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NUMERICAL MODELLING OF WATER LEVEL CHANGES IN TIANJIN LOW-TEMPERATURE GEOTHERMAL SYSTEM, CHINA

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ABSTRACT

The Tianjin geothermal field is a typical sedimentary basin low-temperature geothermal system which includes a 6-layer reservoir of two kinds. One is a closed clastic rock subsystem where geothermal water is present in the pores, the other a semi-open and semi-closed bedrock subsystem where karst geothermal water is present. This report focuses on the Wumishan group reservoir which is located in the deepest layer. The Wumishan group belongs to a bedrock geothermal system that mainly lies in the Cangxian uplift and is the main reservoir under exploration and utilization. The reservoir is used for space heating and swimming pools. The depth range of this reservoir is 988-3000 m and the temperature ranges from 75 to 105°C. There are 122 geothermal wells (35 geothermal reinjection wells) in the Tianjin area which belong to the Wumishan group reservoir. The total production rate was 1362.2×10^4 m^3 in 2010, an increase of 72.8×10^4 m^3 from 2009. The Wumishan group production rate is 46.6% of the total production in 2010. The reinjection rate was 550.4×10^4 m^3 in 2010, which covers 40.4% of the total production. In order to study the dynamic changes in the Wumishan group reservoir, the water level, temperature and production were monitored. The water level has dropped quickly in recent years as a result of increased production. However, the temperature shows almost no change. This report describes the development of numerical models of the Wumishan group reservoir. Two types of models were constructed, a lumped parameter model using the Lumpfit program and a simple distributed parameter model using TOUGH2. The models were then used to predict future water level changes for three production scenarios. The water level is expected to drop 26.6 m in the next 10 years with the same production as in 2010, 24.3 m once reinjection is increased by 10%, and 37.2 m after 10% production has been added. The results presented here show that increasing reinjection and reducing production are good methods for helping to prolong the life of geothermal systems.

1. INTRODUCTION

Tianjin is located in the northeast section of the North China Plain near Bohai Bay, at the lower reaches of Haihe River valley, with the Bohai sea to the east and Yanshan Mountain to the north. The total area is 11,900 km^2. Tianjin has jurisdiction over 15 districts and 3 counties (Figure 1).

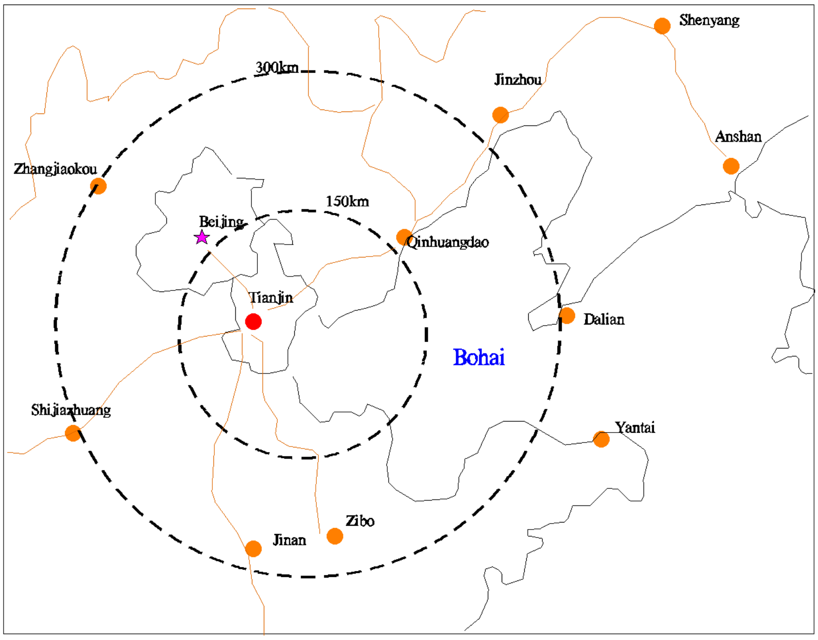

FIGURE 1: Location of Tianjin

Tianjin belongs to a warm temperature zone and has a sub-humid continental monsoon climate. The four seasons are sharply distinguished, and this results in great differences in temperature and a wide variety of scenery throughout the year. The yearly average temperature is over 12.3°C, and the frost free period lasts about 200 days. Winter temperatures are low enough to make space heating a necessity.

Tianjin has relatively rich geothermal resources. Its reserves and utilization of these are ranked number one in China. The Tianjin geothermal field is a typical low-temperature system. The geothermal distribution area is 8700 km^2, about 77% of the total Tianjin area. Ten distinct geothermal systems have been confirmed. As a clean energy source, the geothermal resource is widely used for space heating, potable water, agriculture, etc. The production rate reached 2921 × 10^4 m^3 and the space heating area was about 12.33 × 10^4 m^2 in 2010. The reservoir contains 6 layers but the lowest one, the Wumishan group reservoir, is the main production layer and is mainly used for space heating in Tianjin. The Wumishan reservoir accounts for 50% of the geothermal space heating area. In recent years, the large scale exploration and utilization of this reservoir has resulted in a rapid decline of the water level. This makes it very important to evaluate the geothermal energy of the Wumishan group reservoir in order to maintain a sustainable production (Tian et al., 2010).

2. GEOLOGICAL SETTINGS

2.1 Geological structure

Tianjin geothermal field is located in a sedimentary-fault basin in the northern part of the North China Platform and is divided into a northern and a southern part by the Ninghe-Baodi fault (Figure 2). Most of the area is covered by Quaternary strata. The outcrop of base rock is limited to the north mountains of Ji County.

The northern part belongs to the secondary tectonic unit. The southern part lies in the Bohai-Bay Basin. From west to east, the southern part constitutes three tectonic units: the Jizhong depression, the Cangxian uplift, and the Huanghua depression, which are cut into numerous tectonic blocks by several east-west, southwest-northeast trending faults. On the whole, the centre part is uplifted with the low-lying part in the east and west. The anticline structure is the main regional trend. The main faults are the Tianjin fault, the Cangdong fault, the Baitangkouxi fault and the Haihe fault. Most of the geothermal fields are located in the Cangxian uplift (Li Jun et al., 2010).

Drilling data have shown that the exposed strata from the surface to the bottom of the Cangxian uplift area are: Quaternary, Neocene, Eocene, Mesozoic, Ordovician, Cambrian, Qingbaikou and Jixian. The Tianjin geothermal reservoir consists of a fractured karst aquifer in the dolomite and limestone bedrock of the medium Proterozoic Jixiannian Wumishan group (Pt2W), the lower Paleozoic Cambrian group (PzH) and the Ordovician (PzO) group. Above that geothermal water is found in the porous clastic rocks of the Tertiary and Quaternary strata (Tianjin Bureau of Geology, 1992).

The Tianjin area is fractured by several southwest-northeast (SW-NE) and west-east (W-E) trending faults which control recharge conditions to geothermal systems.

The Haihe fault is a normal fault that runs NW-SE along the Haihe river for a total of 86 km. Its angle of inclination is between 40° and 60°. The breakpoint depth is 1200-1600 m. This fault cuts the Cangdong fault. It reflects that the fault was reactivated after the formation of the Cangdong fault. It is the boundary between the Panzhuang convex and Shangyao convex, and also between the Beitang concave and the Panqiao concave.

The Cangdong fault is a normal fault. The overall direction is north-northeast, the trend is south-southeast (SSE). Its angle of inclination is between 30° and 48°. It is the boundary between the tectonic units of the Cangxian uplift and the Huanghua depression.

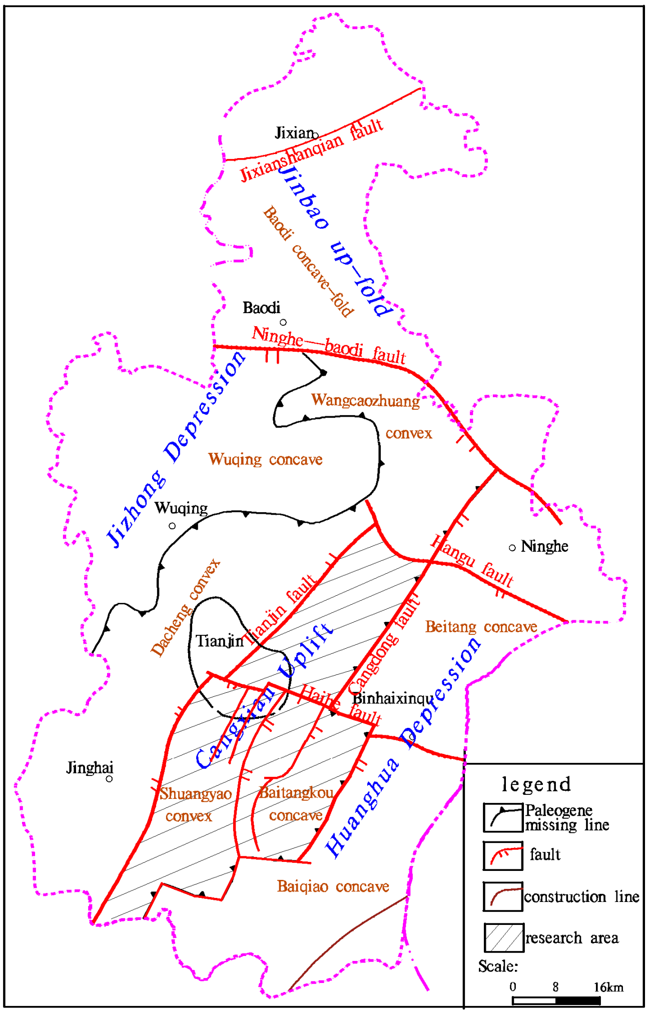

FIGURE 2: The regional tectonics and location of research area in Tianjin

The Baitangkouxi fault is a normal fault, the overall direction is to the north-northeast, the trend is south-southeast, and the angle of inclination is between 30° and 50°. It is the boundary between the Shangyao convex and the Baitangkou concave.

The Tianjin fault is a normal fault moving north-northeast; the tendency is north-northwest. The angle of inclination is between 45° and 65°. The fault marks the boundary between the Dacheng convex and the Shuangyao convex; it also divides the Dacheng convex and the Panzhuang convex.

2.2 Geothermal reservoir

There are two types of geothermal reservoirs in Tianjin. One is a closed clastic rock subsystem where geothermal water is present in pores. The other is a semi-open and semi-closed bedrock subsystem where the geothermal water is present in a karst formation.

From the top to the bottom, the reservoirs are Minghuazhen group reservoir (Nm), Guantaozu group reservoir (Ng), Dongyingzu group reservoir (Ed), Ordovician reservoir (O), Cambrian reservoir (Є) and Wumishan group reservoir (Jxw) (Table 1 and Figure 3) (Wang Kun, 2008a).

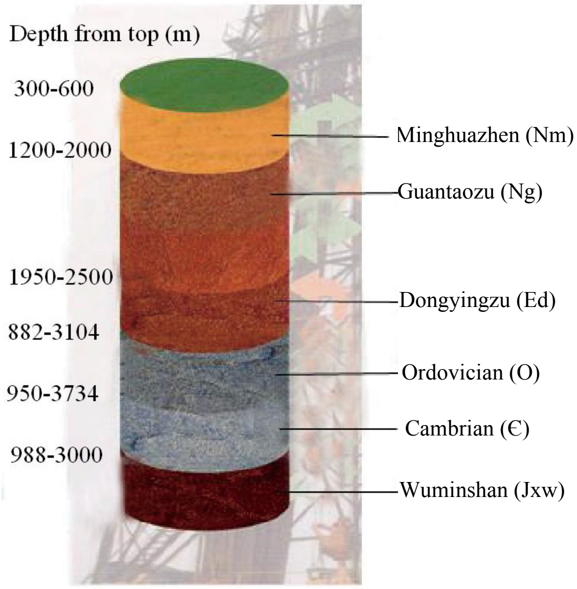

FIGURE 3: Sketch of geothermal reservoir in Tianjin

The Minghuazhen (Nm) group reservoir is found south of the Nihe-Baodi fault. The top is at 300-600 m depth and the bottom at 589-1996 m depth. The unit production is 0.76-5.43 m^3/h·m and the steady temperature of geothermal fluids is 40-70°C at the wellhead. The chemical types of the geothermal fluids are HCO_3-Na, HCO_3·Cl-Na and SO_4·Cl-Na. There are 92 geothermal wells of which 3 are reinjection wells. The reinjection wells have not been used this year.

Guantaozu (Ng) group reservoir is mainly located in the depression area and has a thickness of 100-200 m. The unit production is 0.52-5.13 m^3/h·m and the steady temperature of the geothermal fluids is 55-80°C at the wellhead. The chemical types of the geothermal fluids are HCO_3-Na and HCO_3·Cl-Na. There are 114 geothermal wells (7 reinjection wells). The geothermal fluids are mainly used for space heating, planting, farming, bathing and hot water.

TABLE 1: Main characteristics of primary geothermal reservoirs in the Tianjin area

Geothermal reservoir	**Lithology**	**The top depth (m)**	**Outflow temp. (°C)**	**Flow rate (m^3/h·m)**	**Hydrochemistry**	**Quality assessment**
Minghuazhen	Sandstone, silty sandstone	300-600	40-70	0.76-5.43	HCO_3-Na SO_4·Cl-Na	Good
Guantao	Sandstone w. gravel	1200-2200	55-80	0.52-5.13	HCO_3-NaHCO_3·Cl-Na	Good
Dongying	Sandstone	1900-2500	75-93	0.33-0.34	HCO_3-Na Cl·HCO_3-Na	Good
Ordovician	Limestone	882-3104	48-76	1.62-7.94	SO_4·Cl-Na, HCO_3·Cl-Na	Highly corrosive
Cambrian	Limestone	950-3734	70-80	2.11-3.13	HCO_3-Na HCO_3·SO_4-Na	Highly corrosive
Jixianian	Sandstone dolomite	988-3000	79-105	6-12	HCO_3·SO_4-NaCl-Na	Good

Dongyingzu (Ed) group reservoir mainly lies in the Wuqing district of the Jinzhong depression and the Tanggu district of the Huanghua depression. In the Jinzhong depression, the top is at a depth of about 2500 m, the unit production is about 0.33 m^3/h·m, and the steady temperature of the geothermal fluids is 90-93°C at wellhead. The chemical type of geothermal fluid is HCO_3-Na. In the Huanghua depression the top is at about 1900 m depth, the unit production is about 0.34 m^3/h·m, and the steady temperature of geothermal fluids is 75°C at wellhead. The chemical type of geothermal fluid is Cl·HCO_3-Na. There are 5 geothermal wells (1 reinjection well); the geothermal fluids are mainly used for space heating.

The Ordovician reservoir (O) is distributed unevenly in the Tianjin area that is buried deeply in the depression area. The top is at 882-3104 m depth, the unit production is 1.62-7.94 m^3/h·m, the steady temperature of geothermal fluids is 48-76°C in the wellhead, and the chemical types of geothermal fluids are SO_4·Cl-Na and HCO_3·Cl-Na. There are 34 geothermal wells (13 reinjection wells). In addition, there are 3 reinjection wells which inject water from the geothermal wells of the Jxw reservoir. The geothermal fluids from the Ordovician reservoir are mainly used for space heating, bathing and physical therapy.

The Cambrian reservoir (Є) is distributed unevenly in the Tianjin area, and buried deeply in the depression area. Its top is at 950-3734 m depth, the thickness is 14-1160 m, the unit production is 2.11-3.13 m^3/h·m, the steady temperature of geothermal fluids is 70-80°C at wellhead, and the chemical types of geothermal fluids are HCO_3-Na and $HCO_3·SO_4$-Na. There are 7 geothermal wells (4 reinjection wells). In the case of the Ordovician reservoir, there are 3 additional reinjection wells which inject water from the geothermal wells of the Jxw reservoir. The geothermal fluids from the Cambrian reservoir are mainly used for space heating and bathing.

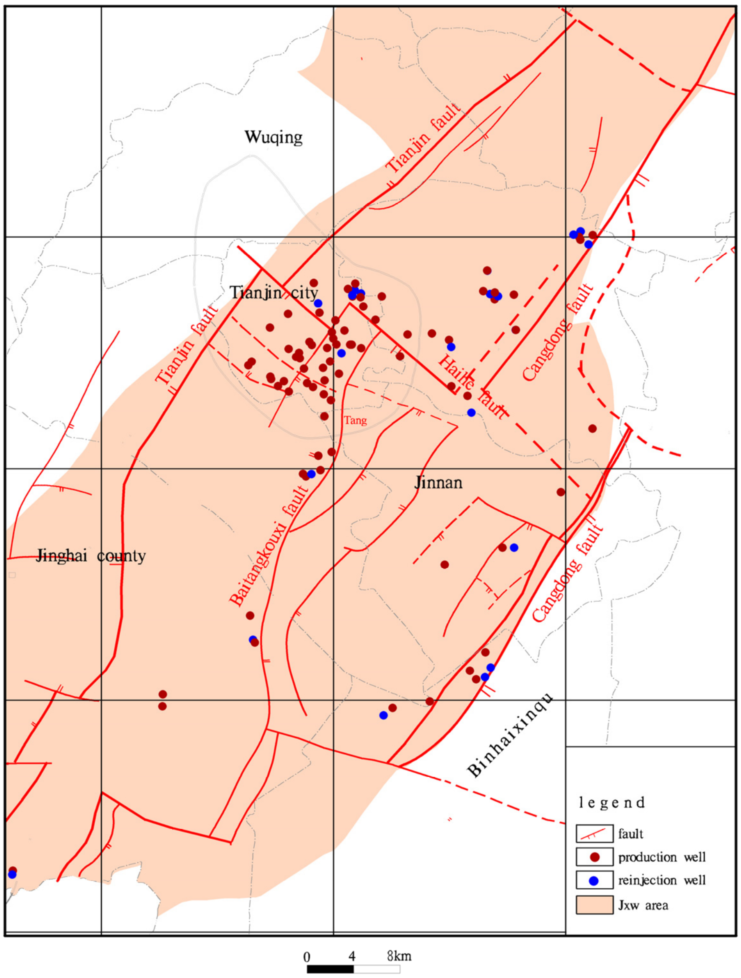

FIGURE 4: The distribution of the Wumishan group reservoir in Tianjin

The Wumishan (Jxw) group reservoir is widely distributed in Tianjin and the thickness is very large. The reservoir is primarily found in the uplift area (Figure 4). The depth to its upper boundary is 988-3000 m. The flow rate is around 100-200 m^3/h but near the Cangdong fault it reaches almost 380 m^3/h. The upper boundary of the reservoir is at progressively greater depths to the west. The karst fracturing is well developed in this reservoir and has formed strong storage capabilities. It is the main production reservoir for space heating in Tianjin. The Cangdong fault, Haihe fault and Baitangkou fault are all conductive faults for the Jxw reservoir. Along these faults, there is a zone of abundant water with a unit flow rate of 6-12 m^3/h/m.

2.3 Conceptual model of the Jxw reservoir

A conceptual model is a descriptive or qualitative model of a system or section of a system that incorporates the essential physical features of the system and is capable of matching the salient behaviour or characteristics of interest to the modeller (Grant et al., 1982). On the basis of the research on the geological conditions, the earth´s temperature field, the hydrodynamic field of geothermal fluids, geochemical analysis, geophysical exploration and well tests, the conceptual model of the Jxw geothermal system was constructed. In the model, the structure of the geothermal system, the heat source, cap rock, hot water flow paths, and recharge path are described. The conceptual model is shown in Figure 5 (Hu Y. et al., 2007; Wang Kun, 2001). The main elements of the conceptual model are as follows:

- The main reservoir formations vary in thickness. The utilized Jxw reservoir is mainly located in the range of the Cangxian uplift.
- The thermal resource is characterised by conduction-dominated heat-flow from the deep crust.

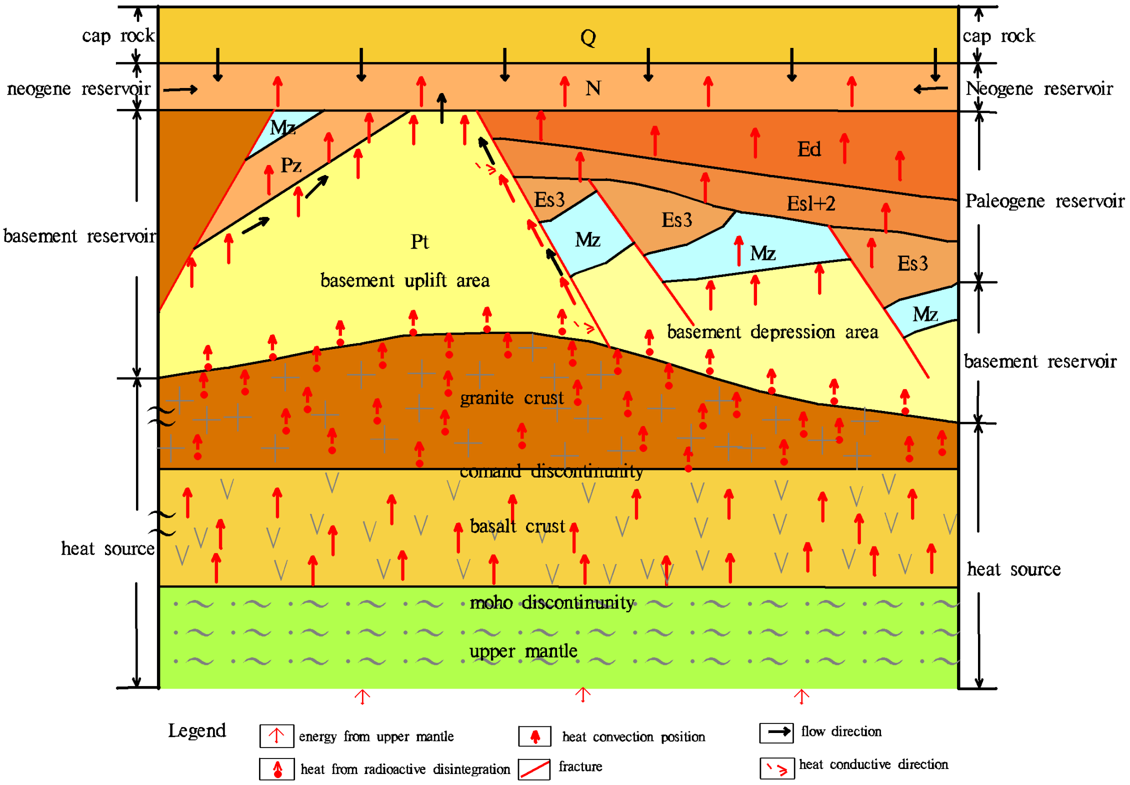

FIGURE 5: The conceptual model of Jxw reservoir in Tianjin

- The Quaternary and Tertiary formations have low thermal conductivity and permeability and act as a cap rock, which causes the permeable formations below to heat up.
- Permeable faults connect the different formations and act as paths for the geothermal fluids.
- The main hot recharge fault of the system is considered to be the Cangdong fault.
- From isotope analysis it is evident that the Tianjin geothermal fluids originate from ancient times.
- Precipitation with an age of 23- 24 ka BP has been sealed from Holocene to the present. It forms a closed deep circulation system.
- The Jxw reservoir belongs to semi-open and semi-closed bedrock subsystems, where the geothermal Karst fluids exist.

2.4 Exploitation and development history of the Wumishan group reservoir

Geothermal exploration started in the 1970s, at the proposal of Mr. Li Siguang, the former Minister of Geological and Mineral Resources. Through the geological surveys of gravity, temperature and drilling, two geothermal anomalous areas were discovered in the districts surrounding the urban area of Tianjin, covering an area larger than 1,000 km^2. The geological institutions carried out a series of exploration and research on geothermal resources in the 1980s, with the financial support of the former Ministry of Geology and Mineral Resources and the United Nations Development Program (UNDP).

By the end of the 1980s, the geothermal resources of Wumishan (Jxw) group reservoir were being used for space heating, greenhouses, hot water, therapy and potable water in Tianjin. The early geothermal utilization was simple and crude. The geothermal water was pumped directly into heating systems without heat exchangers. This resulted in heavy corrosion of the pipelines and, in addition, the high temperature of the waste water caused low heat efficiency and heat pollution.

Through the popularization of heat exchangers, frequency conversion, floor heating and automatic controlling techniques, and especially the success of reinjection tests in 1990s, the geothermal resources have been widely used in many cities due to economic planning. Along with the rapid growth of the real estate market, the demands for geothermal energy have increased enormously. There is rapid growth in the number of geothermal wells and the total area of space heating (Wang K. and Han J., 2007).

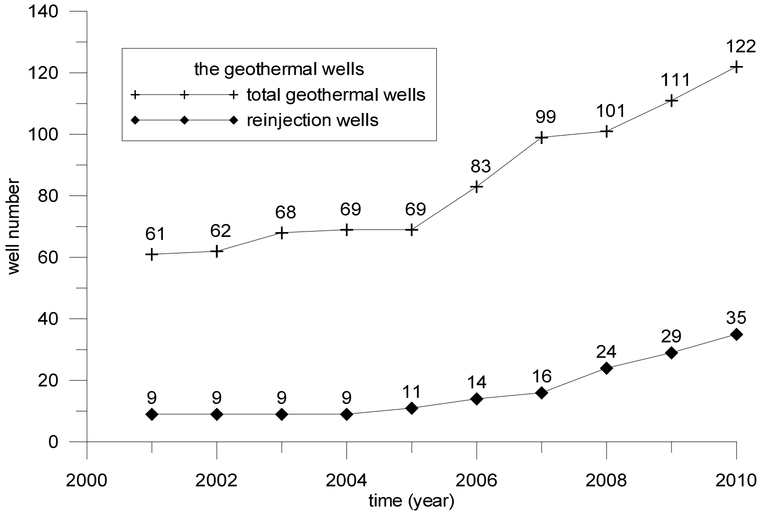

FIGURE 6: The increase with time in the number of geothermal wells in the Jxw reservoir

Figure 6 shows the increase in the number of geothermal wells in the area since the year 2000. Currently (end of 2010), there have been 122 geothermal wells drilled into the Wumishan group reservoir, of which 87 are production wells and 35 are reinjection wells. The detailed characteristics of typical geothermal wells can be found in Table 2 (Zhao Na, 2010; Li Junfeng, 2004). The total production volume was 1362.2 × 10^4 m^3 in 2010, which is an increase of 72.8 × 10^4 m^3 since 2009. The production volume of Jxw reservoir is 46.6% of the total production volume of the geothermal resources. There are 83 production wells and 35 reinjection wells in the study area. The reinjection volume was 550.4 × 10^4 m^3 in 2010, which corresponds to 40.4% of the production volume of the Jxw reservoir. The reinjection volume has increased by 66.5 × 10^4 m^3 since 2009 (Figure 7). The geothermal resources are used for space heating, breeding, planting, hot water and mineral water development, to name a few examples (Tian et al., 2010).

TABLE 2: Detailed characteristics of typical geothermal wells in the Tianjin area

Well no.	Well location	Drill. time	Top thickn. (m)	Well depth (m)	Production/ injection zone (m)	Reserv. temp. (℃)	Flow rate (m^3/h)
DL-19	Xindihe reservoir	1986.8	1805.5	1842	1805.48-1842	97	Artesian
DL-22	Guanzhuang	1997.1	2168	2546.42	2168-2546.42	94	176
DL-24B	In the east of Sihezhuang	2000.7	1870	2338.68	1870-2338.68	93.5	133
DL-38	Tianjin wanshun	2006.4	2004	2508.44	2004-2508.44	93.5	115.36
DL-40	Donglihu	2007.1	1794	2328	1794-2328	98.5	126
DG-45	Living area of Zhongtang town	2003	1930	2519.27	1930-2519.27	101	102
HB-02	21, Zhongfangqianjie	1999.1	2930	3506.8	2934-3506.80	86	108
HD-02	189, Weiguodao	1994.1	2644	2808	2644-2808	80.5	92
HX-14	Cunzhenli in Heiniucheng str.	1994.2	1641	1911	1641-1911	89.5	216.5
HX-25B	476, jiefangnanlu	1995	1502	1658	1502-1658	95	112
JH-02	Tangguantun	1996.3	2546	2777.5	2546-2777.5	84	100
JH-05	Daqiuzhuang in Jinhai county	1986	1664	2001.9	1664.0-2001.9	77	120
JN-07	Beizhakou in the Jinnna distr.	2004.6	1998	2618.58	1998-2618	92	140
XQ-07	Dasizhen across governmen	1985.4	1431.9	1610	1432-1610	84	72.2
XQ-13	Darenzhuang chem. compound	1999.9	3100	3470.8	3100.8-3470.8	95	100

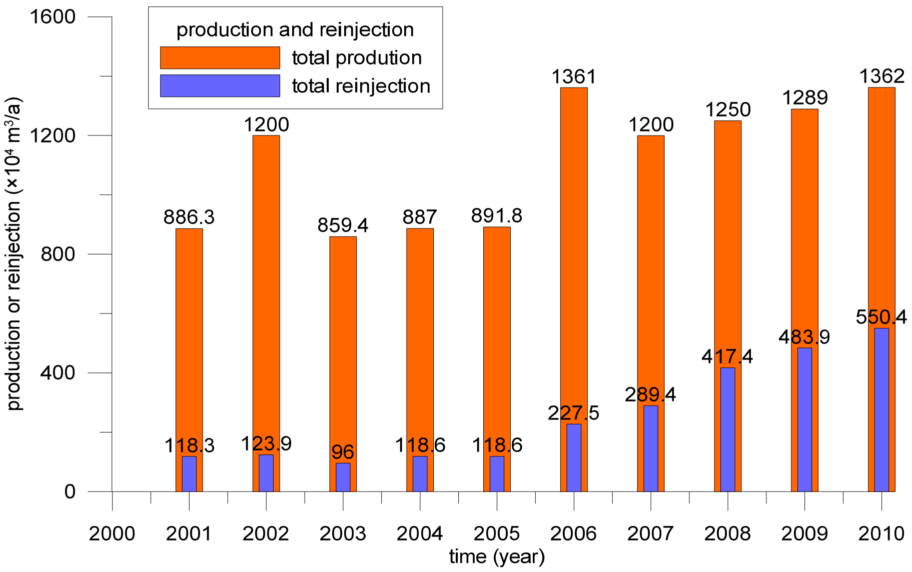

FIGURE 7: The production and reinjection wells in the Jxw reservoir

3. PRODUCTION AND MONITORING DATA

Dynamic monitoring of geothermal resources began in the late 1980s. All geothermal wells are monitored in Tianjin; in 2010 the production wells were 311 and the reinjection wells were 64. Some geothermal wells are monitored twice a month and are called important monitoring wells. Some geothermal wells are monitored once a month and are called general monitoring wells. In 2010 there were 90 important monitoring wells of the Jxw reservoir (Tian et al., 2010). After analysing the water quality, interpreting temperature and pressure logs, an annual report of geothermal dynamic monitoring is compiled using the dynamic monitoring data. Figure 8 shows the main production areas and wells of the Jxw reservoir.

The main work of geothermal resource monitoring includes (Wang Kun, 2008b):

1) An investigation of the production status of every geothermal station, such as its heating area or how many

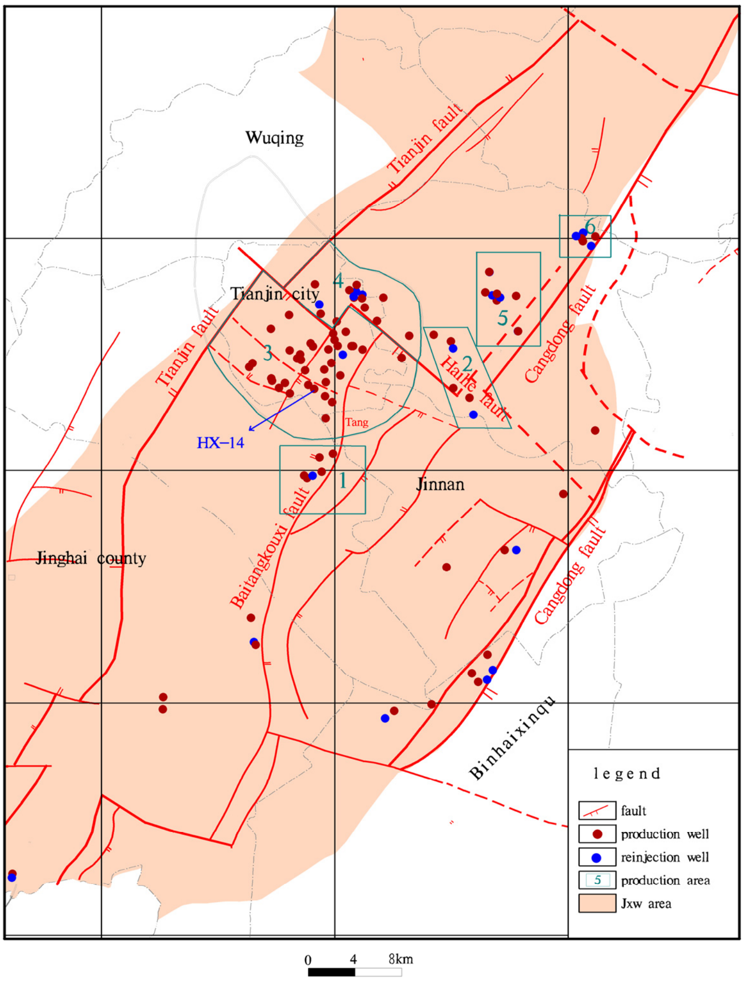

FIGURE 8: The six main production areas of Jxw reservoir

families are using geothermal water, and a status check of monitoring instruments, such as the thermometers and pressure gauges of geothermal wells.

2) Monthly collection of data on the water level, temperature and flow rate of production and reinjection.
3) Water samples are taken from controlling geothermal wells every winter. The samples cover the main geothermal fields, ranging from Tertiary to Proterozoic.
4) Analyzing the technical problems of production and reinjection in doublet systems during the space heating period, and taking note of possible technical faults, such as the decline in the reinjection rate and corrosion etc.
5) Predicting the developmental potential of the geothermal production and reinjection according to dynamic monitoring data.

3.1 Production data

Flow rate monitoring is an important part of the assessment of geothermal reservoirs. Too much production will result in a rapid decline of the water level. We have chosen six concentrated exploitation areas to calculate the total volume of production and reinjection. The six areas are shown in Figure 8. These are 1) the Dasi production area, 2) the Donglikaifa area, 3) and 4) two areas in the centre of Tianjin city, 5) the Konggang area and 6) the Donglihu area.

The volume of total production and total reinjection was calculated for the six areas and is shown in Figures 9-14. The number of production wells and reinjection wells is also shown there.

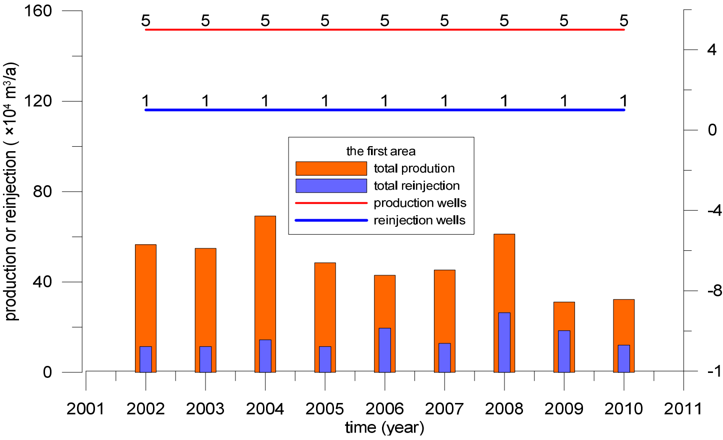

FIGURE 9: Production in area 1, the Dasi area

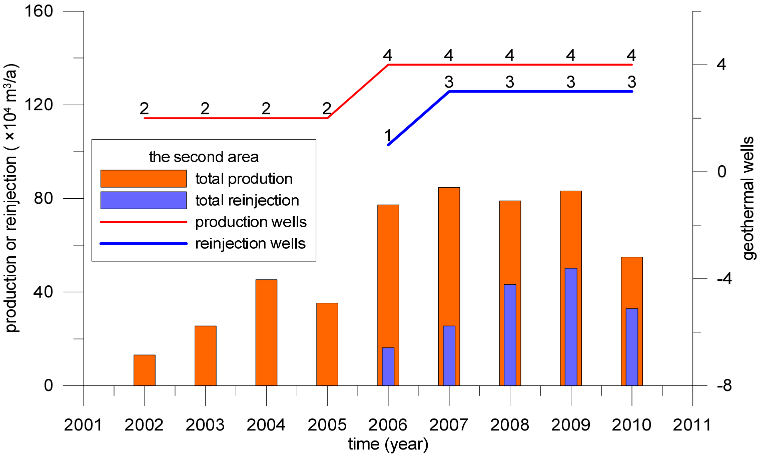

FIGURE 10: Production in area 2, the Donglikaifa area

In area 1, the production volume reached a maximum in 2004 and was at its minimum in 2009 (Figure 9). The production volume was relatively large before 2008 with some production wells being closed after 2008. In area 2, there was no reinjection before 2006, so the rate of production was only influenced by reinjection after 2006 (Figure 10). There are 4 production wells and 3 reinjection wells in the area. The reinjection volume needs to be added in order to keep the exploitation balance. Production from area 3 is very concentrated. The production volume is far greater than the reinjection volume. In 2010 there were 38 active production wells and only 6 reinjection wells (Figure 11). In area 4, the number of production wells and reinjection wells has been constant since 2002 (Figure 12). The production has also been fairly stable during the period, but the production peaked in 2008. Area 5, the Konggang area, is a new production field so there was no production before 2005 (Figure 13). During the first two years, there was only production with no reinjection. However, since 2007 over 70% of the geothermal fluids have been reinjected into the reservoir. In area 6, the Donglihu area,

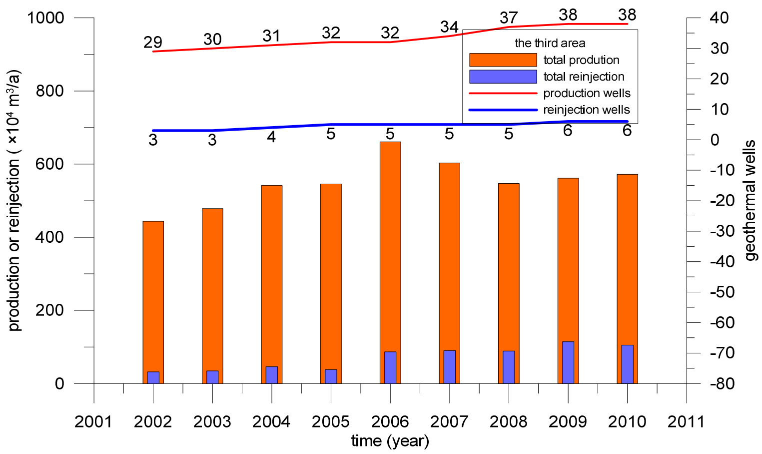

FIGURE 11: Production in area 3 in Tianjin centre

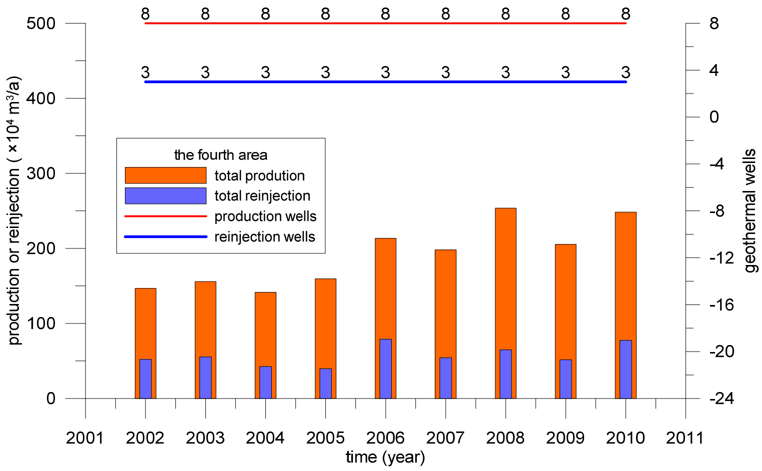

FIGURE 12: Production in area 4 in Tianjin centre

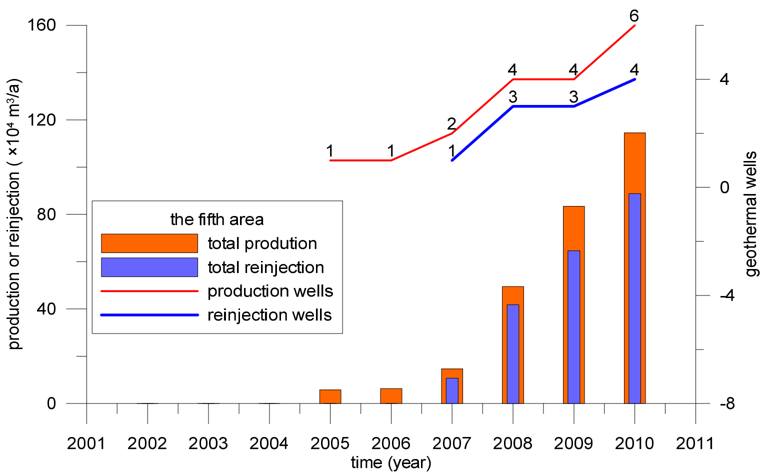

FIGURE 13: Production in area 5, the Konggang area

production was limited before 2007 (Figure 14). Since then it has grown continuously along with increased reinjection. There was no reinjection before 2007, but in 2010 there were 4 reinjection wells in operation.

According to the data from the six different production areas, the volume of both production and reinjection has been increasing in recent years. The number of production and reinjection wells has also increased. However, the number of reinjection wells is far lower than the number of production wells in areas 3 and 4. If we want to keep the balance of production and reinjection there, it is necessary to take measures. It is also impossible to drill new reinjection wells in the two areas now. A useful method to solve this problem would be to convert some production wells into reinjection wells.

3.2 Water level

In the natural state, the recharge, runoff and drainage of reservoir fluids keep a dynamic balance and the water level of the reservoir changes little. The development and utilization of geothermal fluids undermine that original state of dynamic balance. The most intuitive reaction is a change in the water level and pressure in the reservoir. The data collected through monitoring of the water level in geothermal wells can be used to estimate the state of the reservoir and to predict the future response to production. This provides a reasonable basis for developmental planning and scientific decisions on the utilization of geothermal resources; and illustrates the importance of monitoring the water level, temperature and production of the reservoir.

To eliminate wellbore effects, it is necessary to convert the monitoring data to uniform temperatures. Variations in the wellhead temperature between different measurements can cause changes in the water level which do not represent changes in the state of the reservoir. This report will use the same water column temperature as a uniform temperature in order to convert the observation data. The fluid temperature of geothermal wells and depth can be approximated to have a linear relationship due to thermal conduction properties. The water level is corrected by Equation 1:

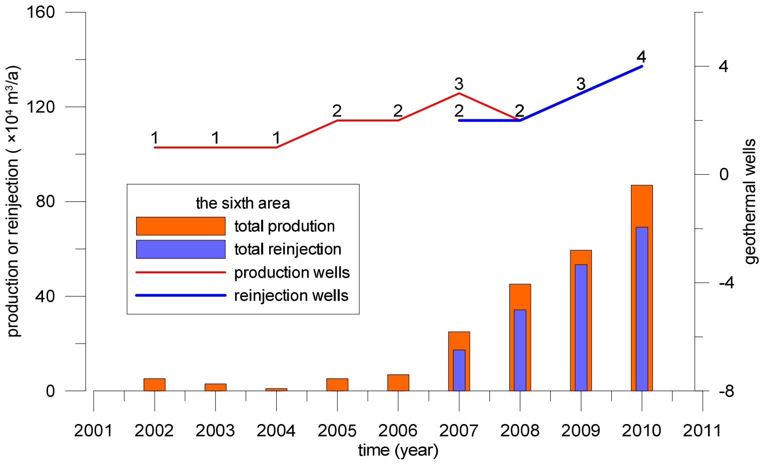

FIGURE 14: The sixth concentrated exploitation area

$$h = H - \frac{\rho_{average}[H - (h_1 - h_0)]}{\rho_1} \tag{1}$$

where h = The corrected water level (m);

H = The depth to the mid-point of the reservoir (m);

$\rho_{average}$ = Average density of the water column in the well, corresponding to the average of the wellhead and reservoir temperatures (kg/m^3);

h_1 = Monitored water level in the well (m);

ρ_1 = Density corresponding to the conversion temperature (kg/m^3); and

h_0 = Distance from the wellhead to the ground surface (m).

According to the relevant technical requirements for the different purposes of research and comparative analysis, the corrected water level was calculated using two conversion temperatures in Wumishan group reservoir:

1) The monitored water level was converted using the average surface temperature of 20°C in the area to show the conditions of the static and dynamic water level in order to introduce the pump depth of actual production;

2) The monitored water level of the Wumishan group reservoir was also converted using an average water column temperature of 60°C. This shows the conditions of the surface pressure distribution, providing basic information for the research and evaluation of the geothermal resources.

3.2.1 Regional water level

Using the monitoring data of the water level, we can get the regional water level distribution in 2010 (Figure 15). The water level of Jxw reservoir was at a depth of 62.6-130 m in 2010, gradually increasing from southwest Tangguantunzhen to Daqiuzhuang in Jinghai. On one hand, the depth of the water level has a good relationship with the properties of fault. The water level is relatively shallow along the deep conductive faults (for example Cangdong fault and Baitangxikou fault), but seems deeper closer to water blocking faults. Around the Tianjin fault, there is a depression cone where the maximum depth to the water level reaches about 130 m. The shallowest depth of the water level is found in the Tangguantun area southwest of Tianjin, where the depth of the water level is 62.6 m. On the other hand, the deeper water level also corresponds to larger production, for example in the areas 3 and 4.

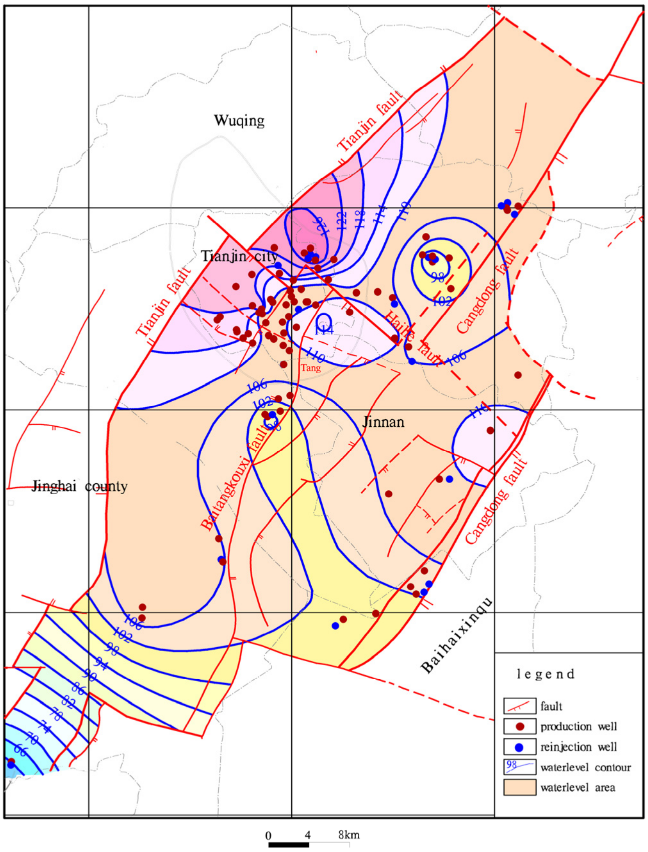

FIGURE 15: The contour of the water level in 2010 (20°C surface temperature)

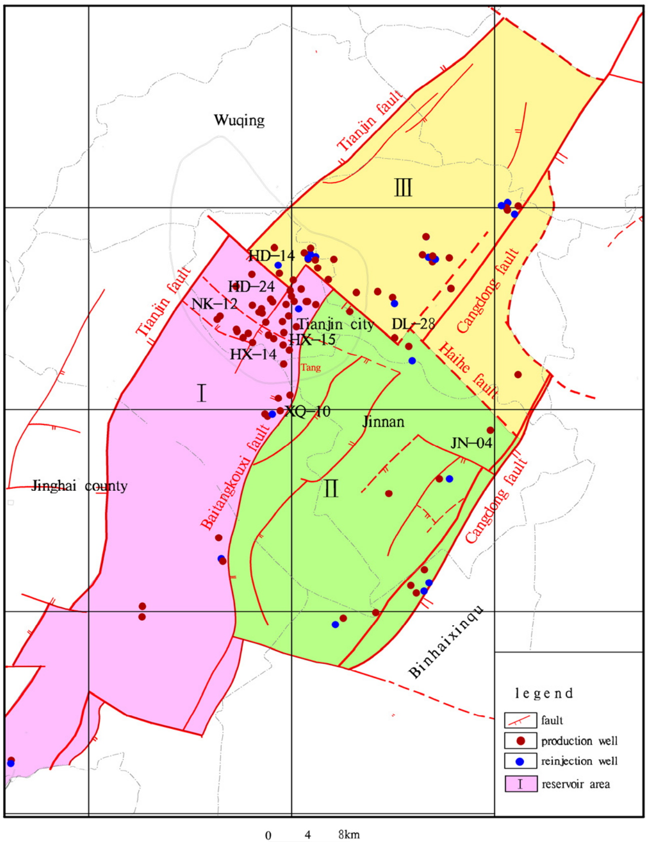

FIGURE 16: The three different zones of the Jxw reservoir in Tianjin

3.2.2 Water level of different areas

The geothermal wells of the Jxw reservoir are mainly located in the Cangxian uplift, where the exploitation areas are concentrated. The water level characteristics exhibit large differences in the geothermal wells, allowing the area to be divided into three zones, shown in Figure 16. The primary factors which influence the water level are faults of different properties, reservoir depth and exploitation conditions, etc. The study area is divided into three zones (Figure 16).

Area I: This area lies in the Suangyao convex of the Cangxian uplift, south of Haihe fault, west of Baitangxikou fault and east of Tianjin fault. The geothermal wells of this area are mainly located in the Hexi district, Hedong district, Nankai District and Jinghai County. Within it are 71 geothermal wells (including 18 reinjection wells). The top of the reservoir is at 1200-3200 m depth. The temperature of the geothermal fluids is 70-89°C at wellhead. The production rate in 2010 was 754.5 × 10^4 m^3 and the reinjection rate was 255.2 × 10^4 m^3. The depth of the static water level was 62-122 m (Figure 15); while the decline of the water level was 1-9 m/year in 2010.

Typical monitoring curves for the geothermal wells show clearly the changes in the production and water levels with time. Examples can be taken from wells HX-14, HX-15, HD-24, NK-12 and XQ-10. According to the monitoring curves of the water levels and production, the change in the water level has a direct relationship with production (Figures 17-20).

Wells HX-14 and HX-15 produce a lot during the winter heating period, when the instantaneous production of each well is 20-88 m^3/h, causing the water level to decline by 20-30 m. The recovery of the water level is very fast during the production stop after the heating period. The average water level decline was 5.69 m/year between 2001 and 2010 in well HX-14. In well HX-15, the average water level decline was 4.49 m/year. The difference between the two wells is due to less production in well HX-15 in the latter part of the period (Figures17 and18).

Well HD-24 did not produce in the period 1999-2002, but has been in production for space heating since 2003. Before 2003, the water level decreased during the heating period due to the influence of other production wells in the same reservoir and recovered after the heating period. The average decline of the water level drop was 0.3 m/year in this period. After the start of production in 2003, the average decline of the water level increased to 2.80 m/year for the period 2003-2010 (Figure 19).

Well NK-12 is a production well for space heating. It has an instantaneous flow rate of 56-70 m^3/h. During the heating period, the water level drops by 10-60 m but recovers rapidly during the summer period, when there is no heating. During 2001-2010, the average decline of the water level was 2.27 m/year (Figure 20).

Well XQ-10 is used for space heating and has an instantaneous flow rate of 30-58 m^3/h. The water level drops significantly in the heating period, by 10-30 m, but recovers rapidly after the heating period (Figure 21).

Summing up, most of the geothermal wells in area I have a large production volume. In spite of that, the drawdown of the water level is smaller in this area than elsewhere because the region is close to the Baitangkouxi fault which recharges the reservoir. The decline of the water level close to the Baitangkou fault is less than that close to the Tianjin fault.

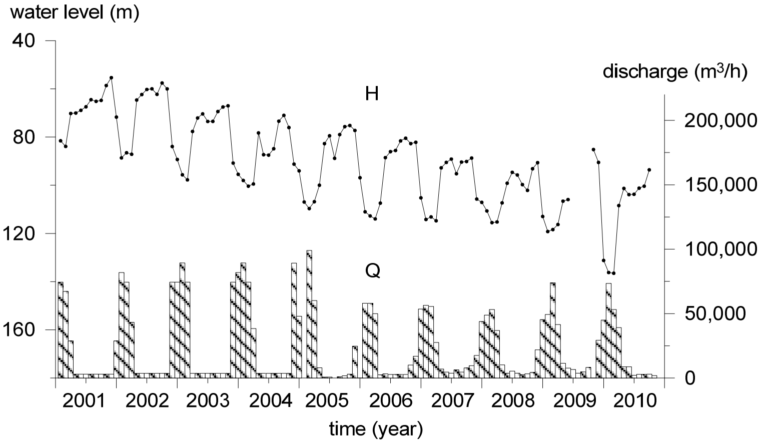

FIGURE 17: Production from well HX-14

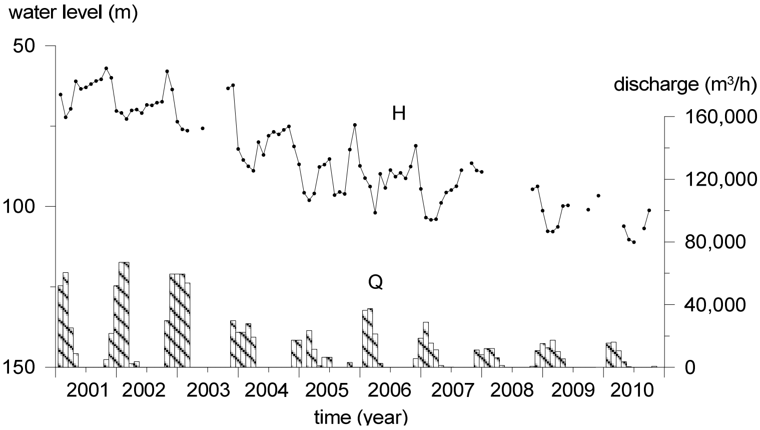

FIGURE 18: Production from well HX-15

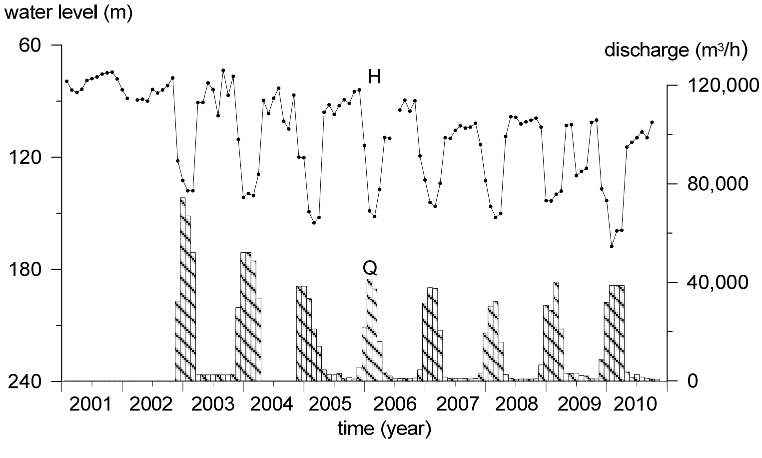

FIGURE 19: Production from well HD-24

Area II: This area lies in the Baitangkou depression and the Xiaohanzhuang convex of the Cangxian uplift, east of the Baitangxikou fault, south of the Haihe fault and west of the Cangdong fault. In the area, there are 23 geothermal wells (including 7 reinjection wells), mainly located in the Dongli district, Xiqing district, Jinnan district and Dagang district. The top of the reservoir is found at 1400-3600 m depth. The temperature of geothermal fluids is 84-98°C at wellhead, the production rate is

224.9×10^4 m^3, the reinjection rate is 130.5×10^4 m^3, the static water level is at 98-114 m depth (Figure 15), and the decline of the water level was 2-8 m/year in 2010.

Well JN-04 is within area II and has a long series of monitoring data. The well is mainly used for space heating and bathing. As there were problems with the monitoring equipment for some periods, the dynamic monitoring data of water level is not continuous. The instantaneous flow rate of the well is 30-80 m^3/h. The average decline of the water level was 5.64 m/year from 2001 to 2010 (Figure 22).

Area III: This area lies in the Panzhuang convex of the Cangxian uplift, north of the Haihe fault, east of Tianjin fault, west of the Cangdong fault and south of the Hangu fault. There are 33 geothermal wells (including 10 reinjection wells) in area III, mainly located in the Dongli district and Hedong district. The top of the reservoir is found at 1600-3000 m depth, the temperature of the geothermal fluids is 80-102°C at wellhead, the production rate is 327.8×10^4 m^3, the reinjection rate is 164.7×10^4 m^3, the depth of the static water level is 98-126 m (Figure 15), and the decline of the water level was 2-9 m/year in 2010 (Table 3).

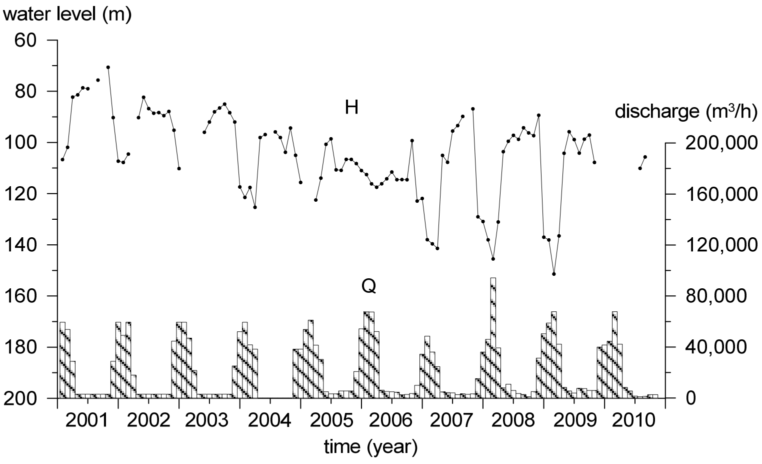

FIGURE 20: Production from well NK-12

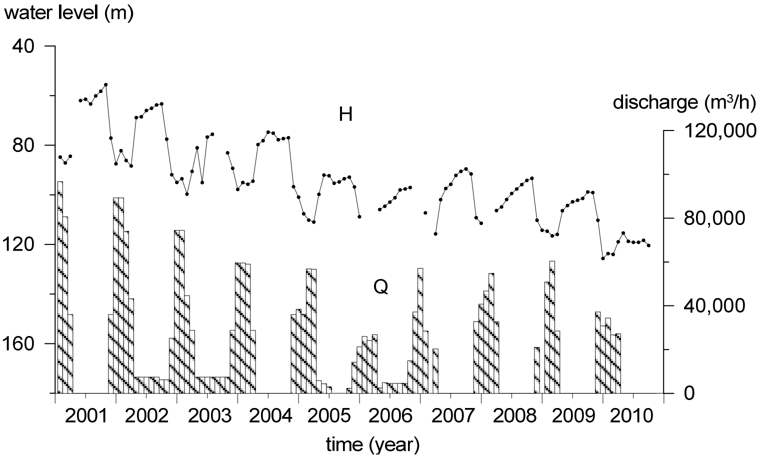

FIGURE 21: Production from well XQ-10

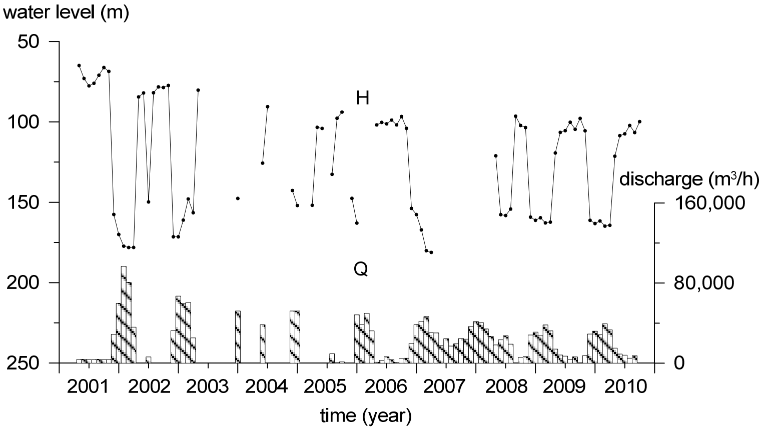

FIGURE 22: Geothermal well JN-04

3.3 Temperature

The geothermal field conditions of a region are a comprehensive reflection of the area's geological conditions and geological history. The main factors affecting reservoir temperature are cap rock thickness, bedrock depth and form, structural features, faulting, lithology, groundwater activity and magmatic activity, etc. The exploitation of geothermal resources has shown that the folding of the bedrock surface and faults are the main influence on the distribution of both regional and local geothermal fields.

Groundwater activities play the main roles in the piedmont and near fault zone. But the impact of recent intrusive activity is restricted to local sites.

TABLE 3: The depth (m) of the water level in monitoring wells in area III

Well no.	**2007**		**2008**			**2009**			**2010**		
	Water level		**Water level**		**Decline**	**Water level**		**Decline**	**Water level**		**Decline**
DL-28	Static	98.81	Static	102.26	3.45	Static	107.18	4.92	Static	111.35	4.17
	Dynamic	145.55	Dynamic	128.70		Dynamic	137.56		Dynamic	150.37	
HD-14	Static	104.71	Static	111.22	6.51	Static	113.18	1.96	Static	115.06	1.88
	Dynamic	143.79	Dynamic	143.52		Dynamic	142.21		Dynamic	158.39	

3.3.1 Regional temperature

The temperature distribution of a reservoir has a close relationship with the geological structures of the region. The geothermal anomalies with higher temperatures are located in anticline structures. Similarly, the temperature of the geothermal fluids is higher close to faults in the same convex unit. For example, the temperature of the geothermal fluids reaches 102°C close to the Cangdong fault on the Panzhuang convex in the Dongli district. The geothermal fluids commonly have high temperatures near the Haihe fault, Baitangxikou fault, Cangdong fault and cross-sections of the faults, which shows that these faults play an important role in controlling and conducting heat (Figure 23).

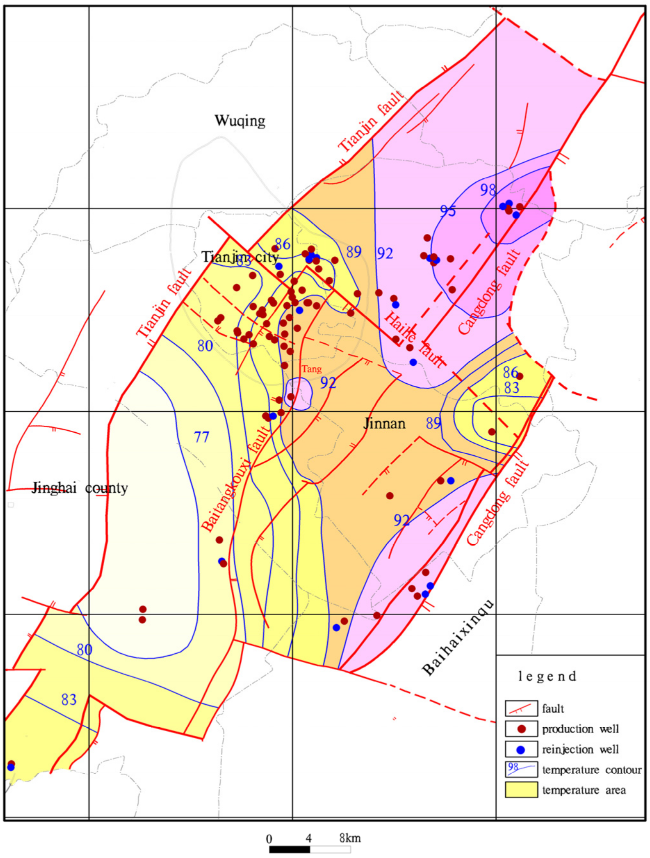

FIGURE 23: The temperature contours of the Jxw reservoir in Tianjin

3.3.2 Temperature of production wells

According to the temperature monitoring data of several typical production wells over some years, the static temperature at wellhead remains almost the same. This shows that the geothermal wells basically keep a steady temperature. The reservoir temperature shows no clear changes caused by long-term exploitation and utilization in Tianjin (Figure 24).

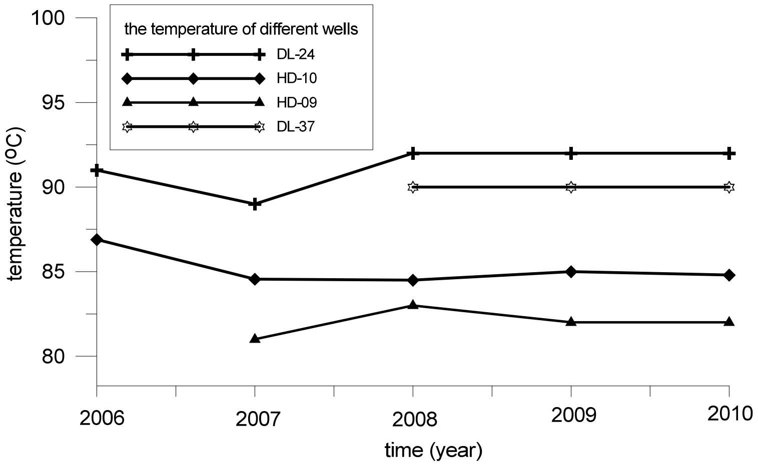

FIGURE 24: Temperature behaviour with time in different geothermal wells

3.3.3 Temperature of reinjection wells

It is important to monitor reservoir temperature under large scale reinjection conditions for a few years. Well HX-25B was chosen to obtain such monitoring data as it is a typical reinjection well which also had well logs. Here the same reinjection well is used to monitor the changes of the reservoir temperature by comparing temperature measurements made in different years after reinjection started.

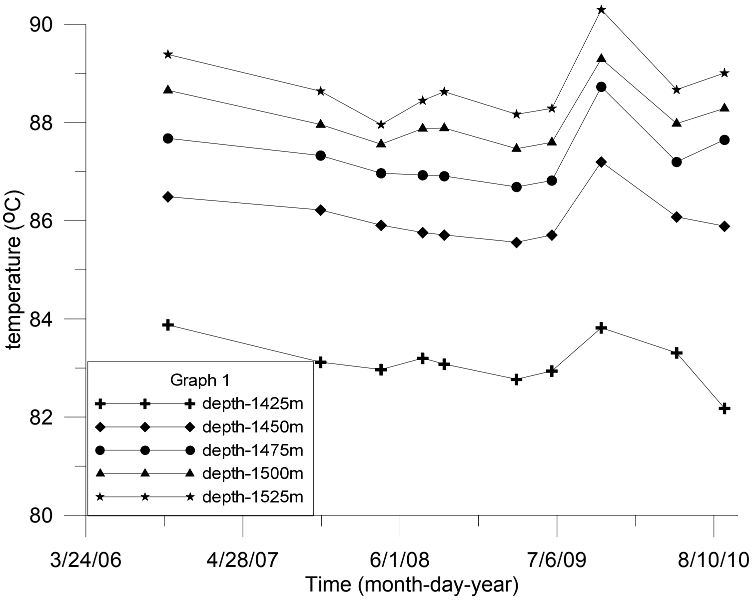

FIGURE 25: Temperature at different depths in well HX-25B

Reinjection well HX-25B has been in use since 1995. The annual reinjection rate is between 20 × 10^4 and 30 × 10^4 m^3; and some measurements of the reservoir temperature have been made in recent years. The temperature curves of the well (Figures 25 and 26) show that the temperature increases rapidly in the top 100-200 m of the well section, then more slowly until, at about 400 m depth. From there, the temperature increases linearly to the top of the crystalline bedrock at 1455 m. In the crystalline basement, there is a sharp increase in the temperature gradient because the thermal conductivity of fractured bedrock is large, the convection of geothermal fluids is strong, and the conditions for runoff are better.

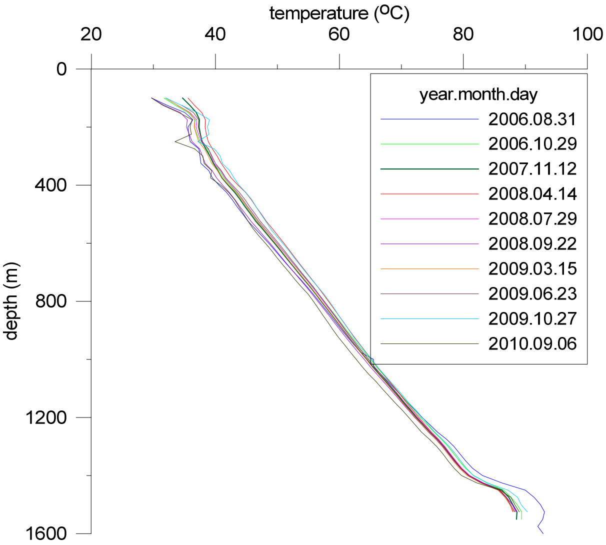

FIGURE 26: Well logs of geothermal well HX-25B made in different years

According to the temperatures measured in the wells, the highest temperatures are found close to the conductive fault zone. Furthermore, monitoring data confirm that there is almost no change in reservoir temperature as a result of exploitation or reinjection.

The reservoir temperature is between 80 and 102°C in the study area. Exploitation and reinjection do not seem to have influenced the reservoir in the short time the monitoring data covers. In order to study the changes in reservoir temperature, it is necessary to accumulate long-term temperature monitoring data in this reinjection well.

4. LUMPED PARAMETER MODEL

4.1 Lumped theory

The method of lumped parameter modelling has been used successfully for about two decades to simulate monitoring data from several low-temperature geothermal reservoirs in Iceland and elsewhere (Axelsson and Gunnlaugsson, 2000; Axelsson, 1989). A lumped model consists of a few capacitors or tanks that are connected by conductors or resistors. Figure 27 shows an example of a two-tank open model which has little recharge. The two tanks simulating the geothermal system are connected through permeable channels (resistors) with conductivity σ_1 and σ_2. Lumped simulators

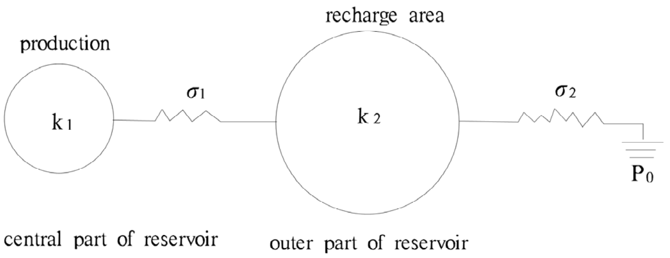

FIGURE 27: Two-tank open Lumpfit model

have been used to assess the production capacity of reservoirs by predicting future water level changes for various production scenarios.

Lumped parameter models can be set up by using the program LUMPFIT (Axelsson and Arason, 1992). The computer program automatically fits observed water-level or pressure change data with the model's production response by using a non-linear, iterative least-squares technique for estimating the model parameters. The parameters characterize the response of the model to production. The two main properties of the model are the storage coefficient of a tank (κ_i), and the flow conductance of a resistor (σ_i). The storage coefficient reflects the volumetric storage of different parts of the geothermal reservoir depending on volume, porosity and storage mechanism. The following formula is used for the storage coefficient in a case of compressibility controlled storage (Axelsson, 2003):

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

where V = Volume of the reservoir (m^3);
ρ = Liquid density (kg/m^3);
c_t = Total compressibility of the liquid-saturated formation (Pa^{-1}).

The total compressibility of the liquid-saturated formation is given by the equation:

$$c_t = c_w + (1-\varphi)c_r \tag{3}$$

where c_w, c_r = Compressibility of the water and rock, respectively (Pa^{-1});
φ = Porosity of the formation.

The conductance parameter (σ_i) reflects the fluid conductivity in the different parts of the reservoir and depends on permeability, viscosity, and geometry. The formula (assuming radial 2-D flow) is as follows:

$$\sigma_i = \frac{2\pi k_i h}{v \ln\left(\frac{r_{i+1}}{r_i}\right)} \tag{4}$$

where k_i = Permeability (m^2);
h = Thickness of the reservoir (m);
v = Kinematic viscosity of water (m^2/s);
r_{i+1}, r_i = Radii of different model parts (m).

4.2 Lumpfit results

4.2.1 Lumped model

In order to set up a lumped model, we need the monitoring data of the water level in a monitoring well which is believed to represent the conditions in the reservoir, and the total production from the reservoir as a function of the monitoring time. Geothermal well HX-14 was chosen as the monitoring well, with the production and water level monitored at the same time in this well. The well has continuous data of the water level and production with time from 1997 to 2010 (Figure 28). It is located in the area of concentrated exploitation, and represents the regional status there. Here, the water level of geothermal wells has declined rapidly as a result of production, so there are many reinjection wells to counteract the water level decline.

The distribution of the geothermal wells is divided into 6 areas close to the monitoring well (Figure 8). To investigate the zone of influence from production on the monitoring well, three scenarios were constructed.

1) The total production is taken as the production from the areas 3 and 4;
2) The total production is selected from the areas 2, 3 and 4;
3) The total production is selected from areas 1, 2, 3 and 4, with a total of 55 geothermal wells in these.

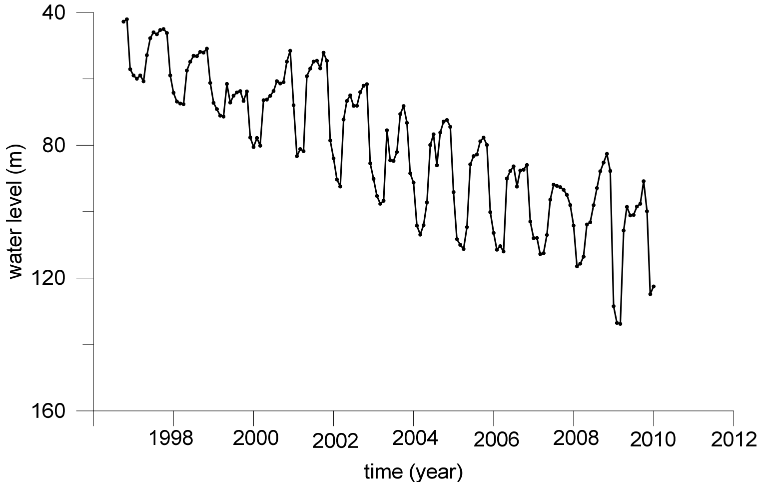

FIGURE 28: The water level of monitoring well HX-14 (60°C water column)

TABLE 4: The parameters of the two-tank open and three-tank closed lumped models for well HX-14 in Jxw reservoir

Number of tanks	2	3
Model type	Open	Closed
A1	0.0714	0.0717
L1	1.329	1.34
A2	0.00229	0.00132
L2	0.00414	0.00944
B		0.0011
K1	3444.06	3627
K2	114008	109430
K3		136202
Σ1	17.8	17.8
Σ2	18.7	22.14
Coeff. of determ. (%)	90.8	90.4
R.m.s misfit (m)	6.39	6.5
Standard deviation (m)	6.48	6.6

The production input in Lumpfit was set equal to the total production minus the total reinjection for the different cases. The results of the lumped models for the three scenarios showed that the third one gives the best fit to the water level data.

These results show that the water level in well HX-14 is influenced by the production in all four areas. The reason for this is that the Baitangkou, Cangdong and Haihe faults are conductive faults that supply fluids to the geothermal system in the Jxw reservoir. As a result, pressure changes due to production migrate rapidly between the areas.

4.2.2 Lumped results

After the data was prepared, different models were tried in Lumpfit with a varying number of tanks. The two-tank open model and the three-tank closed model gave the best results. Table 4 shows the parameters of the lumped models. Comparing the two models shows that the two-tank open model gives a slightly better fit to the data than the three-tank closed model. This indicates that there is some recharge to the area of concentrated exploitation. However, it is not known where the recharge comes from. Figure 29 shows the measured water level of well HX-14

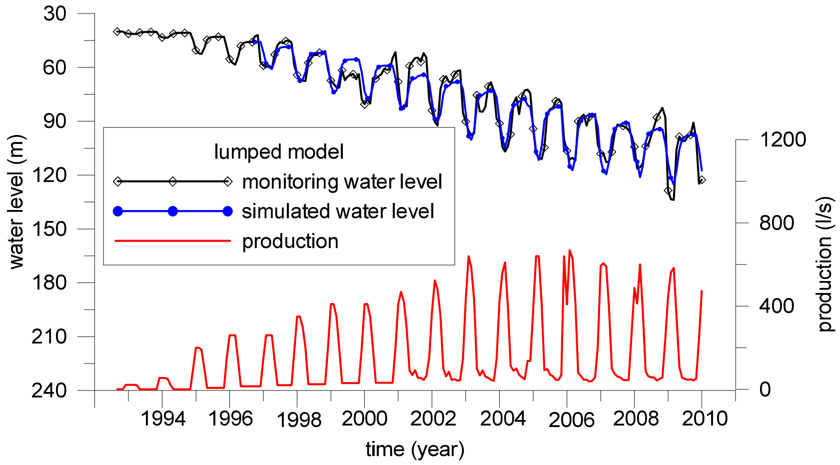

FIGURE 29: Measured water level in HX-14 and simulated water level for the two-tank open model

compared with the simulated water level by the two-tank open Lumpfit model.

4.2.3 Lumped predictions

In order to assess the production potential of the Jxw geothermal system, the lumped parameter model was used to predict water level changes caused by long-term production. Three production scenarios were calculated for the reservoir, using the best-fitting two-tank open model (Table 5).

The heating season was assumed to be 125 days; hence, the non-heating season was 240 days during the prediction period. During the heating season, the production is large and during the non-heating season it is small. Using this model, the water level was predicted for the next 10 years (Figure 30), starting from 2010.

TABLE 5: The water level predicted results of a lumped model for three cases

Cases	**Largest production(l/s)**	**Smallest production (l/s)**	**Lowest water level in 2020 (m)**	**Highest water level in 2020 (m)**
Case 1	584	44	151.39	123.2
Case 2	661	48	162	129.3
Case 3	546.6	43.5	149.14	121.4

Case 1: Production kept a constant value, the same as in 2010. The largest regional production was 584 l/s, the smallest regional production was 44 l/s. According to the two-tank open model, at the end of the simulation period in 2020, the lowest water level was at 151.39 m and the highest at 123.2 m (Figure 30).

Case 2: Production was increased by 10% compared to 2010, but reinjection kept at the same value as in 2010. The largest regional production was 661 l/s, while the lowest regional production was 48 l/s. According to the two-tank open model, the lowest water level was 162.0 m and the highest 129.3 m, at the end of the simulation period in 2020 (Figure 30).

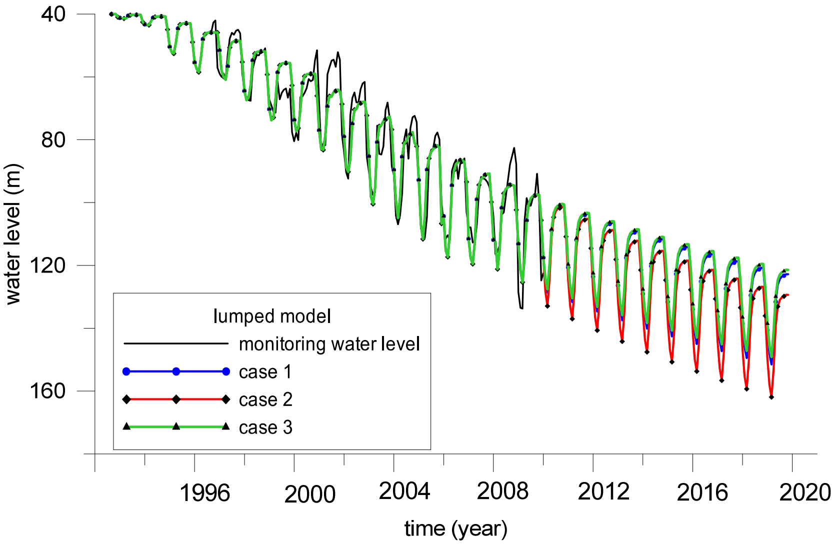

FIGURE 30: Monitored and predicted water levels for the two-tank open model

Case 3: Reinjection was increased by 10% compared to 2010, but production was kept at the same value as in 2010. The largest regional production was 546.6 l/s, the smallest regional production was 43.5 l/s. According to the two-tank open model, the lowest water level was 149.14 m and the highest 121.4 m, at the end of the simulation period in 2020 (Figure 30).

Comparing the three cases, it can be seen that the water level is influenced by the volume of production and reinjection. If we want to prolong the life of the geothermal field, it is very important to increase the reinjection or reduce the production. Presently, it is difficult to reduce the current production capacity making it necessary to increase reinjection.

5. SIMPLE NUMERICAL MODEL

In this report, numerical distributed parameter modelling was carried out by the TOUGH2 computer program (Halldórsdóttir, 2010). TOUGH2 is a general purpose numerical simulation program for multi-dimensional fluid and heat flows of multi-phase, multi-component fluid mixtures in porous and fractured media (Pruess et al., 1999). The chief application areas are in geothermal reservoir engineering, nuclear waste isolation studies, environment assessment and remediation, and flow and transport in variably saturated media and aquifers (Elmroth et al., 1999).

5.1 Simple numerical model for Tianjin Jxw reservoir

In general, a simple numerical model consists of a number of grid blocks (elements) connected to each other. Each element is assigned an appropriate rock type, which has certain permeability, porosity, and other properties partly based on the reservoir's geology.

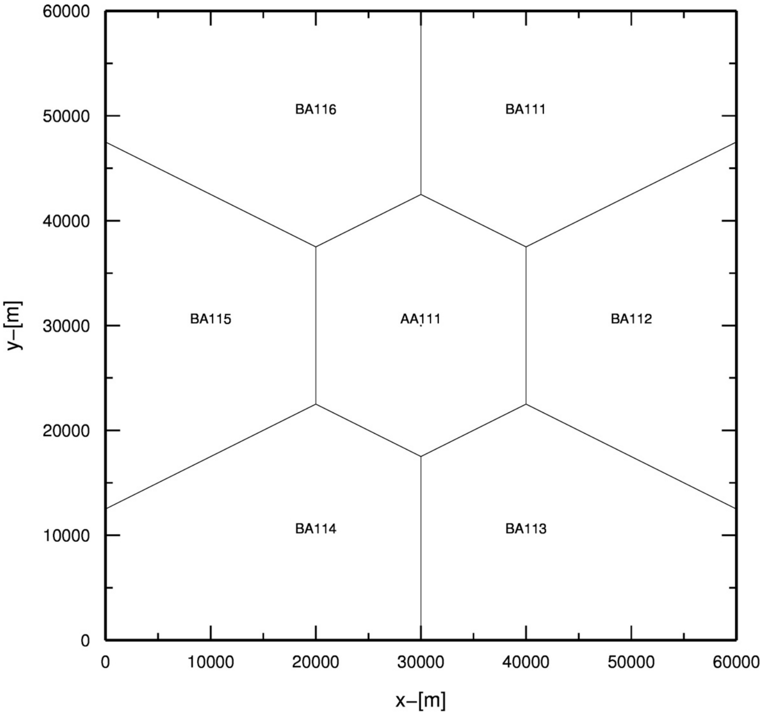

FIGURE 31: Mesh for Jxw reservoir of Tianjin geothermal system, a simple numerical model

The Jxw reservoir covers an area of 2048 km^2 in Tianjin, which lies approximately in the area of the Cangxian uplift (Figure 2). Only Jxw reservoir was addressed in this simple numerical model. The model grid is shown in Figure 31. The concentrated production area is 20 km × 20 km, represented by the inner grid element, and the outer elements represent the recharge areas. The inner element name is AA111 and is active; the 6 outer elements are inactive, which means that they keep a constant pressure and temperature (Gylfadóttir, 2010). According to the basic properties of the Jxw reservoir, the system is at a depth of 2000 m and the reservoir thickness is set to 800 m. The temperature is 90°C and the initial pressure is 24.6 MPa.

5.2 Results

5.2.1 Simulated results

In general, detailed data on geology, hydrogeology, temperature, pressure and long-term production and pressure response are needed for the development of a reliable detailed distributed parameter numerical model of a geothermal system. In this case, however, the study area is so large that it was very difficult to set up a more detailed model in such a short time. In this simple numerical model, the pressure, production and monitoring time are same as in the lumped model, which used data from well HX-14. The inner element (AA111) is the centre, Tianjin city and the area of concentrated exploitation, and outer elements represent recharge areas away from the city.

The outer elements around the inner element are considered the water supply. Hence, the corresponding rock type has higher porosity and permeability. The parameters in the simple numerical model were adjusted until a good match with the observed data from well HX-14 was obtained, as shown in Figure 32. Table 6 lists the parameters of the simple numerical model.

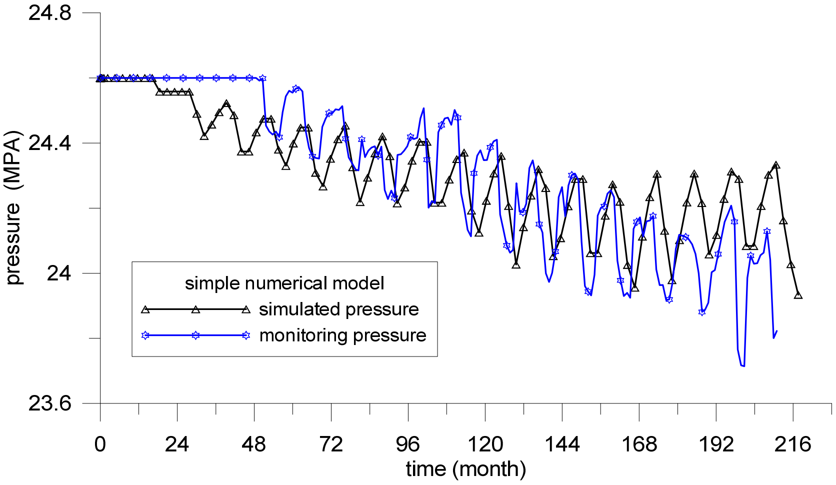

FIGURE 32: Observed and calculated pressures in well HX-14 (TOUGH2 model)

TABLE 6: Rock properties in the simple numerical model of the Jxw reservoir

Rock type	**Density (kg/m^3)**	**Porosity (%)**	**Permeability (m^2)**			**Thermal conductivity (W/m/°C)**	**Heat capacity (J/kg/°C)**
			X	**Y**	**Z**		
Proterozoic	2700	7	7.9×10^{-14}	7.9×10^{-14}	1.0×10^{-14}	2.0	900

5.2.2 Predicted results

Similar to the Lumpfit model, a simple numerical model was used to predict changes in the reservoir pressure in the three production cases already described. The results are presented in Table 7.

TABLE 7: The predicted pressure results of the simple numerical model

Cases	**Largest production (kg/s)**	**Smallest production (kg/s)**	**Highest pressure in 2020 (MPa)**	**Lowest pressure in 2020 (MPa)**
1	574.2	43.3	24.318	24.004
2	649.9	47.2	24.302	23.932
3	537.4	42.8	24.384	24.184

Case 1: Production kept at the same value as in 2010. The largest regional production is 574.2 kg/s, the smallest one is 43.3 kg/s. The predicted pressure is shown in Figure 33.

Case 2: Production is increased by 10% compared to 2010, while reinjection is kept the same value as in 2010. The largest regional production is 649.9 kg/s, the smallest regional production is 47.2 kg/s. The predicted pressure is shown in Figure 33.

Case 3: Reinjection is increased by 10% compared to 2010; while production is kept at the same value as in 2010. The largest regional production is 537.4 kg/s, the smallest regional production is 42.8 kg/s. The predicted pressure is shown in Figure 33.

According to the simple numerical model results, increasing reinjection and reducing production are good methods for protecting geothermal systems. It is very important to increase the reinjection flow rate in order to maintain sustainable use of the geothermal resources in the future.

In this simple numerical model, there was assumed a steady recharge. This means that the pressure reaches a balance after a few years of production (Figure 33). In reality, balance is not reached in such a short time, which indicates that in this model, the parameters are not reasonable, for example the boundary conditions, permeability, etc.

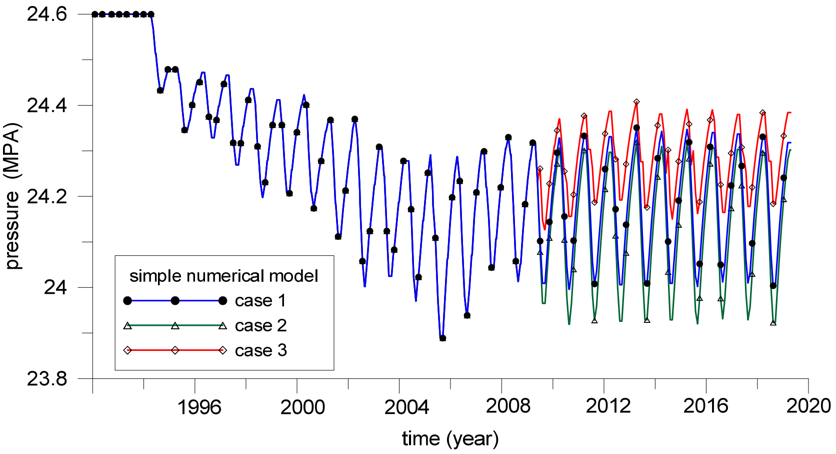

FIGURE 33: The predicted pressure changes of the simple numerical model (TOUGH2)

6. CONCLUSIONS

1) According to the geological conditions, the Wumishan group mainly lies on the Cangxian uplift and is the main geothermal production reservoir. The geothermal wells of this reservoir are mainly located in the centre of Tianjin city.

2) There are 122 geothermal wells that have been drilled into the Wumishan group, including 87 production wells and 35 reinjection wells. In 2010, the production rate was 1362.2 × 10^4 m^3 and the reinjection rate was 550.4 × 10^4 m^3.

3) According to the dynamic monitoring data, the depth to the water level is 62.6-130 m and the decline of the water level was 2-15 m in 2010.

4) The properties of faults influence the distribution of the water level in the study area. The water level is relatively shallow along the deep conductive faults (e.g. the Cangdong fault and the Baitangxikou fault), whereas the water level is relatively deep close to faults that obstruct water flow (such as the Tianjin fault).

5) Based on the dynamic monitoring data, a lumped model was set up for the concentrated exploitation area. Well HX-14 has been used as a monitoring well; the regional production was taken as the production around the monitoring well. A two-tank open model gave the best fit to the monitoring data. This indicates that there is some recharge to the area where mining is most concentrated, because there are conductive water faults around the monitoring well. Based on the Lumpfit model, three production scenarios for the concentrated exploitation area were set up:
   - Case 1 with production kept at a constant value, same as in 2010; case 2 increased by 10% compared with 2010, and case 3 with reinjection increased by 10% compared with 2010.
   - For case 1, the water level drops 26.6 m over the next 10 years if the same production is kept as in 2010, 24.3 m if reinjection is increased by 10% (case 3), and 37.2 m if production is increased 10% (case 2).
   - Comparing the three cases, it is obvious that the water level is influenced by production and reinjection. To prolong the lifetime of the geothermal fields, it is very important to either increase reinjection or reduce production. However, to maintain the current standard of living, production cannot be reduced. Therefore increasing the reinjection is the only choice.

6) Using the dynamic monitoring data, a simple numerical model was also set up for the study area. The area of concentrated production was set up as an inner element, encircled by an outer area that recharged the system. The model's parameters were calibrated using TOUGH2.

Using the simple numerical model, the change of pressure was predicted for the same three cases as for the Lumpfit model:

- The results show that the pressure would reach a balance if there is a steady recharge area around the area of concentrated exploitation. This is why it is important to increase reinjection for future development.

7) Future plans include the development of a more complicated model of the Wumishan group geothermal reservoir, the analysis of the water level of other reservoirs as well as the potential assessment of geothermal resources in Tianjin.

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