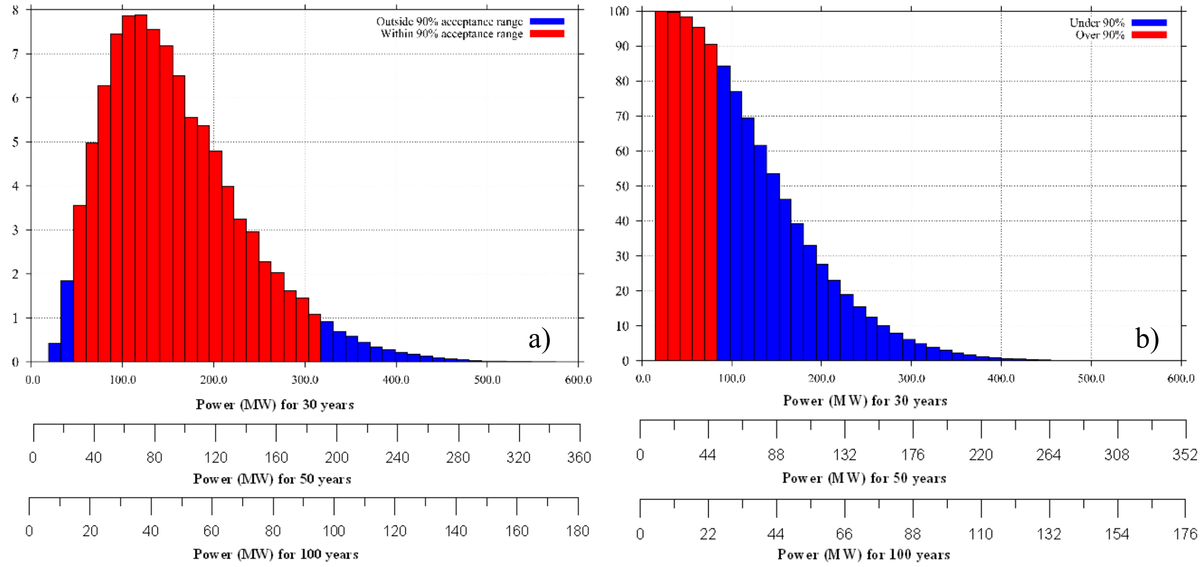


FIGURE 16: a) Probability and b) cumulative probability distributions for the estimated thermal power potential of the third block in the Xiongxian geothermal field

4.2 The recovery factor

One of the major uncertainties in the assessment of the Xiongxian geothermal reservoir is the value of the recovery factor. The ratio of the material (or energy) that can be recovered to the material (or energy) in place is termed the recovery factor (Rybach and Muffler, 1981). The parameter value depends on many factors, i.e. recharge conditions, reinjection, permeability, economic and technological conditions, etc. All the factors above can be hard to estimate in a large low-temperature geothermal area with complicated reservoir properties. There seems to be some agreement that the recovery factor for a reservoir of good permeability can be as high as 50% (Nathenson, 1975). But good permeability can rarely be found in nature, especially for a sedimentary conduction-dominated reservoir. According to the assessment method for geothermal resources set up by the Geology and Mineral Department of China (Xie et al., 1985), for a large scale sedimentary basin, the recovery factor for the sandstone in Cenozoic can reach about 25% when the porosity is larger than 20%. The values for carbonate and igneous formations are assumed to be about 15% and 1%, respectively. According to the investigation report on the Niutuozhen uplift, the accessible resource holds different values in Tertiary sandstone and Jixian dolomite system. Other low-temperature fields with similar reservoir conditions have been assumed to have a recovery factor between 1% and 15%. For example, according to the geothermal resources assessment report of Xiaotangshan town geothermal reservoir (Pan et al., 2005), the recovery factor used in the Jixian system was 1.10% and in the Cambrian system about 1.15%, which shows much lower values than in other countries with the same stratum conditions.

Based on the Xiongxian production history data from 1973-2005, the cumulative production has reached 2.7×10^{7} m^{3} for 33 years, which corresponds to 0.03% of the total water reserve in the formation. Because the age of the geothermal water is 12-33,000 years and reinjection has not been carried out in 2005, we can assume that for the past 32 years, the recovery factor may be the same order of magnitude as 0.03%, which is far from the average value for other low-temperature reservoirs. Beside the reasons that have been mentioned above, there are other reasons that can affect these results, for example, the technology level, the energy demand and economic reasons. For the next 50 years, the parameters above can affect the magnitude of the recovery factor.

Based on the pressure prediction results obtained by the lumped parameter model, the pressure will not drop abruptly in the next 15 years, and the Xiongxian government has decided to drill several reinjection wells as an artificial recharge source for the dolomite reservoir. The effect of the reinjection water can not only counteract part of the withdrawal from the formation and directly improve the recovery factor, but also sustain the water level at a stable state. The heat source mechanism and recharge conditions will not change much on this small time scale. Assuming that the production increment and reinjection do not impact the porosity and permeability much during the next 50 years, and that the cumulative production can reach 5-10 times that of the past 32 years, in the next 50 years, the recovery factor can be increased to a minimum magnitude of 0.1%. The most probable range is in the range 0.1-1% with a small chance of exceeding 1%. If some of the parameters above do not satisfy the assumptions, for example, the over-exploitation problem or lack of reinjection, the recovery factor may exceed 1% at the beginning, but decrease after 20-30 years and consequently cause a series of other problems inside the reservoir.

Figure 17 shows the recovery factor versus the potential power in the 3 different blocks for Xiongxian geothermal field. There are three different lines in each plot which, respectively, represent the maximum thermal power within the 90% probability, the minimum power within it and the mean power for the next 30, 50 and 100 years. Figure 18 shows the same results for the reservoir confined by the Xiongxian administrative boundary.

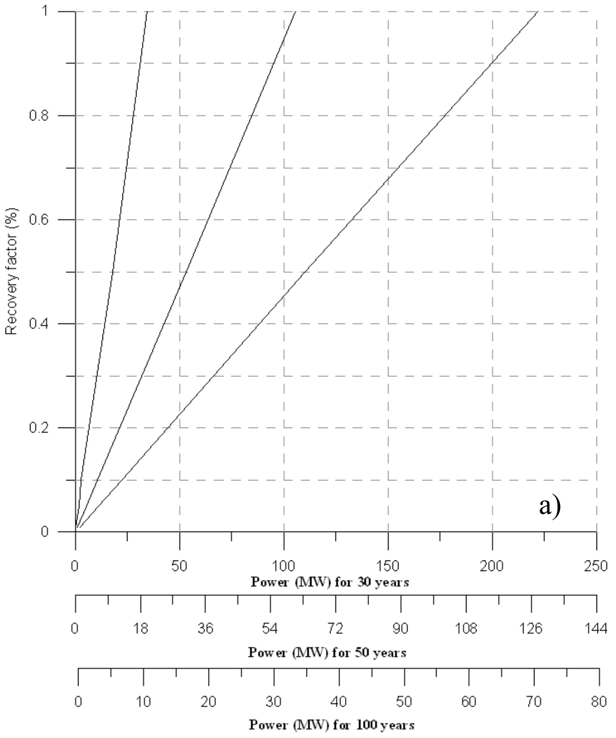
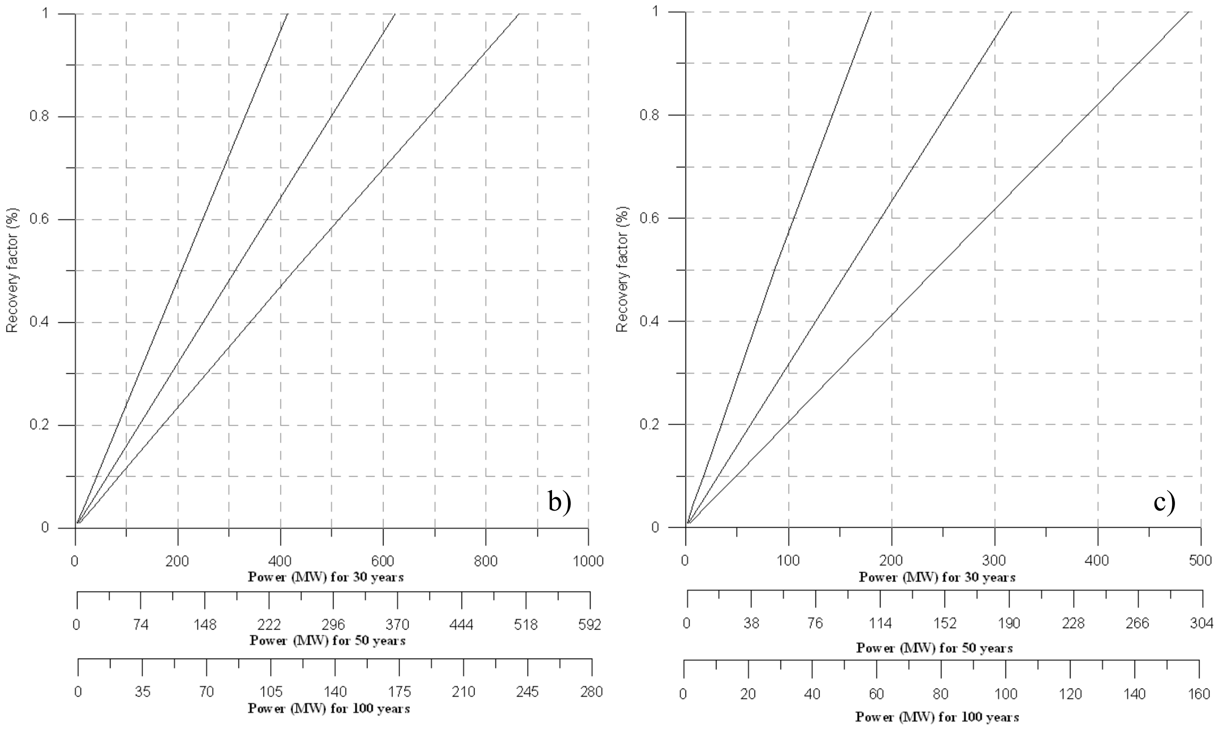


FIGURE 17: Thermal power versus recovery factor for the three individual blocks in Xiongxian geothermal system, a) Block 1, b) Block 2, and c) Block 3



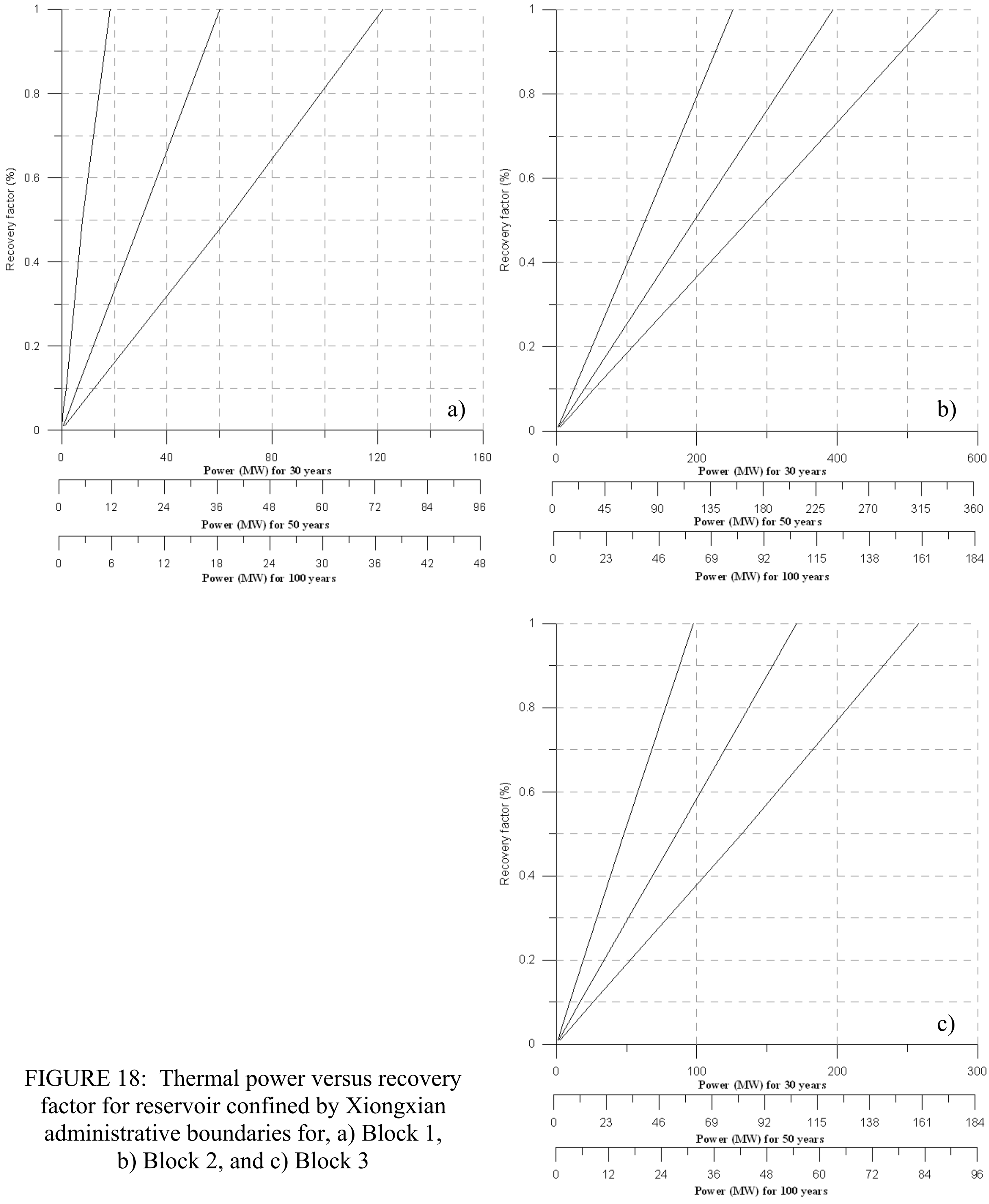


FIGURE 18: Thermal power versus recovery factor for reservoir confined by Xiongxian administrative boundaries for, a) Block 1, b) Block 2, and c) Block 3

5. CONCLUSIONS AND RECOMMENDATION

In this report, the lumped parameter model and the volumetric method have been used to estimate the future pressure changes and thermal power potential of the Xiongxian geothermal system. The simulation results indicate that it has good reservoir conditions for future exploitation. For avoiding abrupt pressure drop and making the development sustainable, the exploitation management must be strengthened and long term monitoring adopted for the production and reinjection wells. The detailed conclusions of the study are summarized as follows:

The Xiongxian geothermal system is one of the most important geothermal fields in the Huabei plane. There are several permeable faults situated around the reservoir system, which make a certain contribution to the recharge of the reservoir. The whole reservoir can be divided into three individual sub-systems: the Neogene reservoir system consisting of alternating sandstone and mudstone with an effective thickness of 225 m on average; the Jixian reservoir system mainly composed of a dolomite with an effective thickness range of 285-315 m; and the Tertiary system consisting of sandstone with an effective thickness of about 138 m. The sub-systems are productive, but as injecting return water into sandstone still has some difficulties, the reinjection wells are all designed for the dolomite reservoir.

The Xiongxian geothermal system is a typical low-temperature sedimentary reservoir with conduction-dominated heat flow. There are several faults around the periphery area of the reservoir, so parts of the hot water can also convect to the upper formations. At the top of the Tertiary formation, the temperature is in the range of 25-60°C, and at the Tertiary bottom, the value can vary from 40 to 92°C. The temperature in the bottom of the Jixian reservoir is in the range of 60-118°C. The temperature distribution in each individual reservoir is very similar to the gradient map.

Based on the simulation of pressure changes of the past few years, predictions of the pressure drawdown have been made for three different production scenarios. The prediction results show that by keeping a production rate of 70 l/s as in 2005, the withdrawal can maintain equilibrium with the outer reservoir system. By increasing the production rate to 80 or 95 l/s, the water level will still remain stable but the drawdown becomes larger than for the first scenario. The Xiongxian government has made the decision to drill reinjection wells around the production wells, so the return water can be injected into the dolomite formation to counteract the drawdown caused by the increasing production of new wells. Therefore, a continuing net extraction rate of 70 l/s is the most likely scenario for development of the Xiongxian geothermal system.

The results of the volumetric method indicate that the total heat content stored in the formation is about 30×10^{19} J, that the calculated total water quantity in the whole reservoir is about 160×10^{9} m^3, and that the energy contained in the water is 300×10^{17} J. In the process of Monte Carlo calculation, different recovery factors were set for the different formations. The results show that the mean thermal power for all three formations can reach 160 MW_t for the next 100 years. The recoverable thermal power that can then be exploited has a potential between 48 MW_t and 300 MW_t for the next 100 years with 90% probability. The cumulative distribution shows that the model predicts with 90% probability that the thermal power will be more than 76 MW_t for the next 100 years.

Based on the discussion for the recovery factor, it can be stated that the reservoir properties, economical conditions and technology level all can restrict the magnitude of the recovery factor. It is assumed that the recovery has only been 0.03% for the past 32 years. It is also assumed that in the future the permeability and recharge conditions will not change much, the pressure will have a constant drawdown and nearly reach equilibrium with the recharge. Therefore it is assumed that in the next 50 years the cumulative production can reach 5-10 times that of the past. Then the recovery factor will increase to the most probable range of 0.1-1% with a small chance of exceeding 1%.

Temperature monitoring has been carried out in some of the geothermal wells, which shows that the reservoir temperature apparently has not changed. Several reinjection wells will be drilled into the Jixian system, so the injected water may cool the production wells if the permeability between the productions wells and reinjection wells is high or some horizontal fracture connects the production and reinjection wells. Therefore, it is necessary to carry out a tracer test for surveying the connectivity between the production and reinjection wells. Long-time temperature monitoring is important to detect signs of reservoir cooling.

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