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CONCEPTUAL MODEL AND POTENTIAL ASSESSMENT FOR THE XIAOTANGSHAN GEOTHERMAL FIELD, BEIJING, CHINA

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ABSTRACT

The Xiaotangshan low-temperature geothermal field is located about 20 km north of the city of Beijing. The geothermal water has been used for space heating, health spas, greenhouses, fish farming etc. for nearly 30 years. Xiaotangshan is one of the two most exploited and studied geothermal fields in Beijing. The geothermal energy is stored in limestone and dolomite reservoirs. The area identified with the geothermal resource is about 86.5 km^2 with three separate reservoirs. The temperature of the geothermal water is 38-70°C. The geothermal water contains SiO_2 and other components that are good for human health, and has been used in balneology for more than 300 years. In this paper a conceptual model of the Xiaotangshan geothermal field is developed. An empirical method and lumped parameter modelling are used for production potential assessment of the field. A two-tank lumped model is used successfully to simulate the production and water level history and used to predict future water level changes in the geothermal reservoir. The results show that if the annual production of 87 l/s is maintained, the water level will decline about 19 m in 20 years. This indicates that great emphasis should be placed on management of the geothermal exploitation in this field in the future. Geothermal reinjection is a very efficient method for maintaining reservoir pressure and will be required for sustainable development of geothermal resources in the Beijing area. Based on the volumetric method, the total heat stored in the Xiaotangshan reservoir to a depth of 3000 m is estimated as 1.9×10^{19} J. The total geothermal water volume is estimated to be 9.9×10^{8} m^3, which corresponds to about 2.1×10^{17} J of heat. Allowing an average annual drawdown of 1.5 m in the future, a production of 4.4×10^{6} m^3/a can be maintained according to a dynamic correlation method.

1. INTRODUCTION

The Xiaotangshan geothermal field is located in a northern suburb of Beijing City (see Figure 1). It used to be a natural hot spring area with a total of eleven hot springs, which have been famous for more than 300 years. Local legends say that the imperial family of the Qing Dynasty (1644-1911) went there to relax. Throughout history, water from the hot springs has been used for bathing and health spas (Liu et al., 2001).

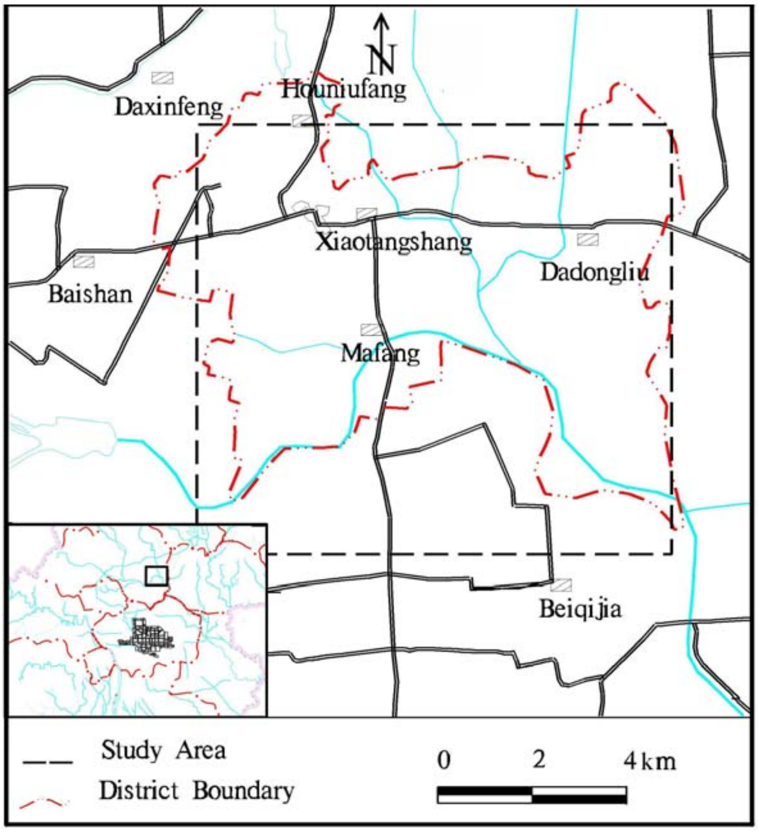

FIGURE 1: Location of the Xiaotangshan geothermal field in Beijing

Geothermal energy has been widely accepted by society in China, with an increase of geothermal utilization in Beijing. In the planning of many construction projects, geothermal energy has often been considered for space heating and domestic hot water supply. At present, geothermal water is used for space heating, bathing, greenhouses, fish farming, spas and recreation, bringing great economical, environmental and social benefits (Zheng, 2004). Multi-purpose usage is also common, often a combination of space heating and domestic hot water supply. This makes it difficult to calculate the percentage of different types of utilization (Liu et al., 2002). However, it is estimated that domestic hot water (including bathing, recreation and spa use) is the dominant use (see Table 1).

The Xiaotangshan geothermal field is one of the earliest explored geothermal fields in China. The original geothermal exploration was carried out in the 1960s, by the Hydrogeology and Engineering Geology Team of Beijing and the first geothermal borehole was drilled in 1974. Since then, the number of wells in the geothermal field has been continuously increasing. After 1986, geothermal water exploitation and utilization has become more and more popular in Beijing, and the area of geothermal exploitation increased to more than 40 km^2. In 1998, The *"Geothermal resources assessment report of Xiaotangshan geothermal reservoir"* was published by the Beijing Institute of Geological Engineering (Pan et al., 1998). Now, the maximum depth of geothermal wells is more than 3000 m.

TABLE 1: Geothermal water use in 2001 in the Xiaotangshan area

Total production (m^3)	**Space heating (m^3)**	**Domestic water (m^3)**	**Greenhouse (m^3)**	**Fish farming (m^3)**
3,890,000	630,000	1,200,000	890,000	1,180,000

There were 63 geothermal wells in use in the Xiaotangshan geothermal field in 2002, producing water with a temperature range of 38-70°C. The yearly production from the Xiaotangshan field corresponds to an average production of about 120 l/s. This has resulted in a water level drawdown on the order of 1.5 m/a (Hjartarson et al., 2005). The geothermal system at Xiaotangshan consists of three separate reservoirs called the Wumishan group (Jxw), Tieling group (Jxt), and Cambrian system (Є).

Geothermal monitoring in Xiaotangshan started in the 1970's, which included monitoring of flowrate, temperature and water chemistry. More than 30 years' production history is available for the Xiaotangshan geothermal field. The water production has caused a considerable pressure decrease in the reservoir. Therefore, the assessment of the geothermal potential and predictions in the pressure changes of the reservoir due to production have become important issues for the government in order to improve the management of the resource. The present study is based on the monitoring data and the results of previous work in the geothermal field. The main objectives are as follows:

- To study the hydraulic relationship between the three reservoirs;
- To improve the conceptual model of the Xiaotangshan geothermal field;
- To predict the water level changes by lumped parameter modelling;
- To evaluate the production potential for each of the three reservoir.

2. BACKGROUND

2.1 Study Area

This study is focused on the geothermal resources of the Xiaotangshan area, which is located in a northern suburb of Beijing city (see Figure 1). The Xiaotangshan geothermal field encompasses about 86.5 km^2 and is bordered by the Nankou-Sunhe fault (F9) in the southwest, and the Huangzhuang-Gaoliying fault (F10) in the southeast, and has a reservoir temperature over 40°C at depth less than 2000 m in the north (see Table 2 and Figure 2).

2.2 Previous studies

Xiaotangshan is one of the two most studied and exploited geothermal fields in Beijing. For more than 300 years the geothermal water has been exploited and utilized in many ways. In the latter stage of the 1950's, exploration drilling was started in the Xiaotangshan hot spring area in order to provide water for hot spring utilization in a local sanatorium (Zheng, 2004). Geothermal exploration in Beijing started in the 1960's, and large-scale geothermal development commenced in the early 1970's.

In the period of 1974-1975, the Xiaotangshan hot springs dried up, after the drilling phase began. In 1985, a report was published by the Hydrogeology and Engineering Geology Team of Beijing, entitled "*Potential assessment report of Xiaotangshan geothermal field, Beijing, China"* (Li et al., 1985). Since the late 1990's, geothermal direct use in Beijing has developed greatly. Recently, to combat air pollution in the city, the utilization of clean energy, including geothermal, has been encouraged by the government. By the end of 2004, over 70 geothermal wells had been drilled in the Xiaotangshan area, with the deepest being over 3000 m in depth.

2.3 Geological information

2.3.1 Geological setting

Geologically, the Beijing area is characterized by a series of grabens and horsts bounded by faults, running in parallel from southwest to northeast These faults, which have the same direction controlled by the primary stress of the current tectonics, are the main conduits of underground water, and play a major role in the geothermal activity (Li et al., 1985).

The basement rock formations in the Xiaotangshan field are composed of complicated geological structures and are older in the north than in the south. A Quaternary formation covers most of the geothermal field, consisting of 0-500 m of sand or clay (Liu et al., 2003). The area of the Xiaotangshan geothermal field is inside the Beijing Plain, which is located in a sedimentary basin. The formations in the Xiaotangshan area include:

1. Quaternary (Q): unconsolidated sediments;
2. Tertiary (R): shale, mudstone and basalt;
3. Cretaceous (K): mudstone and conglomerate;
4. Jurassic (J): andesite, tuff and mudstone;
5. Carboniferous-Permian (C-P): sandstone and shale;
6. Ordovician-Cambrian (O-Є): limestone;
7. Qingbaikou (Qn): shale, sandstone and marlstone;
8. Jixian (Jx, China's standard formation profile name):
   Tieling Group (Jxt), dolomite
   Hongshuizhuang Group (Jxh), shale
   Wumishan Group (Jxw), dolomite

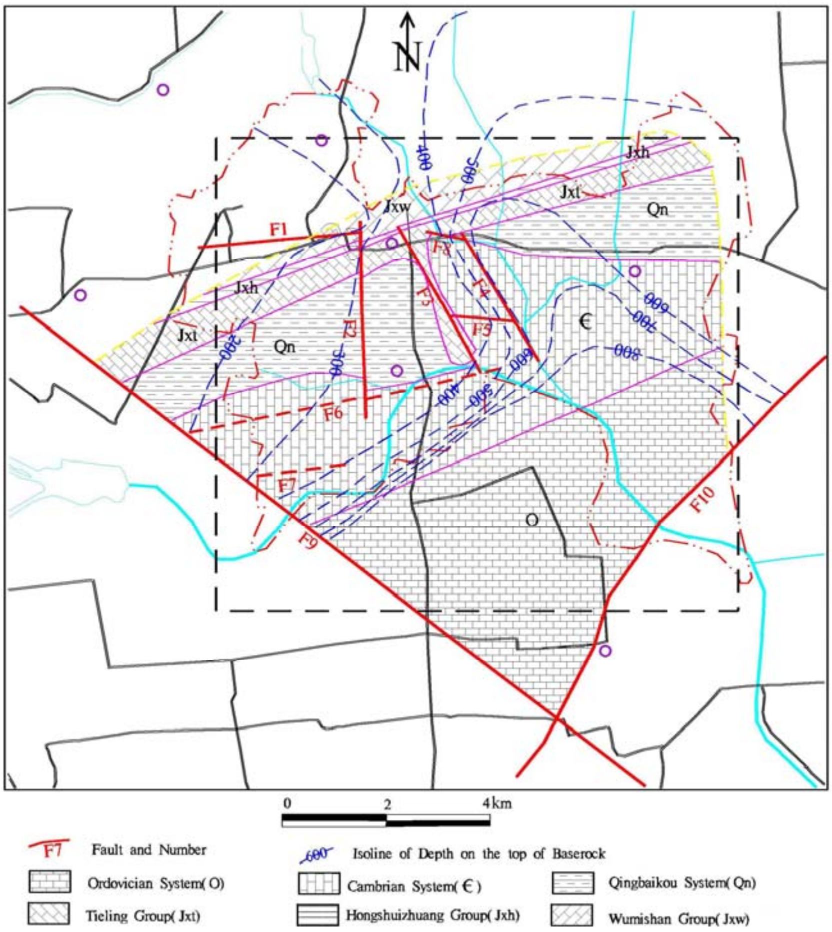

FIGURE 2: Geological map of the Xiaotangshan area

Figure 2 shows a geological and structural map of the field. The rock outcrop occurring at the Xiaotangshan Sanatorium in the northern part consists of a Wumishan formation (Jxw) which belongs to the Jixian system. The Jxw formation is the oldest of reservoir formations in the Beijing area, and consists of sedimentary rocks with a thickness of more than 2000 m. So far, no single borehole has penetrated all the formations in the Xiaotangshan field. The Jxw formation is about 1.2-1.4 billion years (BY) old from the mid-upper Proterozoic era. The Jxh formation, which is shale, is about 80 m thick. The Tieling formation (Jxt), which is about 1.0-1.2 BY, consists of dolomite and its thickness is about 350 m. The Qingbaikou system, which is 0.8-1.0 BY, is made of limestone and shale in the range of 0-600 m in different areas in the field. The Cambrian system, which is 500-570 million years old, consists of limestone. Its thickness increases from north to south and reaches 800 m in the southern part of the field. The Jurassic system, which is 136-190 MY, is made of volcanic rocks. That formation has been found in geothermal boreholes in the southern and eastern parts of the field (Pan et al., 1998).

2.3.2 Structural features

Due to crustal movement the geological structure of the area is very complicated, with a number of faults and folds. These faults are all rather important in relation to the occurrence of geothermal features in the area (see Figure 2). In some areas the basement rocks are severely folded so that groups of formations that can be found in one place are lacking in another. Geological structures control the distribution and thickness of the formations. The major faults in the field are listed in Table 2 (Pan et al., 1998).

TABLE 2: Major faults in the Xiaotangshan geothermal field (location see Figure 2)

No.	Name	Character		Strike	Length (km)
F1	Asuwei-Xiaotangshan fault	N-block	S-block	NEE	3.4
F2	Houniufang-Xiaotangshan fault	W-block	E-block	NS	3.8
F3	Daliushu-Huluhe fault	W-block	E-block	NW	2.3
F4	Changxinzhuang-Houlingou fault	W-block	E-block	NW	3.0
F5	Liaoyangyuan-Houlingou fault	S-block	N-block	NW	1.3
F6	Yujiafen fault	N-block	S-block	NEE	6.3
F7	Shangxin fault	N-block	S-block	NEE	2.0
F8	Huluhebei fault	N-block	S-block	NE	0.65
F9	Nankou-Sunhe fault	NE-block	SW-block	NW	12.5
F10	Huangzhuang-Gaoliying fault	NW-block	SE-block	NE	9.5

3. GEOTHERMAL DEVELOPMENT

3.1 Well information

There are over 70 geothermal wells in the Xiaotangshan geothermal field (see Figure 3 and Table 3), with 35 of them still producing (Pan et al., 2002). Seven wells produce from the Cambrian reservoir (€), nine wells from the Tieling reservoir (Jxt) and nineteen wells from the Wumishan reservoir (Jxw).

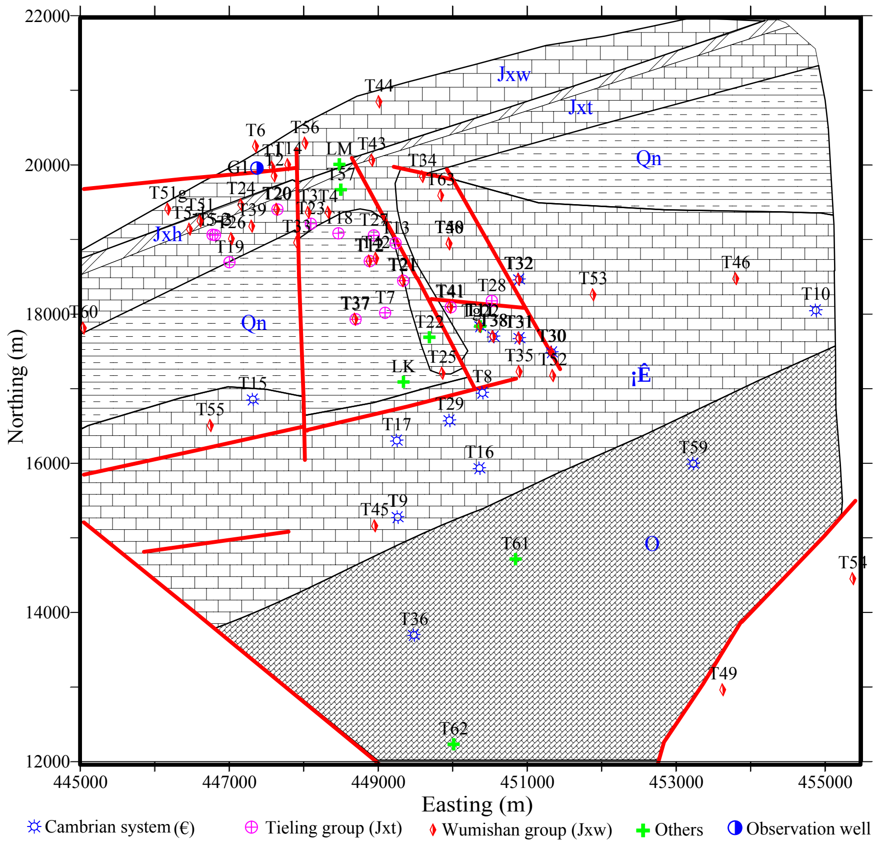

FIGURE 3: Production wells in the Xiaotangshan field classified on basis of different reservoir layers

The first geothermal well (T1) in the Xiaotangshan geothermal field was drilled in 1975. It produces from the Jxw reservoir. The unconsolidated sediments (Quaternary system, Q) extended about 62 m in the well, with the Wumishan group (Jxw) below the Quaternary system. Well T1 is 76.6 m in depth, with a casing to 61.7 m depth. The initial temperature of the water produced was about 53.8°C. During short time production testing, the well yielded about 30 l/s with a drawdown of about 9 m.

TABLE 3: Basic information on selected geothermal wells in the Xiaotangshan field

Well	Drilled	Depth (m)	Initial temp (°C)	Reservoir	Productivity ((l/s)/m)
T36	1995	1800.00	43.5	Є	0.35
T9	1982/1983	1186.47	43.7	Є	1.23
T17	1984	652.74	46.5	Є	3.39
T32	1994	2108.50	58.0	Є + Jxw	1.40
T28	1992/1993	1100.46	51.5	Jxt	0.82
T23	1987	424.73	47.5	Jxt	2.15
T5-2	1978	207.58	42.0	Jxt	4.06
T41	1997	1050.00	60.0	Jxt + Є	2.62
T20	1985	501.58	50.0	Jxt + Jxw	1.58
T44	1999	2053.55	40.0	Jxw	0.40
T33	1994/1995	1370.00	48.3	Jxw	0.40
T1	1975	76.50	53.8	Jxw	3.28
T14	1985	351.12	48.0	Jxw	3.79
T25	1988/1989	1121.01	61.0	Jxw	4.26
T48	2000	1461.00	59.0	Jxw	4.91
T6	1980	360.46	46.0	Jxw	5.18

3.2 Pumping tests

A pumping test lasting 14 days involving many wells was carried out in the southeast part of the field in 1996. During the test, about 16,000 m^3 of water were extracted, mainly from the Cambrian (Є) and Wumishan (Jxw) reservoirs. Results of the test can be seen in Table 4 and Figure 4. Eight production wells were used to extract water, and nine geothermal wells were used to monitor the water level variations in the field. The results show that:

TABLE 4: Result of 1996 well test in southeast part of Xiaotangshan

Well	Reservoir	Draw down (m)	Production (m^3)
T1	Jxw	4.08	
T3	Jxt	1.56	
T8	Є	7.95	20576
T9	Є		19636
T11	Є + Jxt		23800
T16	Є	17.64	18348
T17	Є		18771
T25	Jxw	5.06	
T28	Є + Jx		22749
T29	Є	5.22	
T30	Jx		19080
T32	Jx	21.13	19500
T35	Jxw	4.2	
T36	Є	4.38	
T37	Jxt + Jxw	4.28	
T38	Є + Jxw	4.26	

The Jixian formation (Jx) is in direct contact with the Cambrian formation in the southeast part of the field and together they are classified as the Wumishan group. Well T1 (Jxw) and T3 (Jxt) were used as monitoring wells outside the test field. A water level drop of 4 m was observed in well T1, corresponding to the water level drop inside the pumping field. But a water level drop of T3 was only about 1.6 m, indicating that the pumping in the southeast part of the thermal field affected the water level of the Tieling reservoir (Jxt) less.

The Wumishan group (Jxw) and cambrian formation (∈) have a better hydrological connection; they can be considered as the same exploitation reservoir. The Tieling group, on the other hand, is relatively independent. It is less directly connected with the other formations, especially in the southeast part of the reservoir.

The water level drawdown of well T29 (Є) and well T25 (Jxw) near the pumping centre, with a well separation of 5000 m, are 5.22 and 5.08 m, respectively. The values for the other wells are below this, or in the range of 4.08-5.02 m. The water level drawdown for the Cambrian (Є) and the Wumishan (Jxw) reservoirs is the same. The pumping quantity for Є is about 107,000 m^3, and for Jxw about 51,000 m^3. The same water level drawdown in both formations indicates a good hydrological connection between them.

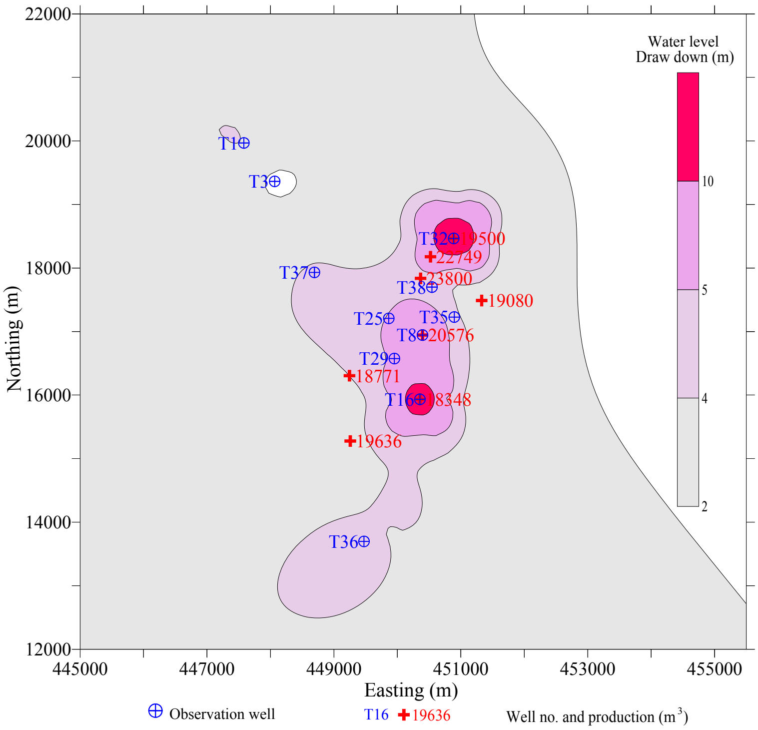

FIGURE 4: Water level draw down distribution during the 1996 well test in the southeast part of the Xiaotangshan field

3.3 Temperature conditions in Xiaotangshan

3.3.1 Horizontal temperature distribution

Except for an exposure of the Wumishan group (Jxw) at the surface in the northwest part of the Xiaotangshan geothermal field, the field is covered with Quaternary unconsolidated sediments. Isothermal maps have been drawn at depths of 500 and 1000 m with the data acquired from multi-well geothermal logging measurements. Comparing the maps, a temperature anomaly can be seen in nearly the same location at both depths (see Figures 5 and 6). The high-temperature anomaly is divided into two parts: one centred at Xiaotangshan town in the northwest part; the other near the centre of the field, southeast of the former anomaly (near wells T21 and T38). At 1000 m the highest temperature is about 60°C in the northwestern part and 65°C in the eastern part.

The temperature distribution map (Figures 5 and 6) reveal a close relationship between the geothermal features and the distribution of faults and other geological structures. The temperature anomalies appear to be controlled by the existence of hydraulically conductive fractures. The northwest part of the temperature anomaly is related to the S-N Houniufang-Xiaotangshan fault (F2) together with the northeast striking Asuwei-Xiaotangshan fault (F1). The central anomaly is associated with the Daliushu-Huluhe fault (F3) and the Changxingzhuang-Houlingou fault (F4). A conclusion drawn from the temperature distribution data of present wells is that between the Daliushu-Huluhe (F3) and the Changxingzhuang-Houlingou (F4) faults, both water temperature and production rate of wells are relatively high. The transmissivity of the Daliushu-Huluhe fault (F3) also appears to be good. Thus, the Asuwei-Xiaotangshan fault (F1) in the northwest and the Daoliuishu-Huluhe fault (F3) in the southeast are likely to be hydraulically conductive faults. It is considered to be a path of higher upflow than the Asuwei-Xiaotangshan fault (F1). Boreholes, geophysical and geochemical data have proven that the Daliushu-Huluhe fault (F3) is an important fault controlling reservoir temperature and stratigraphy (Pan et al., 2005).

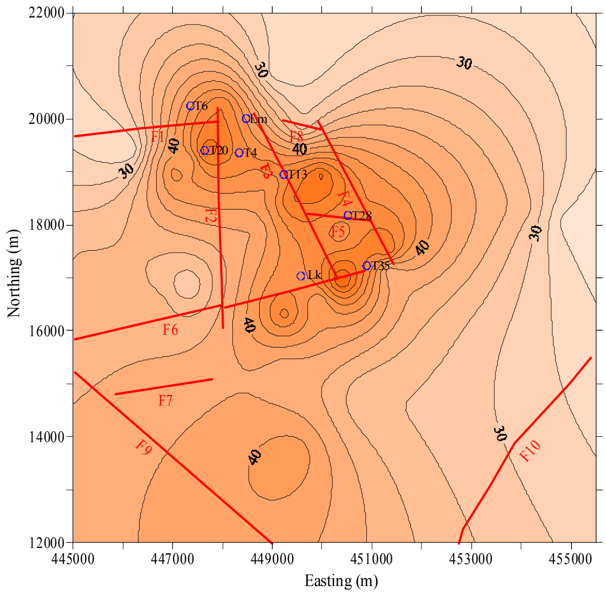

FIGURE 5: Temperature distribution in the Xiaotangshan geothermal field at 500 m depth

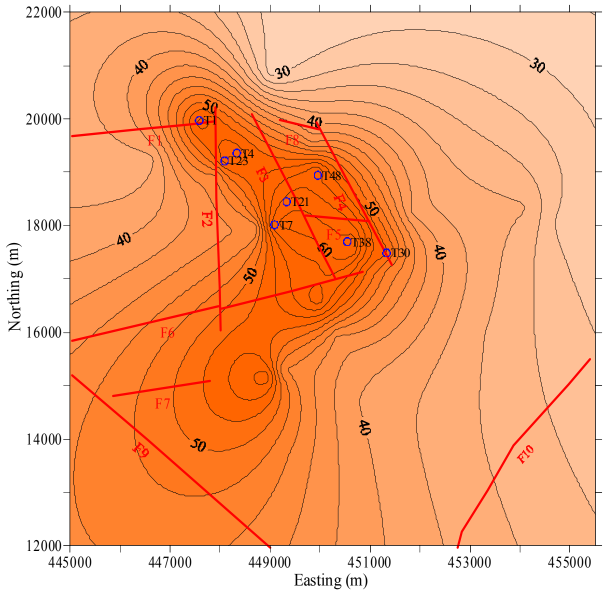

FIGURE 6: Temperature distribution in the Xiaotangshan geothermal field at 1000 m

3.3.2 Vertical temperature distribution

Figure 7 shows a temperature log from well T33. It is clear from the log that the temperature gradients in reservoir formations are lower than in aquicludes. In the geothermal field the formation order from top to bottom is Quaternary formation, Jurassic system, Cambrian system, Qingbaikou system and Jixian system. Table 5 shows temperature gradients of reservoirs and aquicludes in different wells. Temperature gradients of reservoir formations range from 1.33-1.78°C/100 m, and for aquicludes from 2.95-5.5°C/100 m.

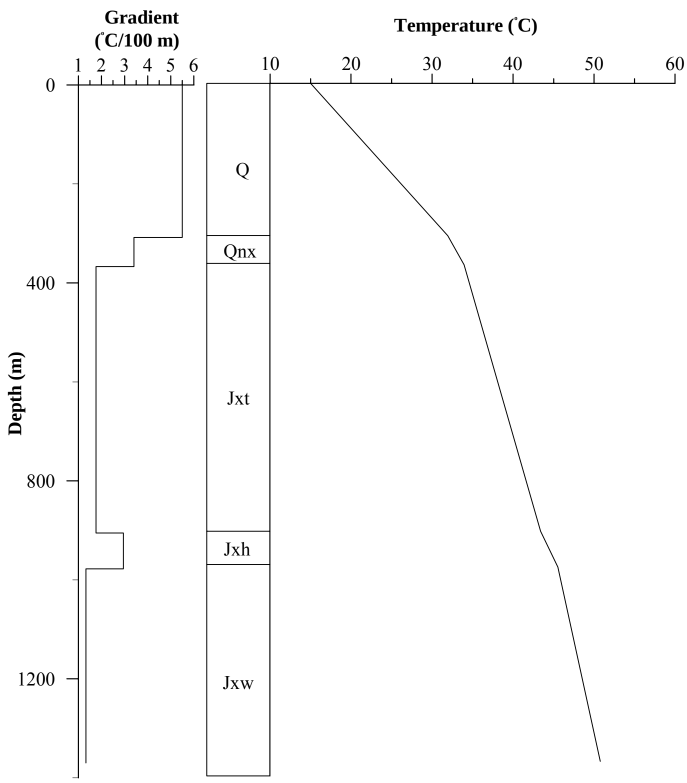

FIGURE 7: Temperature log of well T33, Xiaotangshan field

These results show that the temperature gradients of aquicludes are clearly higher than the gradients of the geothermal reservoirs, reflecting the functions of the two strata in the nature of the geothermal resources. The geothermal reservoirs have a limited temperature gradient because of convection, greater storage capacity and different thermal properties while the; aquicludes are poorly connected and relatively closed, thus, good for insulating and maintaining heat. The average temperature gradient of the three geothermal reservoirs shows that the Wumishan group (Jxw) is an ideal geothermal reservoir compared with the Tieling group (Jxt) and Cambrian system (Є). The quality of the Quaternary and Jurassic systems as aquicludes is better than that of the Qingbaikou (Qn) system.

The results from the statistics and calculations are questionable in certain wells or at a certain depth. For instance, the temperatures in some Quaternary wells are a little higher. The geological formations reflect the temperature gradient as well as the geological structure. From previous research, typical temperature gradients for different strata can be used in the Xiaotangshan geothermal field as empirical parameters. Pan et al., 2005 suggested the following values:

Unconsolidated sediments: 3 °C/100 m
Shale: 4 °C/100 m
Limestone: 0.8-1.2 °C/100 m
Dolomite: 1.2 °C/100 m

These parameters are different from those calculated in Table 5. Thermal convection may be the main reason. There are 10 main faults in the Xiaotangshan geothermal field, These faults are all quite important to the occurrence of geothermal energy in the area, especially F1, F2, F3 and F4, which have very good permeability, causing enhanced hot water upflow from depth.

TABLE 5: Temperature gradient of reservoirs and aquicludes in the Xiaotangshan field

Well No.	**Temperature gradient of aquicludes (°C/100m)**				**Temperature gradient of reservoirs (°C/100m)**		
	Q	**J**	**Qn**	**Jxh**	**Є**	**Jxt**	**Jxw**
T6	8.00						
T8	10.90				0.43		
T9	5.40	3.60			1.52		
T10	2.05				0.73		
T15	8.00		3.70				
T16					2.33		
T19	8.08				3.72		
T24	8.76				2.67		
T25							0.60
T26						3.70	
T27	2.44		6.60			1.97	
T28	4.38						
T29	3.43						
T30		1.74					2.33
T31		2.01			0.63		
T32		1.25			1.32		0.45
T33			3.05	2.21		1.47	2.04
T34	3.00	11.67		2.20	2.03		0.90
T35					3.20		1.28
T36		1.01			1.60		
T37			2.78	5.00		0.45	
T38	2.49				1.09		0.85
T39	5.22						1.07
T40	4.56				1.38		0.39
T42						0.37	
T44	4.55						0.82
T45							0.82
T46	4.18		1.13			2.60	
T48							2.43
T50					2.30		2.28
T51	8.14						
T55				2.39			1.24
Average	5.50	3.55	3.41	2.95	1.78	1.76	1.33

3.4 Production history

The Xiaotangshan geothermal field used to be a natural hot spring area with a total of eleven hot springs. The thermal fluid had temperatures of 22-52°C. Their total flowrate was about 72 l/s as measured during a survey in 1956. At the beginning of the 1970's, the total artesian flow had decreased to about 12 l/s. In 1974 only one of the eleven hot springs was still flowing with about 0.03 l/s, but it dried up when the first geothermal well (T1) was drilled.

Exploitation of the geothermal reservoirs started in 1974. Figure 8 shows the production history of the Xiaotangshan geothermal field from the three main reservoirs from 1974 to 2004. With more wells and depth range, drilling extended from the Wumishan group (Jxw) to the Tieling group (Jxt) and eventually to the Cambrian system (Є). The three reservoirs under the field are separated from one another to some degree, but connected to each other in some parts of the system. After 1996, the well density in the field increased and more wells started to mine the geothermal water from two reservoirs simultaneously. The allowable production was also significantly increased to a maximum production of 46.9×10^6 m^3 in 1998.

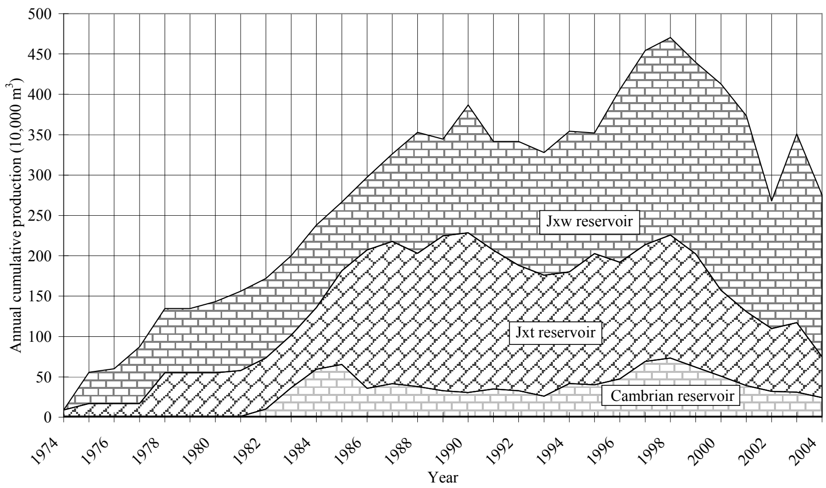

FIGURE 8: Production history of Xiaotangshan geothermal reservoir, 1974-2004

The production has been reduced in recent years; total production was 2.7×10^6 m^3 in 2004. In Figure 9 we can see that the production from Jxw is 2.0×10^6 m^3, or 74% of the total production; production from Jxt and Є is 18%, and 8% of the total production, respectively.

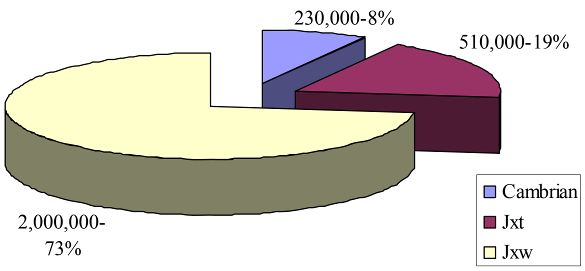

FIGURE 9: Geothermal production from the Xiaotangshan reservoir in 2004, with the contribution of different reservoirs indicated (m^3 and %)

3.5 Monitoring

Geothermal monitoring in Xiaotangshan started in the 1970's. This included monthly production measurements of every geothermal well in the field, and analysis of the chemical composition of the water from three wells producing from the three reservoirs, twice a year. Although the data has been useful for studying the response of the geothermal systems to production, these data are far from enough.

There are three dynamic water level monitoring wells in Xiaotangshan geothermal field at present; well G1 (located in the yard of the Xiaotangshan townhouse), well G25 (located in Xiaotangshan plant nursery) and well G40 (located in the Changxingzhuang village). All three wells are drilled into the Wumishan group (Jxw). No monitoring wells are available for the Tieling group (Jxt) and the Cambrian system (Є). Well G1 has the longest monitoring history; the water level has been measured in the well for more than 16 years. The water level in wells G25 and G40 has been measured since 1999. All the data reflect water level changes due to production. These data are the most important for geothermal resource assessment of the Xiaotangshan geothermal system.

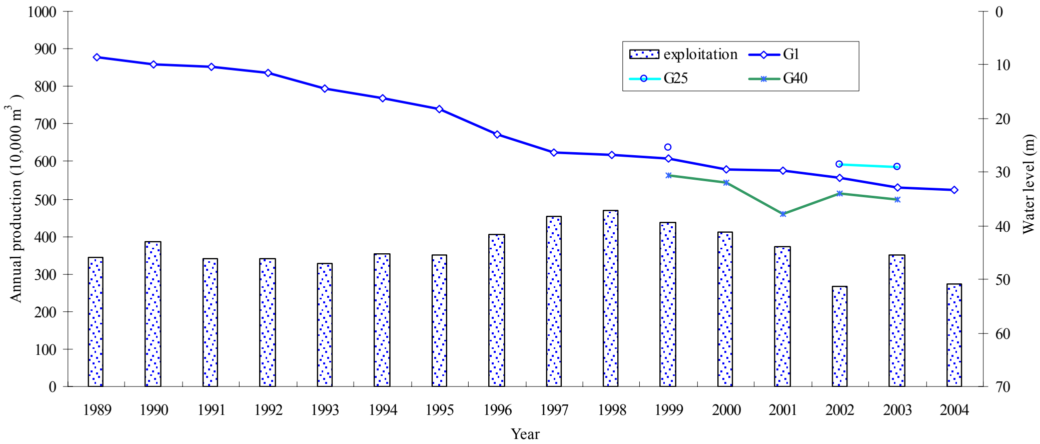

FIGURE 10: Water level drawdown and exploitation history of the Wumishan (Jxw) reservoir, 1989-2004

In the middle of the 1970's, the water head in production well T9 was beyond the surface by several metres. Following increased production, the water level declined year by year. Now the geothermal water level is nearly 40 m below the surface. This can clearly be seen in the data from measuring well-G1, which is in the centre of the geothermal field (Figure 10).

TABLE 6: Water level monitoring data for the Xiaotangshan geothermal field, 1989-2004, along with the exploitation from the Jxw reservoir

Time	Exploitation ($10^3\times m^3$)	G1		G25		G40	
		Water level (m)	Drawdown (m/a)	Water level (m)	Drawdown (m/a)	Water Level (m)	Drawdown (m/a)
1989	3,435	8.58					
1990	3,857	9.83	1.25				
1991	3,406	10.37	0.54				
1992	3,405	11.54	1.18				
1993	3,268	14.44	2.90				
1994	3,533	16.13	1.69				
1995	3,511	18.27	2.14				
1996	4,048	22.94	4.67				
1997	4,532	26.34	3.40				
1998	4,694	26.67	0.33				
1999	4,386	27.37	0.69	25.35		30.53	
2000	4,118	29.39	2.02			31.97	1.44
2001	3,725	29.79	0.40			37.75	
2002	2,670	31.15	1.35	28.50		34.00	
2003	3,500	32.83	1.69	28.94	0.44	35.00	1.00
2004	2,743	33.29	0.45				
Average	3,462		1.65		0.90		1.12

Table 6 presents the monitoring data for the most recent 15 years, which show that the water level depth of monitoring well-G1 has declined from 8.6 m in 1989 to 33.3 m now. The total decline in water level is therefore 24.2 m, and the average decline is about 1.65 m/year. The annual average decline of the water level in monitoring wells G1, G25 and G40 is about 1 m in the last 5 years. Contrast analysis indicates a clear positive correlation between the water level decline rate and the geothermal production. When the production increases, the water level decline rate increases. The production has decreased in recent years, and the water level decline rate has, consequently, decreased (see Table 6).

4. CONCEPTUAL MODEL FOR THE XIAOTANGSHAN FIELD

Based on the analysis of the geologic structure and subsurface temperature conditions, a conceptual model of the Xiaotangshan geothermal field has been developed. The Xiaotangshan low-temperature geothermal field consists of three sedimentary reservoirs, with the geothermal energy stored in limestone and dolomite formations. These are:

1. The Wumishan reservoir (Jxw): dolomite formations, with an effective thickness of 1680 m;
2. The Tieling reservoir (Jxt): dolomite formations, with an effective thickness of 538 m.
3. The Cambrian system (Є): limestone formations, with an effective thickness of 500 m.

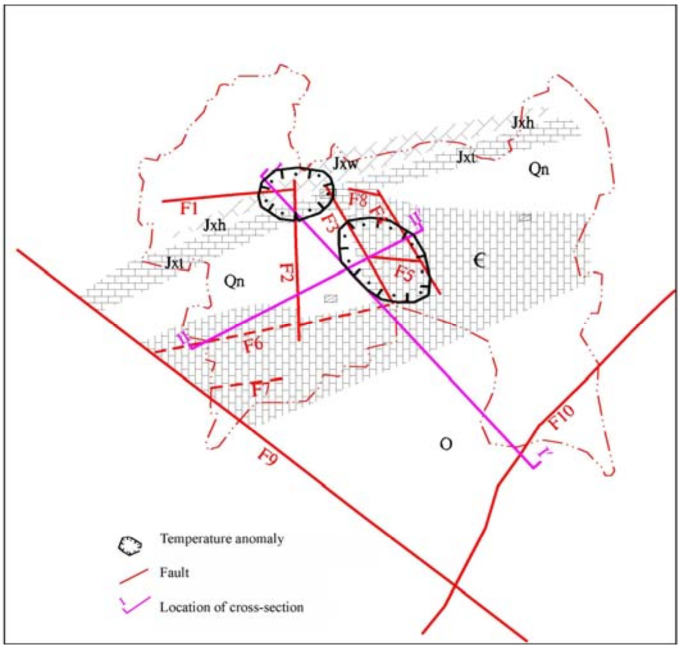

FIGURE 11: Geological and structural map of the Xiaotangshan area

The cap rock is composed of unconsolidated Quaternary sediments, Jurassic andesite and mudstone, and Qingbaikou sandstone and shale.

From Figure 11 we can see that the northwest part of the temperature anomaly discussed earlier is linked with the north trending Houniufang-Xiaotangshan fault (F2) together with the northeast trending Asuwei- Xiaotangshan fault of (F1). The axis of the southeast part of the anomaly has the same trend as the Daliushu-Huluhe fault (F3) and the Changxingzhuang-Houlingou fault (F4). A conclusion drawn from the available data is that within the region between the Daliushu-Huluhe fault (F3) and the Changxingzhuang-Houlingou fault (F4), the water temperature and productivity of wells is relatively high. The transmissivity of the Daliushu-Huluhe fault also appears to be good.

Figures 12 and 13 show that the Asuwei-Xiaotangshan fault (F1), the Houniufang-Xiaotangshan fault (F2), the Daliushu-Huluhe fault (F3) and the Changxinzhuang-houliugou fault (F4) play an important role in geothermal activity by causing enhanced permeability and channels for upflow of hot water from depth. According to the reservoir conditions and the characteristics of the main faults, it seems

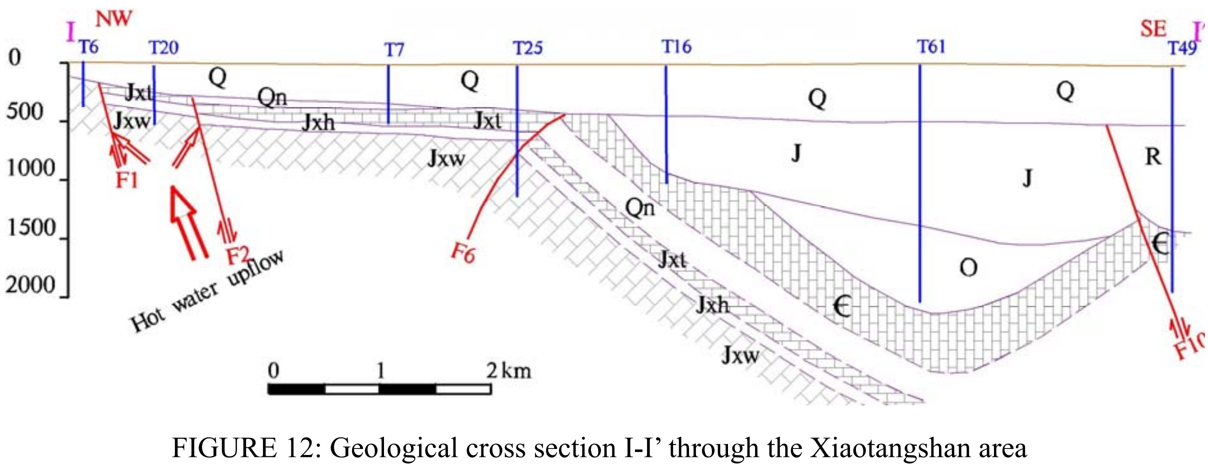

FIGURE 12: Geological cross section I-I' through the Xiaotangshan area (see Figure 11 for location)

that the Jxw and Cambrian system are directly connected in the southeast part of the Xiaotangshan geothermal field, and the Jxw reservoir seems to be connected with the Jxt reservoirs in the northwest part of the Xiaotangshan field, as shown in Figure 13.

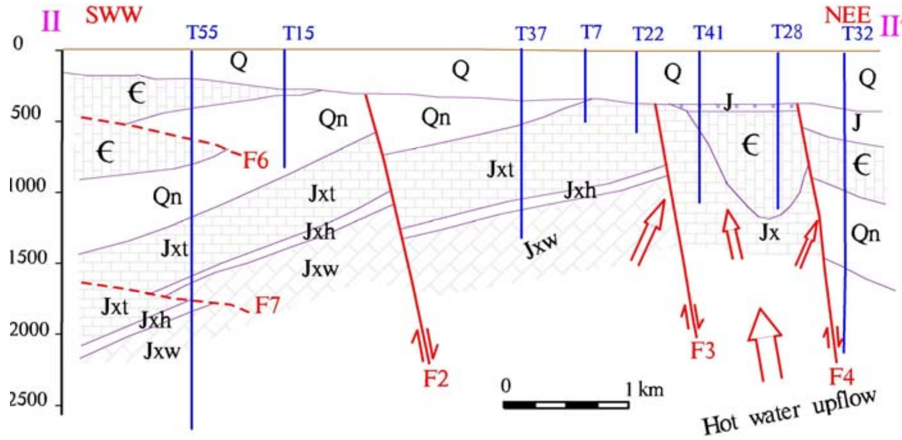

FIGURE 13: Geological cross section II-II' through the Xiaotangshan area (see Figure 11 for location)

5. GEOTHERMAL POTENTIAL ASSESSMENT

One of the most important issues concerning the sustainable use of geothermal resources is how much geothermal fluid can be produced from a given reservoir in the long run. If the production is too high, the reservoir pressure will decline fast and the production capacity of the geothermal field will decrease accordingly. Therefore, it is essential to have a good estimation of the geothermal potential of the field so as to ensure the long-term production of geothermal fluid. Two methods, an empirical method and lumped parameter modelling, are used in this section to estimate the production potential of the Xiaotangshan geothermal field.

5.1 Lumped parameter model

To predict the trend of water level change for a geothermal reservoir, lumped parameter models were developed using the LUMPFIT computer code, developed by Axelsson and Arason (1992). By considering a reservoir as a chain of zero-dimensional tanks that connect to the surrounding reservoirs, or tanks, and ignoring all the spatial variations of the reservoir properties and fluid flow within the tanks, a series of exponential equations are derived. The equations that form the basis of LUMPFIT describe the response and behaviour of pressure change with time in the reservoir to the production without being restricted by geometry (Axelsson, 1989). In a lumped model, (Figure 14), the tanks simulate the storage capacity of different parts of the geothermal system. In general, the first tank in the model can be looked upon as simulating the innermost (production) part of the geothermal reservoir, and the second and third tanks simulate the outer parts of the system (Axelsson et al., 2005).

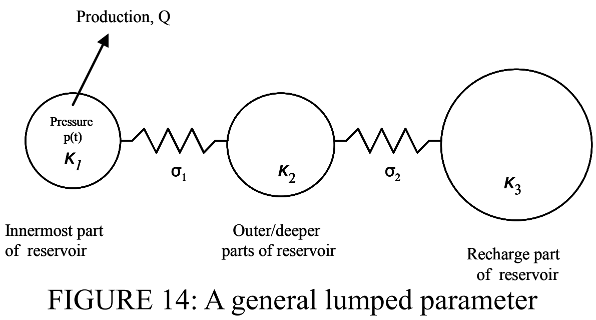

FIGURE 14: A general lumped parameter model used to simulate water level or pressure changes (Axelsson, 1989)

The procedure for finding an adequate model that fits the observed data is as follows: First, begin with a single-tank closed model, then turn to an open one-tank model. After that, a two-tank closed model and a two-tank open model follow. The upper limit of the LUMPFIT program is three tanks. This procedure finds the best fitting model coefficients and the properties that best describe the reservoir. The total production from the three geothermal reservoirs in Xiaotangshan i.e. the Wumishan group (Jxw), the Tiling group (Jxt) and the Cambrian (Є), has been monitored every month from the early

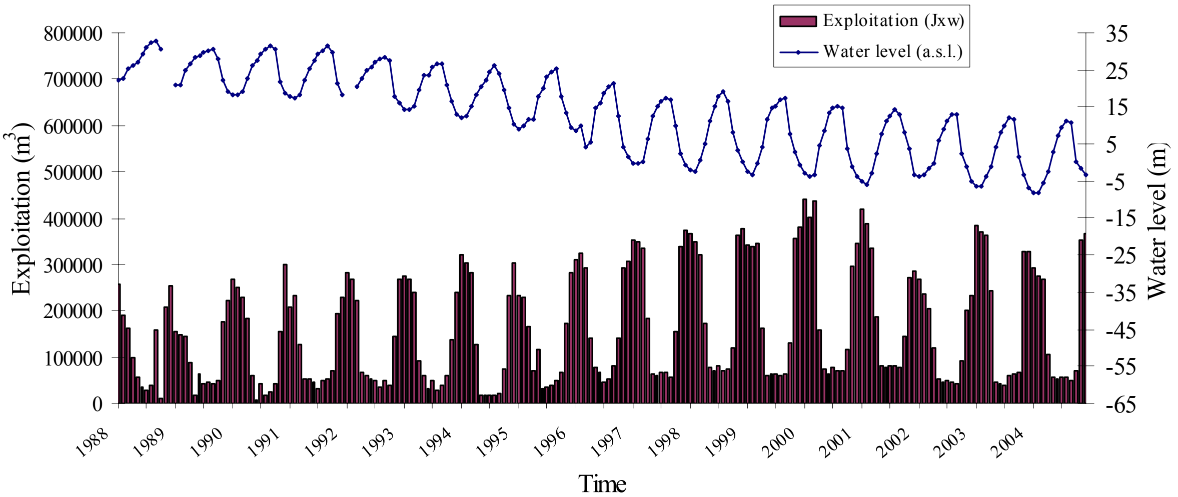

FIGURE 15: Water level changes and production from the Wumishan (Jxw) reservoir in Xiaotangshan for the period 1988-2004

stage of exploitation in 1974. The water level in Well-G1 has been observed from 1988 to now, so sufficient series of monitoring data are available (see Figure 15 and Table 7) for production assessment.

TABLE 7: Production statistics for the Xiaotangshan geothermal field (1995-2004)

Reservoir	Production (l/s)			
	Current	Minimum	Maximum	Average
Jxw	63.6	47.4	81.0	69.0
Jxt	16.0	16.0	51.5	36.7
Є	7.4	7.4	22.9	14.4
Total	87.0	70.8	155.5	120.1

Well G1 is only connected to the Wumishan reservoir (Jxw), not to the Tiling reservoir (Jxt) or the Cambrian reservoir (Є). In the conceptual model, it is assumed that the Jxw reservoir is connected to the Jxt and the Cambrian reservoir. In order to check the validity of this assumption, the monitoring history was simulated with four combinations of the production histories from the three reservoirs:

(a) From the Jxw reservoir only;
(b) From Jxw and Jxt reservoirs;
(c) From Jxw and Cambrian (Є) reservoirs;
(d) From all three reservoirs Jxw, Jxt and Cambrian (Є).

The aim is to try to select the most likely combination by comparing how well the models for different production combinations fit for the data. Figures 16-19 show the production rates and calculated and measured water level history from 1974 to 2005. Table 8 shows the simulation results for the different combinations, including the type of model, model parameters and the coefficients of determination.

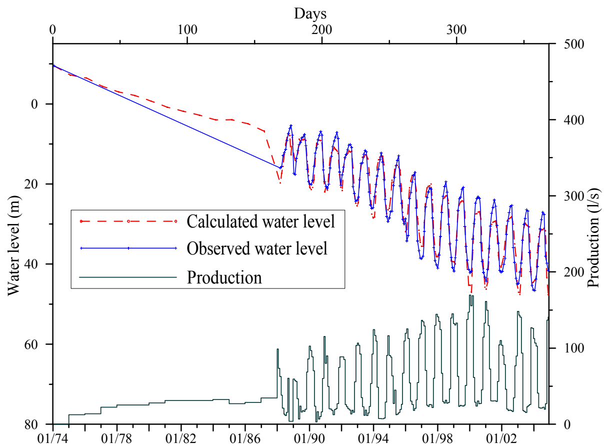

FIGURE 16: Water level simulated by an open two-tank lumped model, based on production from the Jxw reservoir

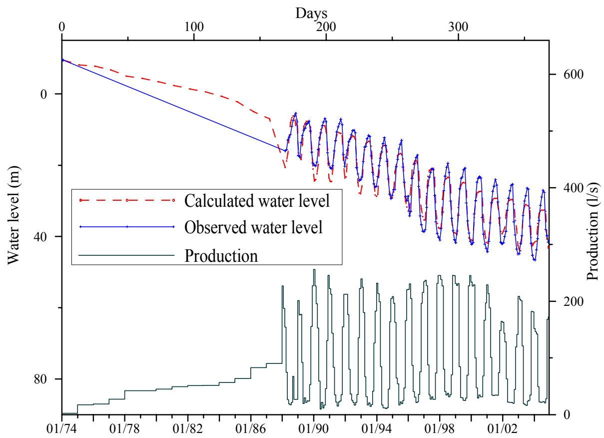

FIGURE 17: Water level simulated by an open two-tank lumped model, based on total production from the Jxw and Jxt reservoirs

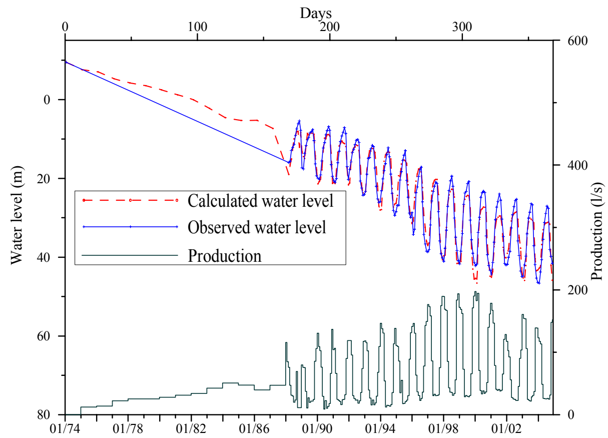

FIGURE 18: Water level simulated by an open two-tank lumped model, based on total production from the Jxw and Cambrian reservoirs

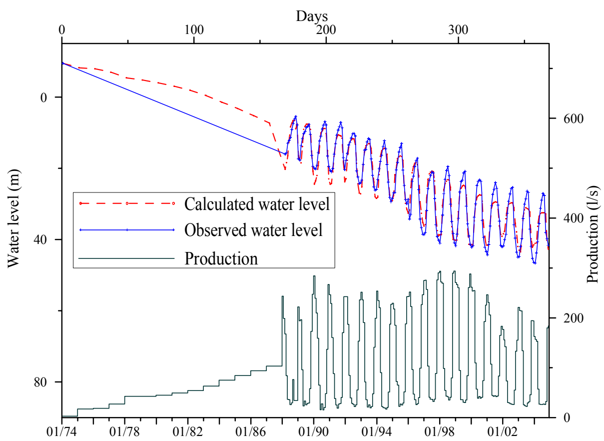

FIGURE 19: Water level simulated by an open two-tank lumped model, based on total production from the Jxw, Jxt and Cambrian

The coefficients of determination of the models mentioned above are about 92-95%, which indicates good fits for all the models. The fifth and the sixth models have the highest coefficient of determination, simulations with the total production the Jxw and Є reservoirs with the total production of the three geothermal reservoirs, respectively. The conclusion is that the three geothermal reservoirs are likely to be all connected, which is in agreement with the geology. The Jxw reservoir is in better connection with the Є reservoir than the Jxt reservoir, because the Jxw reservoir and the Є reservoir are directly connected in the southeast part of the Xiaotangshan field. The Jxw and Є formations are distributed more widely, and their thickness is greater than that of the Jxt reservoir. All of these factors influence the result of the simulation.

TABLE 8: Results of simulating with two tank models

Reservoir	**Jxw**		**Jxw & Jxt**	**Jxw & Є**		**Jxw, Jxt & Є**
Model number	1	2	3	4	5	6
Model type	2 closed	2 open	2 closed	2 closed	2 open	2 closed
A(1)	0.165	0.1747	0.0948	0.1384	0.1441	0.084
A(2)		0.0034			0.00253	
L(1)	1.028	1.195	1.297	1.022	1.153	1.245
L(2)		0.0034			0.0025	
B	0.0023		0.0014	0.0019		0.0012
Coef. determ.	92.0	93.5	93.5	93.1	94.0	93.9
K_1	1607	1510	2796	1916	1833	3150
K_2	114900	77500	191900	1417	104900	2176
$б_1$	0.0006	0.00067	0.0014	0.00073	0.00079	0.00146
$б_2$		0.0001			0.0001	

To sum up, water level changes can be predicted by the open two-tank model based on the exploration from Jxw; by the open two-tank model based on the combined production from the Jxw and Є reservoir, or by the closed two-tank model based on total production.

Table 9 shows the estimated volume and permeability of the Jxw reservoir in the Xiaotangshan geothermal field based on the corresponding model (production from Jxw only). Based on the open two-tank model, with the assumption that the thickness of Jxw reservoir is 1680 m, the estimated area of the Jxw reservoir is 38.5 km^2.

TABLE 9: Estimated Jxw reservoir properties according to the lumped parameter models

Model type	Parameter	Value
Open two-tank	Volume of tank 1 (km^3)	65.0
	Volume of tank 2 (km^3)	3340.0
	Permeability (m^2)	7.41×10^{-14}
Closed two-tank	Volume of tank 1 (km^3)	69.2
	Volume of tank 2 (km^3)	4950.0
	Permeability (m^2)	7.3×10^{-14}

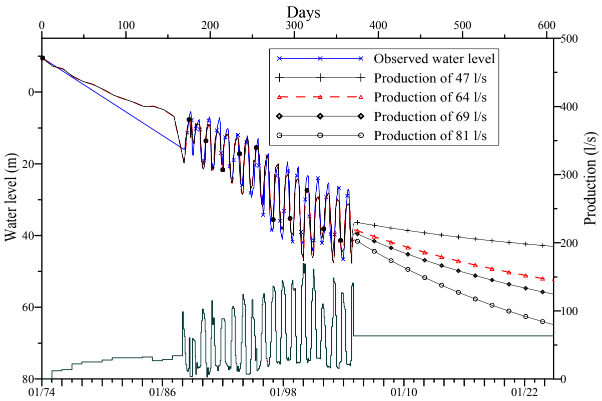

FIGURE 20: The predicted response of the Jxw reservoir for different production rates, calculated by a two-tank open model

Figure 20 shows predictions of waterlevel changes for different production levels for the Jxw reservoir, calculated by the two-tank open model. Table 10 shows values for the predicted water level changes for different production levels from different combinations of reservoirs. Table 10 shows, that with current exploitation, the change in water level is 0.5 m after five years, and 19.1 m after 20 years. With an average production of 120.1 l/s (see Table 7), the water level drawdown is 5.2 m after five years, and 31.0 m after 20 years, the annual drawdown thus ranging from 1 to 1.5 m. With an average production of 155.5 l/s, the annul water level drawdown may increase to about 2 m in the future.

TABLE 10: Predicted water level changes with different production (see Table 7 for production rates)

Reservoir	Prediction cycle (year)	Water level change (m)			
		Current production, 2004	Minimum production 1993-2004	Maximum production 1993-2004	Average production 1993-2004
Jxw	5	-4.8	-9.3	1.0	-3.0
	10	-0.9	-7.4	7.5	1.7
	20	4.8	-4.6	17.2	8.7
Jxw & Є	5	-3.9	-6.8	3.3	-0.5
	10	0.1	-4.2	10.5	5.0
	20	6.5	0.0	22.1	13.8
Jxw, Jxt & Є	5	0.5	0.2	8.5	5.2
	10	6.7	6.2	18.8	13.8
	20	19.1	18.2	39.5	31.0

5.2 Geothermal potential assessment

When speaking about geothermal potential in general, we are referring to how much can be produced from a resource, technically and economically (Zheng, 1996). The Xiaotangshan geothermal field has been exploited since the middle part of last century. Several estimates and assessments of the geothermal resources have been conducted. Here used, are the volumetric method, a dynamic correlation mining method and a parallel method, in addition to the lumped parameter modelling, already discussed.

5.2.1 The volumetric method

The volumetric method can be considered a zero-order modelling method, since it neglects the dynamic response of a reservoir. The following formulas are used in the volumetric method:

Quantity of heat in storage:

$$Q = CAd(T_r - T_0) \tag{1}$$

The water volume stored:

$$V_w = \phi Ad \tag{2}$$

Heat stored in the geothermal water:

$$Q_w = \rho_w C_w V_w (T_r - T_o) \tag{3}$$

Recovery factory

$$R_g = \frac{\phi \cdot \rho_w \cdot C_w}{\phi \cdot \rho_w \cdot C_w + (1-\phi)\rho_r \cdot C_r} \tag{4}$$

where
Q = Quantity of heat stored (J);
A = Area of volume (m^2);
d = Volume of heat storage (m^3);
T_r = Reservoir temperature (°C);
T_o = Reference temperature (°C);
C = Average heat capacity of rock and water (J/(m^3°C));
ρ_r = Rock density (kg/m^3);
C_r = Heat capacity of rock (J/(kg°C));
ρ_w = Density of geothermal water (kg/m^3);
C_w = Heat capacity of water (J/(kg°C));
ϕ = Rock porosity in heat storage;
V_w = Volume of geothermal water (m^3);
Q_w = Quantity of heat in water (J);
R_g = Recovery factory.

The area considered for assessment is the total extent of the Xiaotangshan geothermal field, or 86.5 km^2. Each of the relevant parameters must be estimated for the three reservoirs, respectively. Firstly, we divide the area according to geology and borehole distribution. Based on this, we refer to the geologic structure of the research area, and create a differential network of the area for computing heat storage, with a grid area of 1 km^2 where the computational parameters are based on neighbouring boreholes. Considering the production experience in Xiaotangshan, the exploitation depth should be less than 3000 m, so we make it the lower boundary in the computation. When the depth of heat storage buried below surface is less than 3000 m, the complete thickness is chosen; when it is more than 3000 m, the depth 3000 m is chosen. The complete thickness of the Cambrian and Jixian formations is 500 m and 2000 m, respectively. Other parameters are based on former studies, for instance: rock porosity (ϕ), density of geothermal water (ρ_w), rock density (ρ_r), heat capacity of rock (C_r), etc. (see Table 11).

TABLE 11: Table of parameters used for volumetric assessment for each reservoir in the Xiaotangshan geothermal field (Pan et al., 2005)

Reservoir	ρ_w (kg/m^3)	ρ_r (kg/m^3)	T_r (°C)	ϕ	C_r (J/kg.°C)	C (10^6J/m^3.°C)
Jx(Jxw and Jxt)	938-994	2800	33-115	0.001-0.011	920	2.58-2.59
Є	968-998	2750	22-86	0.007-0.008	920	2.53-2.54

The geothermal reserves, the water storage volume, quantity of heat in geothermal water and the allowable production was calculated for the 86.5 km^2 area in Xiaotangshan, based on the parameter selection above for each reservoir unit. The results are shown in Table 12.

TABLE 12: Estimated heat and water storage in the Xiaotangshan geothermal system, according to the volumetric method

Reservoir	Q (10^{18}J)	V_w (km^3)	Q_w (10^{16}J)	R_g (%)
Cambrian(Є)	2	0.16	3	1.15
Jixian system(Jxw and Jxt)	17	0.83	18	1.10
Total	19	0.99	21	

As Table 12 shows, the total quantity of heat in the Xiaotangshan geothermal field is 1.9×10^{19} J, including 0.2×10^{19} J in the Cambrian system and 1.7×10^{19} J in the Jixian system. The total stored water volume is 0.99 km^3, the stored quantity of heat in the water 2.1×10^{17} J. This includes 0.16 km^3 water storage volume and 3×10^{16} J of heat in the Cambrian system, as well as 0.83 km^3 of water stored in the Jixian system. The estimated recovery factor is 1.15% and 1.10% in the Cambrian system and Jixian system, respectively (Pan et al., 2005).

From 2001, the average annual production has been 3.3×10^6 m^3 in the Xiaotangshan geothermal field, that is 0.3% of the geothermal water in place. According to the production plan for the city zone, the exploitation proportion will be increased to 0.4% in the future. Thus the allowable volume of geothermal water in the whole Xiaotangshan geothermal field that is allowed to be exploited is 4.0×10^6 m^3/a (Liu et al, 2001).

5.2.2 The dynamic correlation mining method

This method, based on a correlation between the water level monitoring history and annual allowable production dictated by Beijing Government, can be used to predict the future allowable production by referring to a certain drawdown.

As discussed earlier, the Xiaotangshan geothermal field had at first natural hot springs the last of which disappeared when production from wells started in 1974. With an increasing number of wells, and deeper drilling with time, the production increased from the Wumishan group, and later from the Tieling group and the Cambrian system. The three reservoirs in the field are connected to one another to some degree in parts of the field. After 1996, the well density in the field increased. More wells mined the geothermal water from the two geothermal reservoirs. Meanwhile the production was increased significantly to a maximum production of 4.69×10^6 m^3 in 1998. Monitoring has been strengthened in recent years, and the production reduced. A correlation was found between production and drawdown for different periods of time, as Table 13 shows. The allowable production per unit drawdown has increased with time since 1996-1999.

TABLE 13: Relationship between allowable production and the drawdown in the Xiaotangshan area

Time	1996-1999	2000-2002	2003-2004
Annual allowable production ($10^6 m^3/a$)	4.41	3.5	3.12
Average annual drawdown (m)	2.3	1.2	1.1
Allowable production per unit drawdown ($10^6 m^3/a.m$)	1.94	2.78	2.92
Total drawdown (m)	25.2	30.3	33.1

A correlation equation, based on the production in different periods and the corresponding drawdown can be obtained (see Figure 21). The equation describing this is:

$$y = - 1.473\, x^2 + 98.065\, x - 1340.7$$

where y = The allowable production per unit drawdown ($10^4 m^3/a$);
x = The total average drawdown since exploitation started (m).

The correlation equation describes a parabolic relation between the allowable production per unit drawdown and the water level drawdown in the geothermal field. The relationship has an extreme mathematical point. At present, the allowable production per unit drawdown is close to the maximum 2.91×10^6 m^3/a while the accumulative total water level drawdown is 33.3 m. Thus it can be predicted that if the water level decline is about 1.5 m per year in the future, the allowable production will be 4.37×10^6 m^3/a. If the water level continues to decline, perhaps a better curve can be defined.

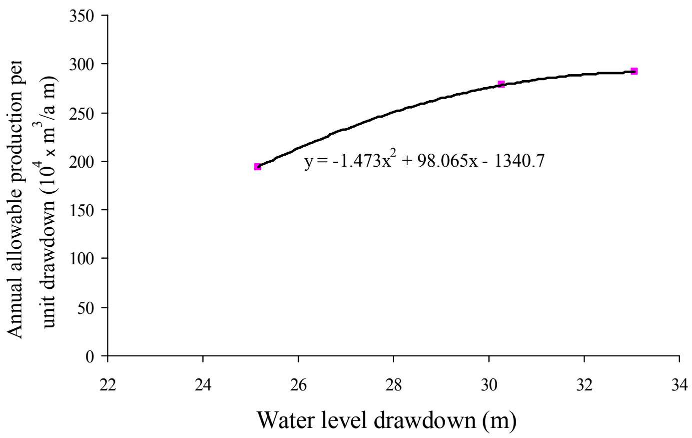

FIGURE 21: Annual allowable production per unit drawdown vs. water level drawdown in the Xiaotangshan field

5.2.3 The parallel method

Because of similarities between the Xiaotangshan and the Urban areas in Beijing, assessment results for the latter can be used to estimate the production potential of the former. A lumped parameter model has been developed for the geothermal fields in the Urban area, based on its high degree of exploration and studies as well as the many years of dynamic monitoring data available. If a geothermal water level decline of about 2 m is assumed annually up to 2020, the production in the Urban geothermal field can be about 7.0×10^6 m^3 annually. The central exploitation area in the urban field is approximately 285 km^2 in area. According to the assessment for the urban area, annual production may be 0.025×10^6 m^3 per square kilometres (Liu et al., 2001). Based on the values, the production from the Xiaotangshan geothermal field can be assessed approximately up to 2020, and the allowable production is estimated to be 2.12×10^6 m^3/a for the 86.5 km^2 Xiaotangshan geothermal field.

5.2.4 Geothermal resource assessment

The allowable production of geothermal water in Xiaotangshan is estimated between 2.12 and 4.37×10^6 m^3/a by the three methods above. The volumetric method and parallel method are conservative means of assessing the geothermal field in Xiaotangshan area. The dynamic-correlation-mining-method depends on the characteristics of the geothermal field itself and the dynamic behaviour of the water level in recent years.

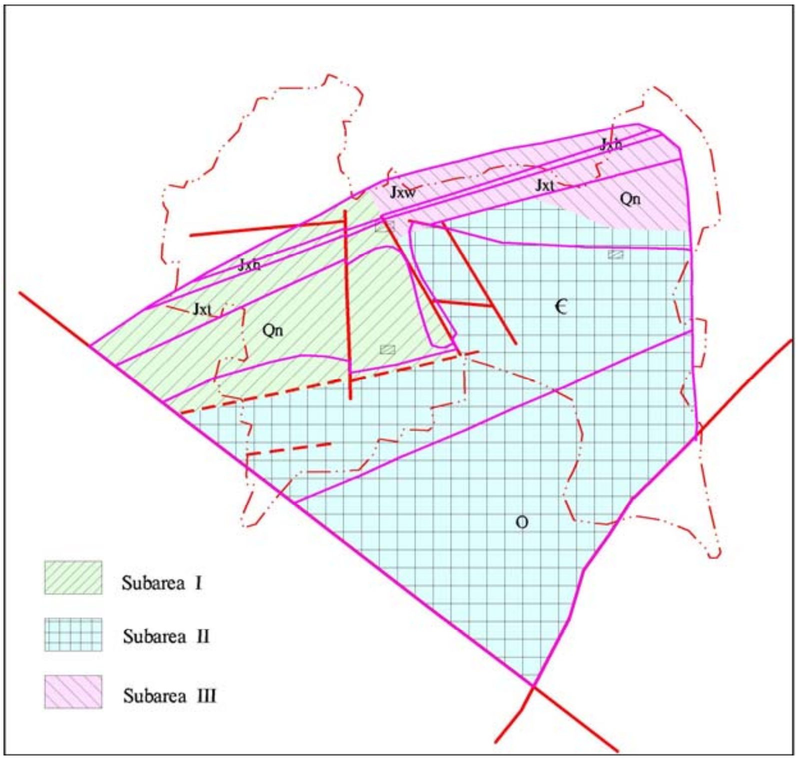

FIGURE 22: Division of the Xiaotangshan geothermal field into subareas used in the resource assessment

The allowable production can be calculated by dividing Xiaotangshan into subareas (Figure 22). Because of the different density of wells in the subareas, and a different degree of exploration, the geothermal resources have been given different grades (see Table 14). Subarea I has nearly 40 wells, which is about 2/3 of all the wells in the field. Wells in subarea III exploit geothermal water from the Jixian system. The water level in an observation well in this area has been monitored for more than 30 years. The degree of geothermal resource investigation is high in subarea I, therefore the resources in the Jixian system in this area are given a "B" grade. The Cambrian system is distributed only in the southern part of the subarea II. It has no monitoring data, and gets only a "D" grade. There are about 20 geothermal wells in subarea II; 10 wells produce water from the Cambrian system, and the other wells produce from the Jixian system. Because of limited monitoring data, subarea III gets a "D" grade. The Jixian reservoir is the only one in subarea III, and it has only two wells. It is, therefore, difficult to classify this subarea, so it gets an "E" grade. The results are presented in Table 15. The allowable production of geothermal water in Xiaotangshan is 4.4×10^6 m^3/a, using the dynamic-correlation-mining-method, about 0.44% of the geothermal water in-place in the Xiaotangshan area.

TABLE 14: Geothermal resources assessment for different subareas in Xiaotangshan

Subareas	**Reservoir**	**Area (km^2)**	**Volume of geothermal water ($10^6 m^3$)**	**Allowable production ($10^6 m^3/A$)**	**Grade**
I	Cambrian	2.2	1.94	1.0	D
	Jixian	20	273		B
II	Cambrian	56.7	161	2.87	D
	Jixian	56.7	397		D
III	Jixian	9.8	131	0.50	E

TABLE 15: Geothermal resource assessment by the dynamic-correlation-mining-method in three Xiaotangshan subareas (see Figure 22)

Subarea	**Area (km^2)**	**Annual allowable production, decline of water level 1.5 m (10^6 m^3)**
I	20	1.01
II	56.7	2.87
III	9.8	0.50
Total	86.5	4.4

5.3 Reinjection

Reinjection is widely used in the management of geothermal fields, and is becoming a kind of routine in many of these, since the first such project was implemented in the famous Geysers in 1969. The purpose of geothermal reinjection is for (1) the disposal of waste geothermal fluid that may cause thermal and chemical pollution in the environment; (2) increased heat mining, as over 90% of the heat in the geothermal reservoirs is stored in the hot rock matrix; and (3) the stabilization of the production capacity of the geothermal field through the maintenance of the reservoir pressure (Liu, 1999). Reinjection has been taken as one of the most important measures in counteracting declining reservoir pressure in geothermal systems under large-scale production, as well as disposing of the waste geothermal fluid that may cause chemical and thermal pollution to the surface water system or the soil system if discharged directly on the land surface.

To ensure the sustainability of the geothermal development in the geothermal field, reinjection experiments were carried out in Beijing in the early 1980's. Recently, the government of Beijing has encouraged reinjection of the return water from geothermal heating systems, by reducing or exempting the geothermal resource fee.

A few reinjection tests have been completed in the Xiaotangshan and Urban areas of Beijing, together with tracer tests. A reinjection experiment in the Xiaotangshan field was carried out in 2000-2002 giving very positive results. During the experiment, a tracer test was carried out to examine the connections between the production and reinjection wells, and consequently to predict the cooling in the production well caused by the injection of colder waste geothermal water. Recently, two other reinjection experiments were started in the geothermal field, and preliminary results will be available by the end of April 2006.

The following is an excerpt from a paper by Liu et al. (2002) discussing reinjection experiments in the Xiaotangshan geothermal field: The earliest reinjection experiment was carried out in Xinyuan Hotel in the winter of 2001. No problems were encountered during the heating period, and the preliminary discovery confirmed the feasibility of reinjection. Xinyuan Hotel is located in the centre part of the Xiaotangshan geothermal field, near the hottest part of the field. The water level of the geothermal field has been declining successively since the pumping of geothermal water started in the 1970's (Pan et al., 1998). The hotel has two geothermal wells used for space heating as well as hot water supply. The production capacity of the two wells is rather good, and they are never used at the same time for production. On the other hand, the temperature of the waste geothermal water from the heating system is still as high as 40°C. Therefore it was proposed to carry out a reinjection experiment in the wells at the hotel as a demonstration project of geothermal reinjection in Beijing. The two wells of the hotel, T11 and T38, were drilled in 1984 and 1996, respectively. The distance between the wells is about 200 m. The geothermal reservoir is Cambrian limestone and Jixian dolomite. The wells intersected the same fault, which plays an important role in the occurrence of geothermal resources in the area of the hotel. Table 16 lists some data for the two wells. The reinjection was carried out from 30 November 2001 to 27 March 2002, for a total of 117 days. The temperature of the reinjected waste geothermal water was 30-44°C. The flow rate of reinjection changed with the atmospheric temperature. It was around 800 m^3/d on the coldest days from 8-20 January 2002, but was below 800 m^3/d on other days. The injectivity of the well did not decrease during the injection. The total amount of water injected was 73,000 m^3. This was about 50% of the water that had been expected for reinjection. However, the winter was warmer than most winters in past decades, and the energy needed for space heating was also much less than in "normal winters". The effect of reinjection in supporting the reservoir pressure was not noticed because of the limited amount of reinjection.

TABLE 16: Information on wells, T11 and T38,
involved in the 2001-2002 reinjection test

		T11	T38
Depth (m)		824.5	1601.0
Strata (m)	Quaternary system	0-388	0-397
	Cambrian system	388-720	397-967
	Jixian system	720-	967-
Diameter of top casing (mm)		177.8	350
Capacity of pump (m^3/h)		30	80
Wellhead temperature (°C)		64	65
Temperature at well bottom (°C)		61.5	65
Production (m^3/d)/Drawdown (m)		1451 /6.42	1780 / 6.31

A tracer test was conducted during the reinjection test. On 8 January 2002, 50 kg of KI were injected into the reinjection well instantaneously, 39 days after the reinjection test started. In all, 165 water samples were collected from the reinjection well until the heating period stopped. Some samples were also collected from other surrounding wells. Iodine was not detected in any of the samples. This indicates that there is no direct path between the reinjection and production wells, and that premature thermal breakthrough is not likely to happen in the production well. It is possible, however, that the amount of tracer applied was not enough or the test period was too short. This calls for another tracer test.

After the injection stopped, a submersible pump was installed in the injection well, intended to restore the injectivity of the well, if there had been reduction. On 15 April, the pump was started. At the beginning, the temperature of the water was around 30°C, and in an hour, the water temperature had reached 63.5°C, i.e. was nearly restored to its normal production temperature of 64°C.

The reinjection experiment shows that the injectivity of the geothermal reservoir is rather good, and that the reservoir also has a good capacity for heating the reinjected colder water. The quantity reinjected has increased year by year. Table 17 shows that reinjection is by now carried out in 6 pairs of wells in the Xiaotangshan geothermal field. The total reinjected volume has reached 1,375,000 m^3 in three years. During 2004 the reinjected volume was 1,027,000 m^3.

TABLE 17: Information on reinjection wells in the Xiaotangshan geothermal field

Location	**Production well no. /reservoir**	**Reinjection well no. /reservoir**	**Amount of reinjection ($10^4 \times m^3$)**		
			2002	**2003**	**2004**
Xinyuan Hotel	T38/ Є + Jxw	T11/ Є + Jxw	10	10	10.3
Training centre of China Mobile	T22G/Jxt+ Jxw	T22/Jxt		14.8	20.8
Xichang sanitarium	Xire1/Jxw				
Hui-ying Aquaculture Development Centre		T3/Jxt			22.4
Exchange Centre of the State Family Planning Commission of China	T51/Jxw	T51G/Jxw			15.1
Modern agriculture science and technology demonstration garden	T35/Jxw	T50/ Є + Jxw			18.6
Plant nursery of Beijing Parkland Bureau	T25/Jxw	T37/Jxt+ Jxw			15.6
Total			10	24.8	102.7

6. SUMMARY AND CONCLUSIONS

The following are the main conclusions of the present work.

1. The Xiaotangshang geothermal field in Beijing, is one of the earliest explored geothermal fields in China. It is about 86.5 km^2 in area bordered by the Nankou-Sunhe fault in the southwest and the Huangzhuang-Gaoliying fault in the southeast. The maximum reservoir temperature is about 70°C and the depth to the main reservoir is less than 2000 m in the northern part. There are two main geothermal reservoirs in Xiaotangshan field: the Jixian dolomite formation (Tieling group and Wumishan group), which is distributed over the entire field, and the Cambrian limestone formation. The depth of the Jixian dolomites increases from the surface in the northwest to more than 2500 m in the southeast.
2. Geological structures control the geothermal resources, especially the Asuwei-Xiaotangshan fault, the Houniufang-Xiaotangshan fault, the Daliushu-Huluhe fault and the Changxinzhuang-Houliugou fault, all of which are very significant in providing good permeability and upflow paths for thermal water from depth. The Wumishan reservoir is the dominant reservoir in the Xiaotangshan geothermal field. It is in good connection with the Tieling reservoir in the northwest part of the field because of the Asuwei-Xiaotangshan and Houniufang-Xiaotangshan faults. It is also directly connected with the Cambrian system in the southeast part of the field.
3. The exploitation was limited to the hot springs, until drillings started in the 1970's. Now there are more than 70 wells in the field, and the deepest is more than 3000 m in depth. The Xiaotangshan geothermal field is one of the two most productive fields in the Beijing area. The total production to date is 740×10^6 m^3 and annual production has been around 3.5×10^6 m^3 for many years.
4. Results of lumped parameter modelling show that if production is maintained below 2.7×10^6 m^3/a (87 l/s) the water level will decline only about 19 m in 20 years.
5. Results of the volumetric assessment method show that the total heat storage in the Xiaotangshan system above a depth of 3000 m is 1.9×10^{19} J for the whole geothermal field (86.5 km^2). The estimated total geothermal water volume is 9.9×10^8 m^3, which contains heat of about 2.1×10^{17} J. The results from a dynamic correlation method indicate that the present production of geothermal water is close to the maximum allowable exploitation, if an average annual drawdown rate of 1.5 m per year in the future is to be maintained. Thus, the estimated allowable production is of the order of 4.4×10^6 m^3/a.
6. Monitoring data show that water level declines year by year, and that the total drawdown reached about 33 m in 2004. The average annual drawdown is 1.65 m. Since reinjection started in recent years, the drawdown rate has decreased. Geothermal reinjection is one of the most important methods for maintaining reservoir pressure and use of it may be the beginning of sustainable development of geothermal resources in the Beijing area.
7. The development and utilization of the Xiaotangshan geothermal field has moved into a comprehensive stage. On the whole, later development should be aimed at strengthening monitoring, controlling the scale of exploitation, increasing reinjection, regulating the distribution of wells, optimizing the resource configuration and enhancing the utilization efficiency. At the same time, the development should prompt a technique for automatic control and monitoring as well as improving the development level on the whole.

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