The United Nations University

GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

Reports 2006
Number 23

RESERVOIR EVALUATION FOR THE LISHUIQIAO-BEIYUAN GEOTHERMAL SYSTEM IN BEIJING, CHINA, BASED ON A SIX YEAR PRODUCTION HISTORY

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ABSTRACT

The Lishuiqiao-Beiyuan geothermal system in Beijing is a low-temperature sedimentary system with conduction-dominated heat flow and a reservoir temperature of about 80°C. Well SR-6, the first geothermal well in the field, was successfully drilled during the winter of 1999-2000 and has been used for district heating since November 2000. In order to make the most of geothermal resources in this area, three more geothermal wells were drilled in 2001-2002, of which well BY-1 has been used for district heating for two years now. Water level and production data from wells SR-6 and BY-1 and water level data from three observation wells have been utilized for simple reservoir modelling including lumped parameter modelling. The results indicate a system area on the order of 160 km^2 and a permeability-thickness as high as 80 Dm in the centre of the field. The permeability decreases towards the edges of the field and the average permeability is estimated to be around 10 Dm. Future water level predictions for both wells SR-6 and BY-1 show clearly the benefits of reinjection. Well SRG-1 is the reinjection well for SR-6, but the distance between the wells is only 230 m and cooling predictions show that there is considerable danger of cooling in SR-6 due to reinjection into SRG-1. Reinjection wells should, in general, be located at a greater distance from production wells. The Beijing government needs to put great emphasis on improved management of the geothermal resources under the city, including improved monitoring and increased reinjection.

1. INTRODUCTION

Beijing, the capital of the People's Republic of China, has been suffering from increasingly severe air pollution during the last decades, and the sky of Beijing is always grey, as is the case for many other cities in China. As the 2008 Olympic Games approach, the government of Beijing has adopted many countermeasures to control air pollution, including increased geothermal utilization. This is an effective method for counteracting pollution. Geothermal energy plays an important role in environmental protection and as an energy supply for Beijing. Geothermal energy has been utilized in the city for about three decades.

1.1 Beijing's geothermal fields

Beijing city is located at the convergence of two second-order tectonic units, the northwest part belongs to the Yanshan platform fold belt (often called W-Beijing uplift), and the southeast part is a part of the Huabei depression (see Figure 1).

Beijing City's location is also on top of a large and deep sedimentary basin where geothermal resources have been found at depth. These resources owe their existence to sufficient permeability at great depth (1-4 km) where the rocks are hot enough to heat water to exploitable temperatures. The sedimentary basin is characterized by a series of grabens and horsts, which are bounded by faults and fractures, mainly directed SW-NE. The most prominent feature in the geological complex is the Beijing Graben, which is 3.5 km deep, 15-20 km wide and 80 km long in a SW-NE direction with the centre of the Graben under Beijing City. Major faults and fractures play an important role in sustaining the geothermal activity by providing the main flow paths for circulating water as well as acting as aquicludes. The water recharge to the basin is believed to be precipitation falling in the hills and mountains on the outskirts of the basin, which percolates to great depth and, consequently, rises as hot water through some of the permeable faults and fractures.

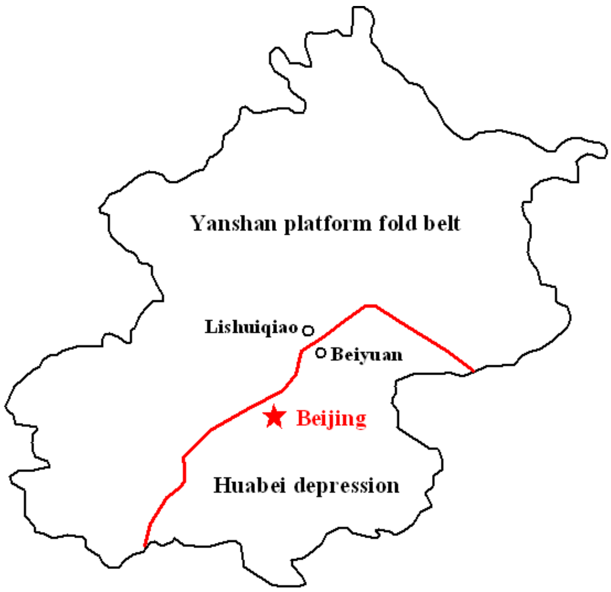

FIGURE 1: The two second-order tectonic units in the Beijing area; also shown is the location of the Lishuiqiao-Beiyuan area

There are 10 main geothermal fields in this Beijing plain with a total surface area of about 2370 km^2. At present, there are about 300 geothermal wells in and around Beijing City, with temperatures in the range of 44-88°C. The Shahe geothermal field is located in the northwest part of Beijing, south of the Xiaotangshan field, with an area of about 100 km^2 elongated NW-SE. The Lishuiqiao geothermal area is part of the Shahe geothermal field, located in the southeast part of the field.

1.2 Previous studies in the Lishuiqiao-Beiyuan area

The Lishuiqiao area is located in between the Baobaoshan and Huangzhuang-Gaoliying faults (see Figure 2), the two of which obviously play a major role in the productivity of geothermal wells in the area. The nature and potential of the area have recently been assessed by Axelsson (2001) and Xu (2002). They simulated the primary data collected on the response of the system to production using lumped parameter models. The simulation results of both studies show clearly that the Shahe reservoir is an almost closed system (with limited recharge). According to the model developed by Xu (2002), the surface area of the reservoir is about 110 km^2. The model also

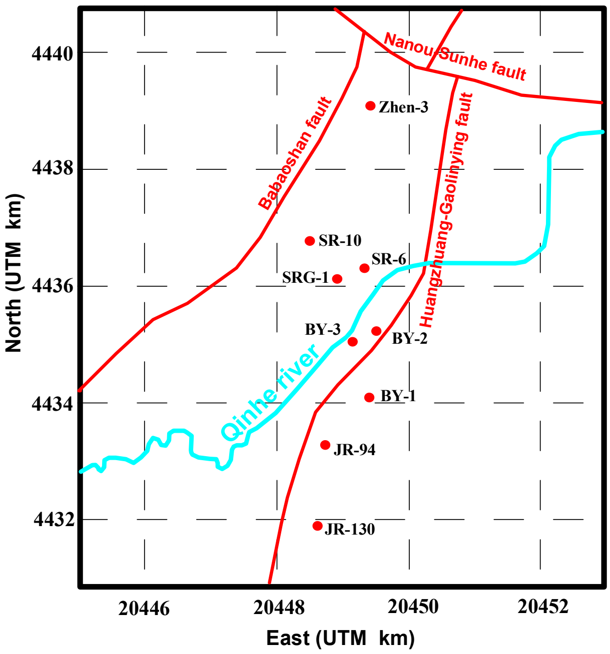

FIGURE 2: A simplified map of the Lishuiqiao-Beiyuan area in Beijing showing the locations of wells and major faults

indicates an average permeability thickness of about 19 Dm. This corresponds to an average permeability of about 0.04 Darcy, assuming a reservoir thickness of 500 m. In this report, the water level predictions for well SR-6 are calculated using lumped parameter models for several different future production scenarios, including scenarios with reinjection into a hypothetical reinjection well.

In 2001 *"A feasibility study for geothermal heating in Beiyuan Garden, Beijing, China*" was completed by Beijing Institute of Geo-Exploration and Technology (Ran et al., 2001). The report suggested that abundant geothermal resources exist in the Beiyuan Garden area that could be used for district heating. Following that, three wells were drilled in the area: BY-1, 2 and 3. The utilization of these wells started in winter 2004/2005. A detailed three-dimensional numerical model was developed by Hjartarson et al. (2005), based on primary data for wells in the Lishuiqiao-Beiyuan area. In 2004, a report was published by the Beijing Institute of Geo-Exploration and Technology, titled "*Geothermal resource assessment in the Olympic Park area*, *Beijing*" (Liu et al., 2004). This report summarized available information on the geothermal reservoirs in the Lishuiqiao-Beiyuan area, such as physical conditions, reservoir properties and the thickness of the reservoir units.

1.3 This work

Considerable additional data on the geothermal systems in the Lishuiqiao-Beiyuan area has been collected since the works of Axelsson (2001) and Xu (2002) were published. These include information collected through the drilling of new wells in Beiyuan Garden as well as production and water-level data from wells in the area for selected periods of different length. The purpose of this work was to assess and model these data in order to re-evaluate the properties of the geothermal system and predict the response of production wells during future utilization and reinjection.

2. AVAILABLE INFORMATION AND DATA

2.1 Formation lithology

The bedrock in the Lishuiqiao-Beiyuan area is composed of complicated geological structures and some questions on these have not been answered yet. A Quaternary formation covers all of the area, consisting of sand or clay. A Tertiary formation exists to the east of the Huangzhuang-Gaoliying fault, but is absent to the west of the fault. The thickness of the Jurassic formation increases from 680 m in the NW to 2380 m in the SW along a direction 65° W of N (see Figure 3). The main features of the formations in the area are presented in Table 1.

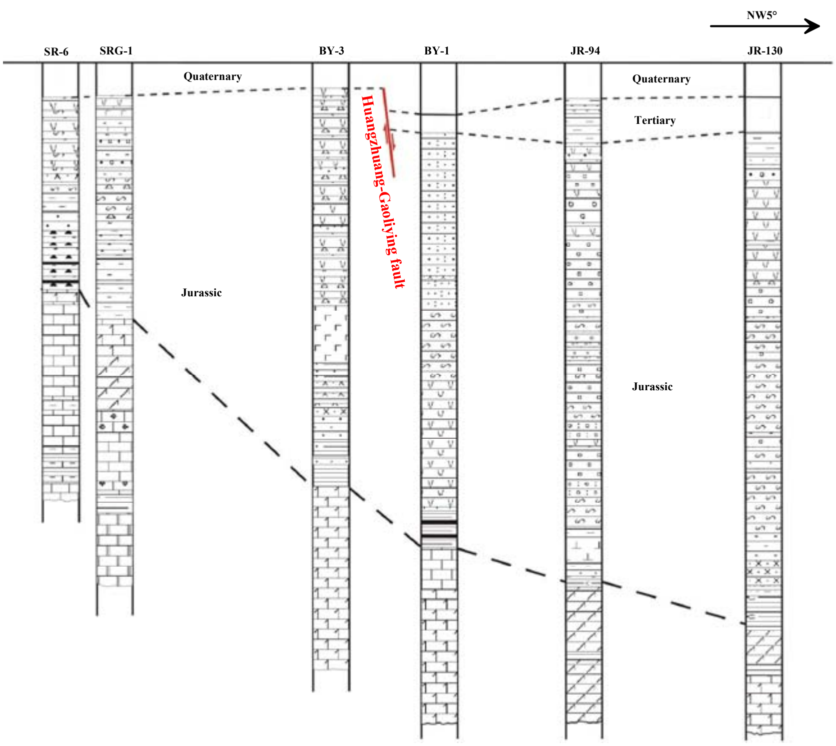

FIGURE 3: A geological cross-section through geothermal wells in the Lishuiqiao-Beiyuan area

TABLE 1: Physical features of the stratum in the Lishuiqiao-Beiyuan area

Stratum	Thickness (m)	Lithology	Density (g/cm^3)	Magnetic susceptibility ($10^{-6}cm^3/g$)
Quaternary (Q)	100-350	Sandy cohesive soil, fine sand	2	70-821
Tertiary (R)	240-370	Mudstone, sandstone and sandy conglomerate	2.25-2.45	62-104
Jurassic (J)	680-2380	Volcanic rock and andesitic pyroclastic rock, gritstone and conglomerate	2.6	76-4280
Permian-Carbonifer. (P-C)	295-532	Mudstone intercalated with coal	2.67	20-26
Ordovician (O)	700	Limestone and dolomitic limestone	2.7	10-40
Cambrian (Є)	500	Limestone and dolomite	2.7	5-18
Qingbaikou sys. (Q_n)	460	Sandy shale and carbonatite	2.69	6-46
Jixianxi Sys. (J_x)	2000-3000	Carbonatite and shale	2.8	6-46

2.2 Main reservoir features

The Permian and Carboniferous formations (P-C) are believed to act as the cap-rock for the geothermal system. The main aquifers are located in the Ordovician and Cambrian formations (O-Є) and in the Jixian system (J_x, Chinese classification). The O-Є consists of quite permeable limestone and dolomitic limestone while the Cambrian formation (Є) is missing in some wells. The Jixian system consists of limestone, shale and dolomite, which also hosts permeable aqufers. Temperature gradients of the reservoir formations are in the range of 1.3-2.0°C/100 m.

Information on the geothermal wells drilled in the Lishuiqiao-Beiyuan area is presented in Table 2 and discussed in more detail below:

TABLE 2: Geothermal wells in the Lishuiqiao-Beiyuan area

Well no.	Date of drilling	Reservoir rock	Depth (m)	Flowrate (l/s)	Temperature (°C)	Application of wells
SR-6	1999/2000	O-Є	2418	40	70	Production
SRG-1	2001/2002	O-Є, J_x	2898	19.3	59	Reinjection
SR-10	2001/2002	O-Є	2750	13.2	62	Observation
BY-1	2001	O, J_x	3648	28.5	74	Production
BY-2	2002	O, J_x	3238	28	73	Production
BY-3	2002	O	3349	21	68	Reinjection
JR-94	2001	O	3610	18.5	70	Production
JR-130	2000	O, J_x	3700	15	76	Reinjection

O: Ordovician Є: Cambrian J_x: Jixianxi System

2.3 Conceptual model of the geothermal system

Xu (2002) described the current conceptual model of the geothermal system under the Lishuiqiao area and presented the simplified sketch replicated in Figure 4. It is based on the results of geophysical prospecting and borehole geology. Up to now the conceptual model has not changed, since limited additional data has become available, but it will possibly be revised after completion of a geo-exploration project of the Beijing plain, which is to be finished in 2007. The main features of the conceptual model of Xu (2002) are presented in Figure 4.

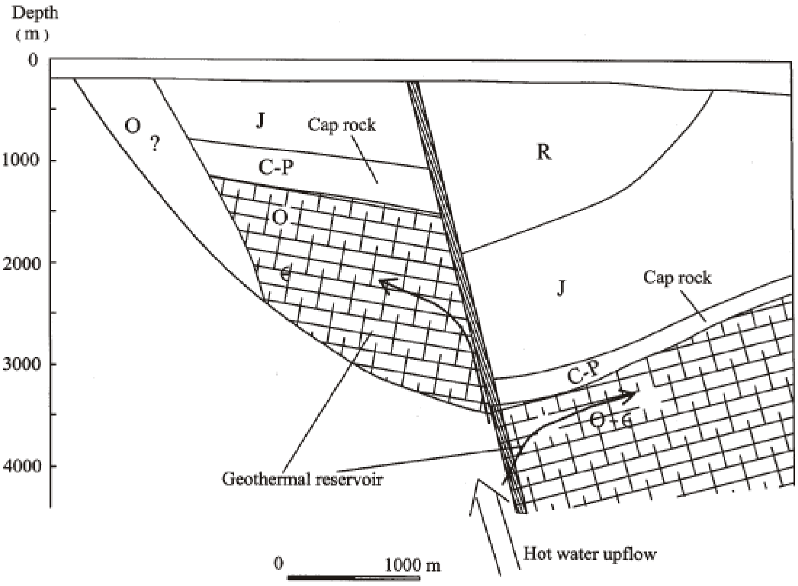

FIGURE 4: A simplified sketch of the conceptual model of the geothermal system below the Lishuiqiao-Beiyuan part of the Shahe geothermal field as presented by Xu (2002)

The reservoir is a low-temperature sedimentary reservoir, with conduction dominated heat-flow, and a reservoir temperature of about 80°C. The production reservoir is in Cambrian and Ordovician limestone formations, with an effective thickness of 460 m. The caprock is a Permian and Carboniferous formation (P-C). The Huangzhuang-Gaoliying fault plays a principal role in causing enhanced permeability and upflow of hot water from depth. Other faults may act as boundaries.

2.4 Current well status

In order to harness the geothermal resource in the Lishuiqiao-Beiyuan area, two companies, Beijing Institute of Geo-Exploration and Technology and Beijing City Tianyin Geothermal Development Company, drilled some geothermal wells in 1999-2002 (see locations in Figure 2 and information in Table 2).

Well SR-6, a highly productive well, is located in the backyard of Beijing Institute of Geo-Exploration and Technology. It has been used for space heating of 37,000 m^2 since November 2000 and for bathing as well as a swimming pool in a hotel on the premises that opened in December 2002. Well SRG-1, which is close to well SR-6, is designed as a reinjection well for well SR-6, and will be fully operational in the winter of 2006/2007. Well SR-10, at a distance of 755 m to the west of SR-6, has not been used for pumping, and is a good observation well for the geothermal system around SR-6.

Wells BY-1, BY-2 and BY-3, located in Beiyuan Garden, are utilized for a geothermal district heating system for the Beiyuan Garden Area 6 apartment complex. They are used for space heating in winter and for domestic hot water supply year round. Well BY-1 is used as the main production well and BY-2 as a supplementary production well; the production of the two wells is enough for the heating system at present. Well BY-3 is designed as a reinjection well for BY-1 and BY-2; its operation will start in the winter of 2006/2007.

2.5 Available monitoring data

The monitoring data available for the modelling effort are as follows:

1. Production history of well SR-6; includes the record of production from March 2000 to July

2006. Measured water level changes are divided into two parts because some water level records have been lost.
2. Data from well SR-10, including the water level history for about one and a half years.
3. Data from well SRG-1, including the water level history for about two years.
4. Data from well BY-1, including the water level history for about a year without production, and production and water level history for about one and a half years.
5. Production history of well BY-2 for about half a year.
6. Data from well BY-3, including the water level history for about a year.

3. ANALYSIS AND MODELLING OF DATA FROM WELLS

3.1 Utilization of monitoring data for well SR-6 for lumped parameter modelling

The production rate and water level data for well SR-6 for the last 6 years (March 2000 - July 2006) were available for this study. However, unfortunately a part of the water level history (April 2002 - December 2003) was lost. Thus, the water level history was divided into three parts: the first part with complete data, the lost data part and a third part with complete data. The waste water from well SR-6 has been injected into SRG-1 starting in winter 2002. This was done without sealing the wellhead and, therefore, when the borehole was full, the remainder of the water was drained to a waste plant through a waste pipeline. Thus, the reinjection ratio has been about 40%.

The water level simulation was approached as two cases, one using the total production data and the other incorporating 40% reinjection during the last 4 years. In the latter case, the reinjection was subtracted from the total production. Eventually, the case which resulted in a better lumped model simulation was selected and used as the basis for further modelling as well as being used to estimate the water level for the lost data period.

3.1.1 Lumpfit description

Axelsson (1989) described an efficient method that tackles pressure change simulation with lumped parameter models as an inverse problem and can simulate such data very accurately, if the data quality is sufficient, even very long data sets (several decades). It automatically fits the analytical response functions of the lumped models to observed data by using a non-linear iterative least-squares technique for estimating the model parameters.

The theoretical basis of the automatic method of lumped parameter modelling is presented by Axelsson (1989). Bodvarsson (1966) discussed the usefulness of lumped methods for interpreting geophysical exploration data. The computer code *LUMPFIT* has been used since 1986 in the lumped modelling studies carried out in Iceland and other parts of the world (Axelsson and Arason, 1992).

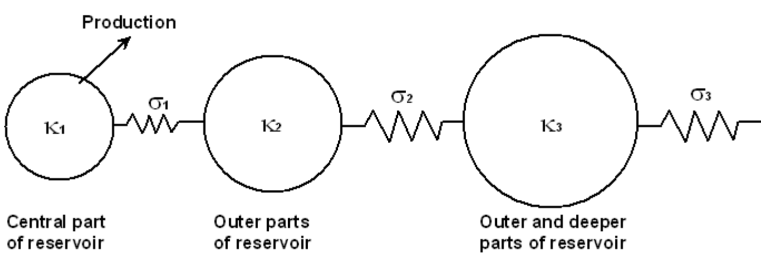

FIGURE 5: A general lumped parameter model used to simulate water level or pressure changes in geothermal systems (Axelsson, 1989)

A general lumped model is shown in Figure 5. It consists of a few tanks and flow resistors. The tanks simulate the storage capacity of different parts of a geothermal system and the water level or pressure in the tanks simulates the water level or pressure in corresponding parts of the system. A tank has storage coefficient (capacitance) κ when it responds to a load of liquid mass m with a pressure increase given by $p = m/\kappa$. The resistors (conductors) simulate the flow resistance in the reservoir, controlled by the permeability of its rocks. The mass conductance (inverse of resistance) of a resistor is σ when it transfers $q = \sigma\,\Delta p$ units of liquid mass per unit time, at the impressed pressure differential Δp.

The first tank in the model in Figure 5 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. The third tank is connected by a resistor to a constant pressure source, which supplies recharge to the geothermal system. The model is, therefore, open. Without the connection to the constant pressure source, the model would be closed. An open model may be considered optimistic, since equilibrium between production and recharge is eventually reached during long-term production, causing the water level draw-down to stabilize. In contrast, a closed model may be considered pessimistic, since no recharge is allowed for such a model and the water level declines steadily with time during long-term production.

The pressure response (p) of a general open lumped model with N tanks, to a constant production (Q) since time $t=0$, is given by the equation:

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

The pressure response of an equivalent N-tanks closed model is given by the equation:

$$\Delta p(t) = -\sum_{j=1}^{N-1} Q \frac{A_j}{L_j}\left[1 - e^{-L_j t}\right] - QBt \qquad (2)$$

The coefficients A_j, L_j and B are functions of the storage coefficients of the tanks (k_j) and the conductance coefficients of resistors (σ_j) of the model.

3.1.2 Estimating water level changes from April 2002 to December 2003

A total of 313 production rate values were available for the last 6 years, 205 for the first period, from March 2000 to April 2002, and 75 for the third period, from December 2003 to July 2006. As a first step of the simulation, water level data for the first period was simulated by *LUMPFIT* for the two production rate cases. The first case involved the production rate without reinjection, the other was based on the assumption of 40% reinjection over the last few years. The procedure for finding an adequate model fitting the observed data is as follows:

- First a single-tank closed model (1-C) is selected;
- Then an open one-tank model (1-O) is selected;
- After that a two-tank closed model (2-C) and a two-tank open model (2-O) follow;
- Finally, the upper limit of the program is three tanks (3-C and 3-O).

The program finds the best solution and calculates the coefficient of determination. Plotting the results and evaluating how well the model simulates the data, in particular the third period, we ended up with the most acceptable solution. The results for the following four cases are presented in Figures 6-9 which present a 3-C model without reinjection, a 3-O model without reinjection, a 3-C model with 40% reinjection and 3-O model with 40% reinjection. These models are termed models 1-4, respectively, and the model parameters are presented in Table 1 in Appendix I.

As a second step of the simulation for SR-6, water level data for the third period was simulated by *LUMPFIT*, again for the two cases. The results of the simulation are presented in Table 2 in Appendix I and in Figures 10-13.

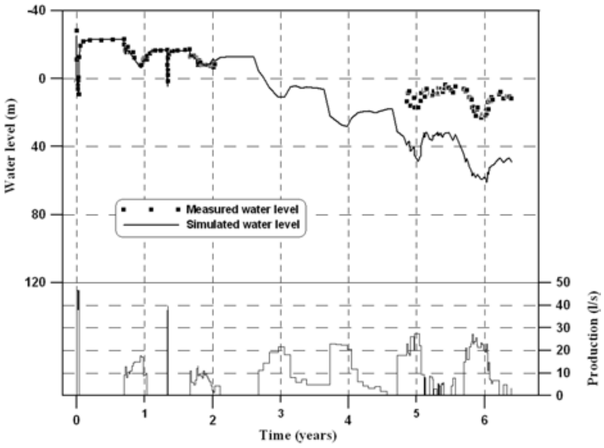

FIGURE 6: Model 1 –Three-tank closed model based on the first period and total production.

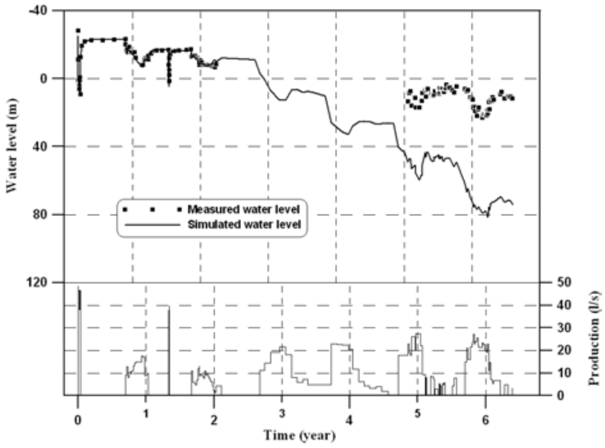

FIGURE 7: Model 2 – Three-tank open model based on the first period and total production

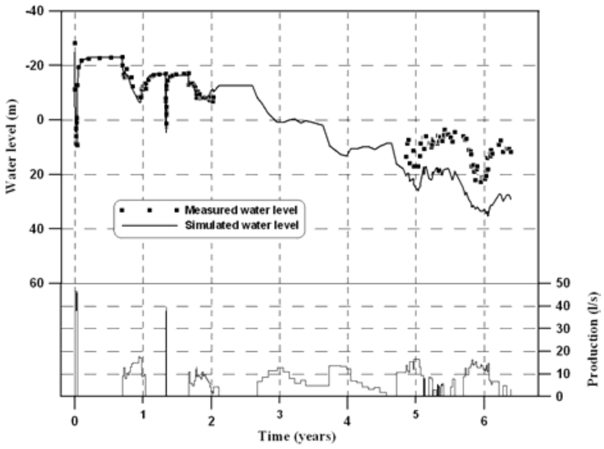

FIGURE 8: Model 3 – Three-tank closed model based on the first period and total production with 40% reinjection

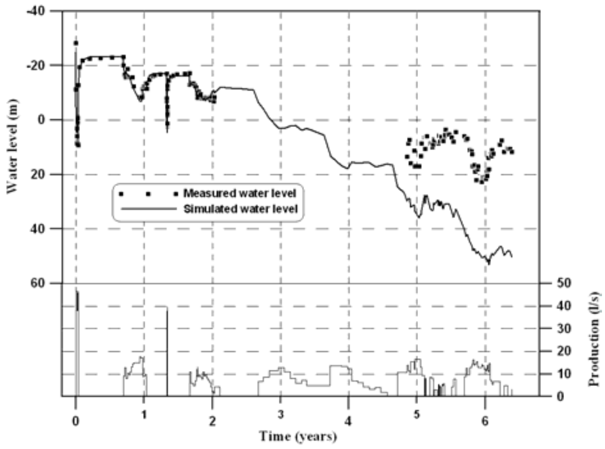

FIGURE 9: Model 4 – Three-tank open model based on the first period and total production with 40% reinjection

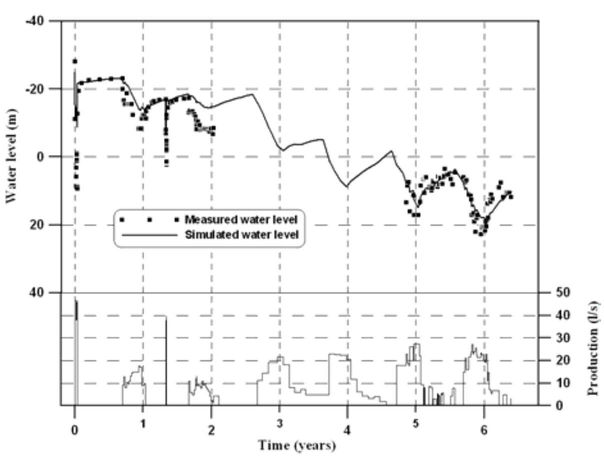

FIGURE 10: Model 5–Two-tank closed model based on the third period and total production

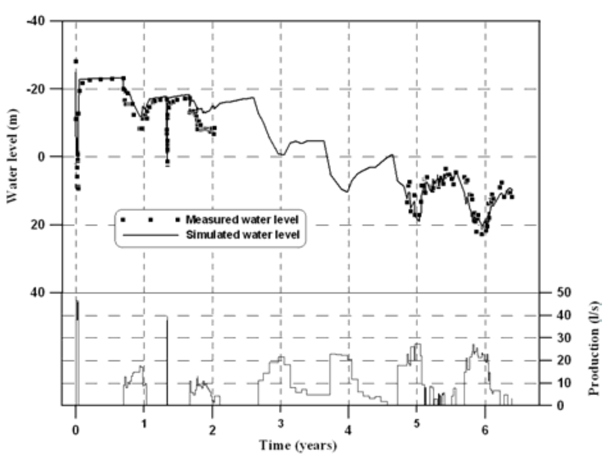

FIGURE 11: Model 6 – Two-tank open model based on the third period and total production

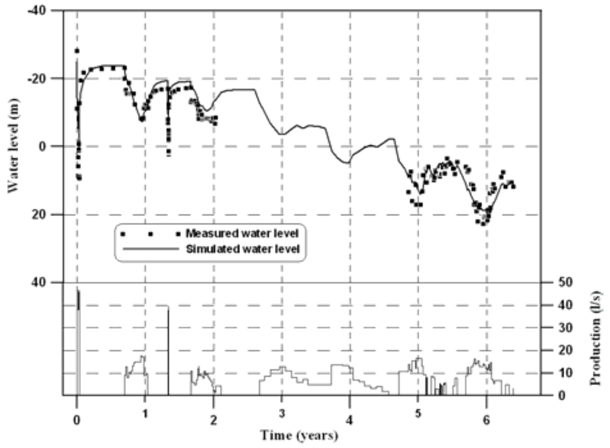

FIGURE 12: Model 7 – Two-tank closed model based on the third period and total production with 40% reinjection

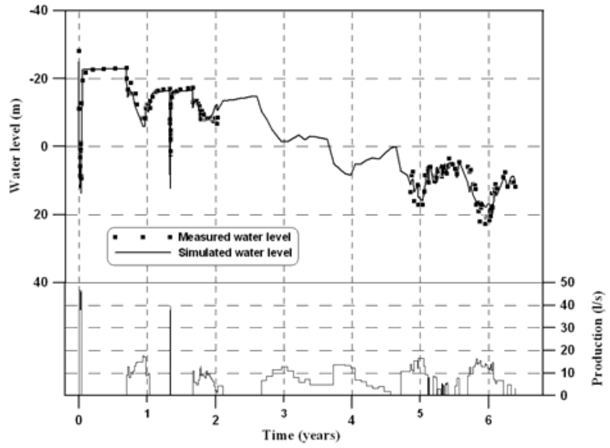

FIGURE 13: Model 8 – Two-tank open model based on the third period and total production with 40% reinjection

Based on the results presented in Tables 1 and 2 in Appendix I, and in Figures 6-13, it appears clear that model 8 gives the best solution, i.e. the best simulation of the whole water level history. This has two important consequences. First, model 8 (using the *LUMPFIT* program) can be used to estimate the water level changes for the period with missing data (second period, mentioned above). Thus the production history of well SR-6 can be completed, including water level and production rate data. Second, incorporating the 40% reinjection in SRG-1 into the production history leads to a better simulation, which is not surprising.

The third stage of the SR-6 simulation involves simulating all the SR-6 production history (including the estimated water level data for the second period) with *LUMPFIT*. The simulation is, again, done by open and closed models, for the two production cases used previously (without and with reinjection). The results of the simulations are presented in Table 3 in Appendix I and in Figures 14-17.

The results finally show that model 12 is the best model based both on the value of the coefficient of determination, which is 96.6%, and by considering the overall fit (see Figure 17). In the following sections we will use the parameters of models 11 and 12 to estimate the main reservoir parameters and to predict water level changes in the future.

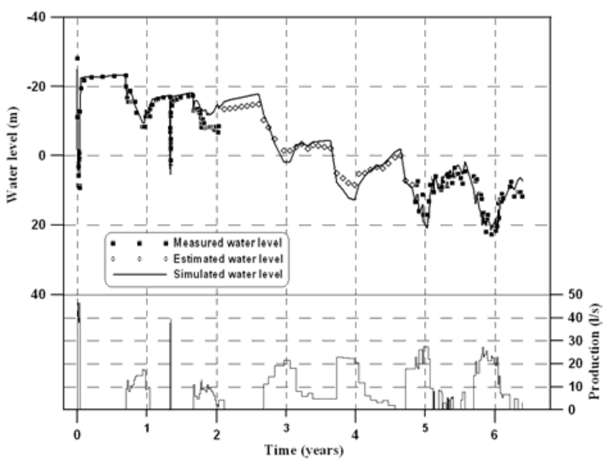

FIGURE 14: Model 9 – Two-tank open model based on the whole history and total production

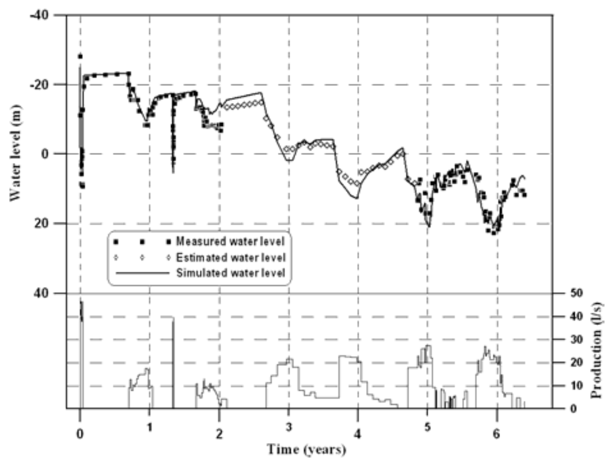

FIGURE 15: Model 10 – Three-tank closed model based on the whole history and total production

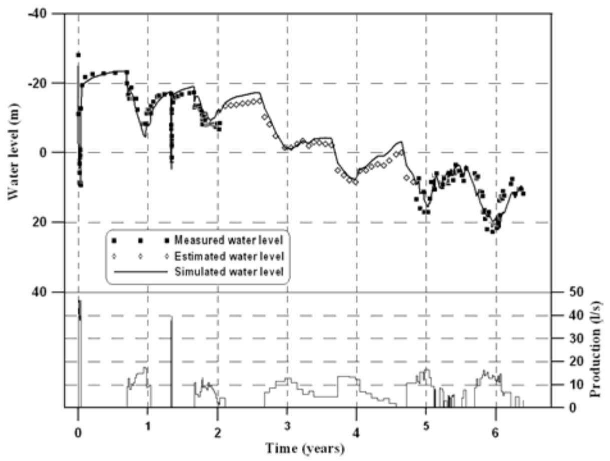

FIGURE 16: Model 11 – Two-tank open model based on the whole history and production with 40% reinjection

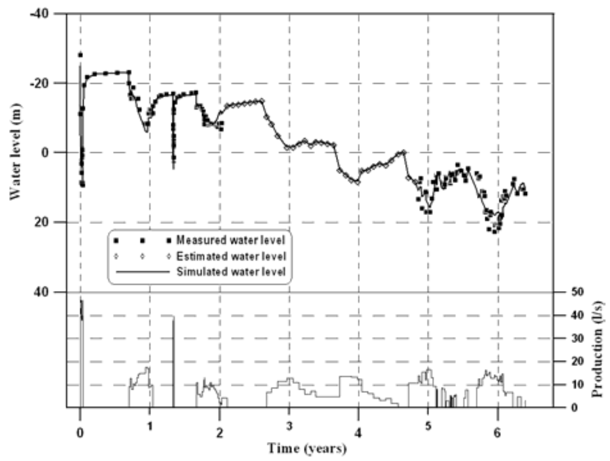

FIGURE 17: Model 12 – Three-tank closed model based on the whole history and production with 40% reinjection

3.2 Reservoir properties and boundaries

3.2.1 Reservoir properties from lumped parameter models

The main reservoir properties of the Lishuiqiao-Beiyuan system can be estimated by using the parameters, i.e. the storage coefficients κ_i and the conductance coefficients of resistors σ_i, of the lumped parameter models 11 and 12 from Table 3 in Appendix I. This is done here by assuming a reservoir thickness of 460 m (Liu et al., 2004), an average porosity of 5% and confined and two-dimensional flow. Using the following series of equations, the volumes of different reservoir parts, their area and permeability can be estimated (see also Figure 18):

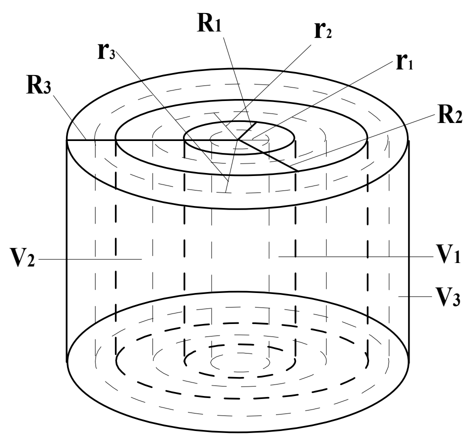

FIGURE 18: Three-tank model with two-dimensional flow

$$s = \frac{\Delta m}{\Delta p V} = \rho_w \left[\phi c_w + (1-\phi) c_r \right] \tag{3}$$

$$\kappa_1 = V_1 s; \quad \kappa_2 = V_2 s; \quad \kappa_3 = V_3 s; \tag{4}$$

$$R_1 = \sqrt{\frac{V_1}{\pi h}}; \tag{5}$$

$$R_2 = \sqrt{\frac{V_2 + V_1}{\pi h}}; \tag{6}$$

$$R_3 = \sqrt{\frac{V_1 + V_2 + V_3}{\pi h}}; \tag{7}$$

$$r_1 = R_1 / 2; \tag{8}$$

$$r_2 = R_1 + (R_2 - R_1)/2; \tag{9}$$

$$r_3 = R_2 + (R_3 - R_2)/2; \tag{10}$$

$$k_i = \frac{\sigma_i \ln(r_{i+1}/r_i) \cdot \nu}{2\pi h}; \tag{11}$$

where s = Storativity of reservoir (Equation 3; kg/m^{3}Pa);
ρ_w = Water density (kg/m^3);
c_w = Fluid compressibility (Pa^{-1});
c_r = Rock compressibility (Pa^{-1});
φ = Porosity of reservoir;
R_1, R_2, R_3 = Radii of the different tanks (Equations 8-10) (m);
r_1, r_2, r_3 = Radii of corresponding cylindrical shells (Equations 8-10) (m);
κ = Capacitance of a tank (kg/Pa);
σ = Conductance of a tank (kg/Pa);
V = Volume of reservoir (m^3);
v = Kinematic viscosity of water (m^2/s);
h = Thickness of reservoir (m).

Assuming that the rock compressibility is of the order of 3×10^{-11} Pa^{-1} and that the water compressibility is 5×10^{-10} Pa^{-1}, the reservoir storativity is estimated to be 5.3×10^{-8} kg/m^{3}Pa. Consequently, the reservoir parameters are estimated as presented in Table 3 below.

TABLE 3: Estimates of reservoir properties based on lumped parameters

Model	Parameters	First tank	Second tank	Third tank	Total
Closed three-tank model	Surface area	6.04×10^4 m^2	2.80×10^7 m^2	1.30×10^8 m^2	158.0 km^2
	Volume	2.78×10^7 m^3	1.29×10^{10} m^3	5.98×10^{10} m^3	72.4 km^3
	Permeability-thickness	**71.2 Dm**	**6.26 Dm**		
Open three-tank model	Surface area	4.69×10^4 m^2	1.28×10^7 m^2	6.52×10^7 m^2	78.0 km^2
	Volume	2.16×10^7 m^3	5.91×10^9 m^3	3.00×10^{10} m^3	35.9 km^3
	Permeability-thickness	**83.3 Dm**	**19.2 Dm**	**0.75 Dm**	

The results of the calculations for the three-tank closed model indicate that the reservoir area is about 160 km^2, which is greater than the previously estimated area of the Shahe geothermal field, which was about 110 km^2 (Xu, 2002). The reason may be that well SR-6 is near the Huangzhuang-Gaoliying fault, which is believed to be the boundary between the Shahe and Houshayu geothermal fields, and this boundary between the two fields may be open. The estimated area, therefore, also contains a part of Houshayu field.

The estimated permeability-thickness of 71 Dm between the first and second tanks is close to the value of 83.3 Dm for the three-tank open model. This reflects good permeability inside the reservoir. The permeability-thickness between the third tank and the outside is low for the three-tank open model and the permeability-thickness between the second and third tanks of the closed model is only 0.75 Dm, which indicates that natural recharge is very small.

3.2.2 Interference data analysis

Water level data from wells SR-10, SRG-1, BY-1 and BY-3 are available for the period from October 2002 to October 2003. It is assumed that the water level changes observed in all the wells is interference from SR-6, even though it's possible that the water level changes may also partly result from production interference data. The data were first simulated by lumped parameter models, using *LUMPFIT*, because of the variations in the rate of production from well SR-6. Four files were created with water level data for the four wells and the SR-6 production rate for the same period. Information on the models is presented in Table 4 and the resulting simulations in Figures 19-22.

TABLE 4: Type and coefficient of determination of models used to simulate interference data

Location of wells	Type of models	Coefficient of determination
SR-10	3-C	98.00%
SRG-1	2-C	98.38%
BY-1	2-C	97.37%
BY-3	2-C	96.59%

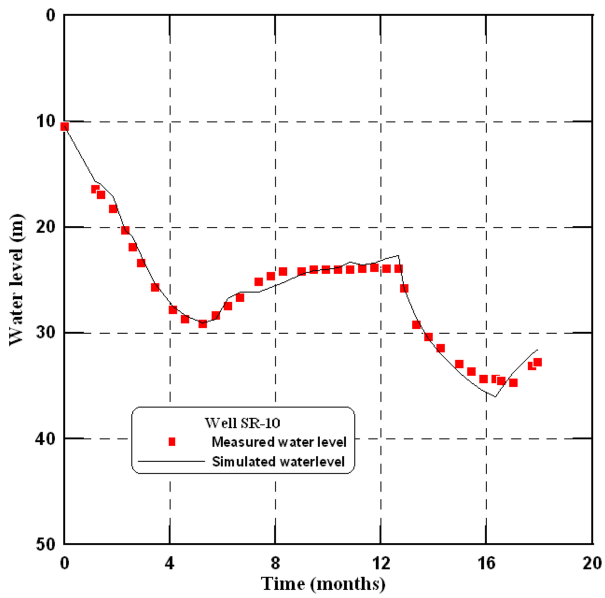

FIGURE 19: Water level changes in SR-10 simulated by a three-tank closed model with production from well SR-6

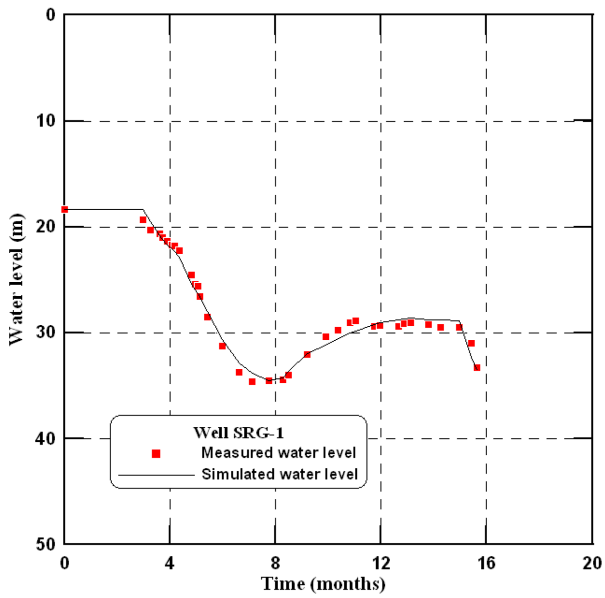

FIGURE 20: Water level changes in SRG-1 simulated by a two-tank closed model with production from well SR-6

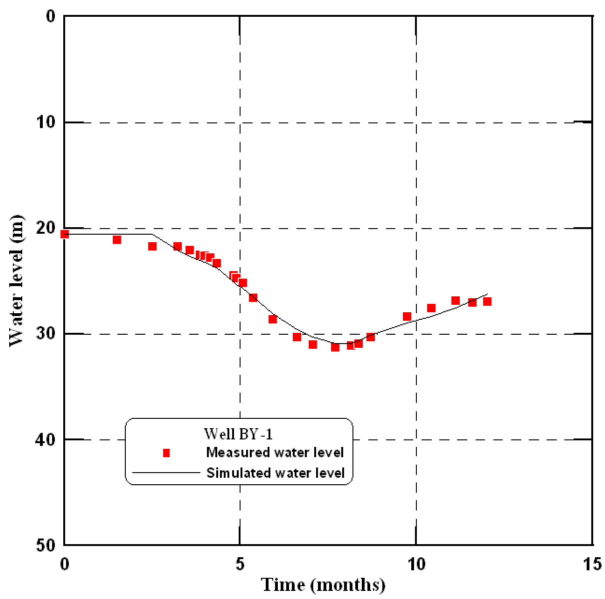

FIGURE 21: Water level changes in BY-1 simulated by a two tank open model with production from well SR-6

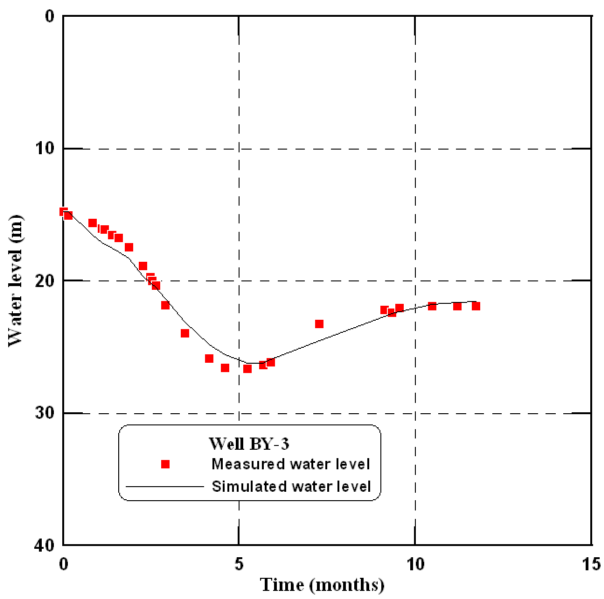

FIGURE 22: Water level changes in SR-10 simulated by a two tank open model with production from well SR-6

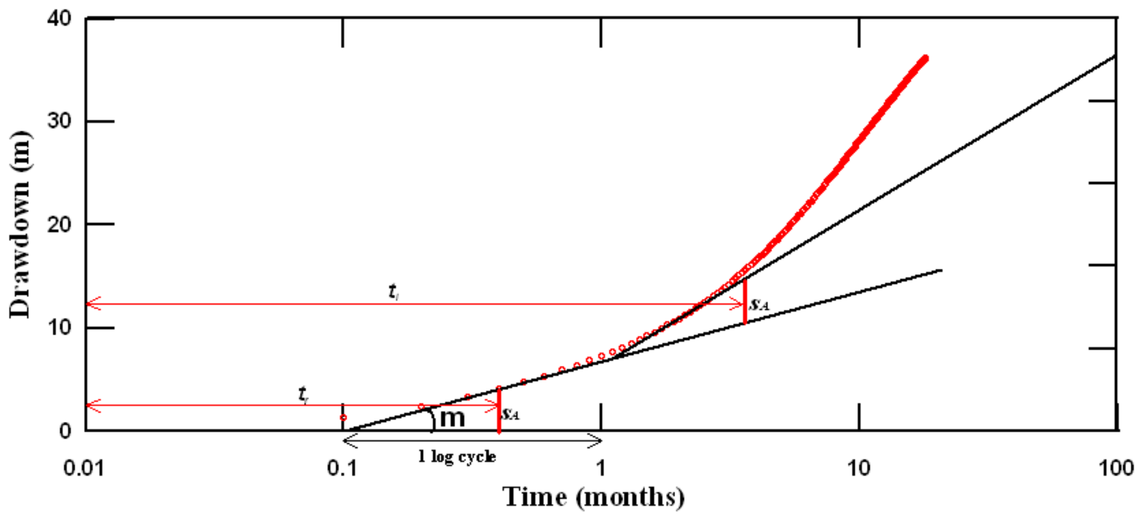

FIGURE 23: Semi-log plot of the calculated water-level change in SR-10 due to production from SR-6 showing a clear doubling of the slope

The match between the data for four wells and the SR-6 simulation curves is quite good. Therefore, the four models are used to calculate the interference for a constant 10 l/s production and the results analyzed by the conventional semi-log method. This is done by creating a new file with *LUMPFIT* assuming a constant 10 l/s production using the parameters of the models for each well (Table 4).The calculated water level drawdown vs. time is plotted on a semi-logarithmic plot (see example for well SR-10 in Figure 23). The straight line with slope *m* is used to estimate the permeability-thickness *kh* and storativity $C_t h$ through the following equations:

$$kh = 2.303 q\mu / 4\pi m \tag{12}$$

$$C_t h = 2.25 \frac{kh}{\mu} \frac{t}{r^2} 10^{-\Delta p/m} \tag{13}$$

where k = Permeability (m^2);
q = Production rate (kg/m^3);
C_t = Total compressibility (Pa^{-1});
Δp = Change of pressure (Pa);
μ = Dynamic viscosity (kg/ms);
r = Distance between wells (m).

The total compressibility of the reservoir is assumed to be 5.35×10^{-11} Pa^{-1}, and the thickness of the reservoir can be estimated based on the data for each well. The results are presented in Table 5.

TABLE 5: The results of interference analysis for wells SR-10, SRG-1, BY-1 and BY-3

Well	*kh* (Dm)	$C_t h$ (mPa^{-1})	Reservoir thickness (m)
SR-10	9.65	2.98×10^{-8}	549
SRG-1	61.1	4.79×10^{-8}	895
BY-1	4.4	6.30×10^{-8}	118
BY-3	9.9	3.94×10^{-8}	736

Based on well SRG-1, the permeability-thickness is estimated as 61 Dm and the reservoir thickness as 895 m, reflecting good permeability between SR-6 and SRG-1. Well SRG-1 is also relatively close to SR-6 and the wells intersect the same formations. The results for SR-10 and BY-3, which are at a greater distance from SR-6, are quite comparable, in particular with regards to the permeability-thickness which is of the order of 10 Dm. The estimated permeability-thickness between BY-1 and SR-6 is only 4.4 Dm and the estimated reservoir thickness is much less than for the other wells. The reason is believed to be the fact that wells SR-6 and BY-1 are on either side of the Huangzhuang-Gaoliying fault, obviously reducing the transmissivity between the wells. In this case, the formations on either side of the fault don't match up. On the other hand, it is clear that the Huangzhuang-Gaoliying fault does not act as an impermeable boundary of the Shahe geothermal field.

3.2.3 Location of a possible reservoir boundary

If an impermeable boundary is present, the rate of drawdown in an observation well will double as if under the influence of an image pumping well (Todd, 1980). To determine the location of the image pumping well and, hence, that of the boundary, we assume that wells SR10, BY-1 and BY-3 are observation wells for production well SR-6. In addition to the normal straight line with slope m, we get a second line with the slope 2m. An example of this is shown in Figure 23 where the second line is tangential to the interference curve. An arbitrary drawdown s_A is selected at a time t_r where the direct influence of the real well is measured. Similarly, a time t_i for the same drawdown to be produced by the image well is defined. Knowing the distance r_r (r_{r1} between SR-6 and SR-10 for example), then the distance r_i between the observation well (SR-10 for example) and the image pumping well can be found by:

$$\frac{r_i^2}{t_i} = \frac{r_r^2}{t_r} \tag{15}$$

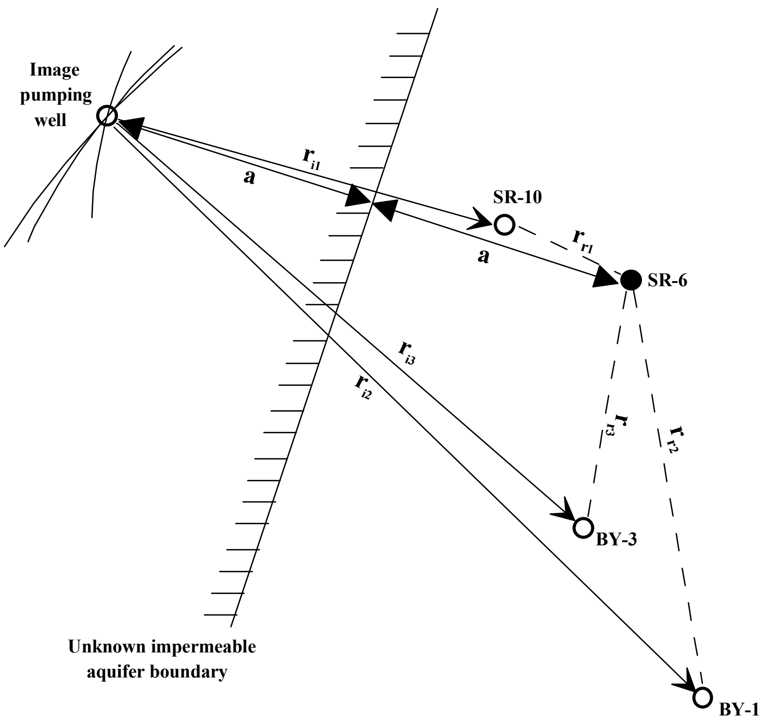

FIGURE 24: Location of an unknown impermeable aquifer boundary near well SR-6, estimated from interference in SR-10, BY-1 and BY-3

In the same way, we can estimate distance r_{i2} between the image pumping well and BY-1, and the distance r_{i3} between the image pumping well and BY-3. The three distances can define a unique intersection point, which is the location of the image pumping well (see Figure 24). The boundary then lies at the midpoint and perpendicular to a line connecting the real and image pumping wells. The value *a* for the distance between the boundary and SR-6 is about 1500 m, which indicates an unknown northeast trending fault in the geothermal area. This boundary could also represent the Babaoshan fault, which has the same direction but is at a distance of 3-4 km from this area. A great uncertainty is inherent in this estimation because of heterogeneities in the structure of the geothermal system.

4. FUTURE PREDICTIONS FOR UTILIZATION OF WELL SR-6 AND REINJECTION INTO WELL SRG-1

4.1 Water level predictions with reinjection

The lumped parameter models developed for SR-6 have been used to calculate water level predictions for a few different future production scenarios. The purpose was to try to foresee how much of the water level in the well may possibly decline in the future and to estimate the production potential of the well. An important part of this was to study the effect of reinjection of the return water upon the water level decline.

Reinjection should be considered an integral part of any modern, sustainable, environmentally friendly geothermal utilization. It started out as a method for waste-water disposal for environmental reasons, but is now also being used to counteract pressure drawdown, i.e. as artificial water recharge, and to extract more of the thermal energy from the reservoir rock (Stefánsson, 1997). As has been shown through experience and theoretical studies, in most cases, reinjection increases the production potential considerably.

Geothermal reinjection started in Ahuachapan, El Salvador, in 1969, The Geysers, California, in 1970 and in Larderello, Italy, in 1974. It is now an integral part of the operation of at least 50 geothermal fields in 20 countries (Axelsson et al., 2005). The main problems associated with injection are: an initial increase in operation costs, possible cooling of production wells (thermal breakthrough), scaling in surface equipment and injection wells, and sandstone reservoir injection.

Well SRG-1 was designed as a reinjection well for SR-6. In 2005, the Geothermal Resources Administration Department of Beijing promulgated a decree that the waste water from district heating must henceforth be reinjected, starting no later than the winter of 2006-2007.

The maximum production from well SR-6 is about 40l/s, but during the last 6 years, the average production has been about 5 l/s during the non-heating season and about 20 l/s during the heating season. The Beijing authorities prohibit waste water from bathing being reinjected into the reservoir. It is assumed, as a base scenario, that the production during the next 20 years will be the same as the average production of the last six years, and, therefore, estimated that 5 l/s will be used for bathing and 15 l/s for district heating in a heating season. If the waste water from district heating would all be reinjected, the reinjection ratio would be 75%.

Use of geothermal energy improves peoples´ living standards. Hence, living spaces using geothermal district heating are expected to increase. Therefore another scenario is assumed, where production from well SR-6 is expected to increase to the maximum 40 l/s, but the non-heating season production kept constant at 5 l/s. The maximum ratio of reinjection is assumed to be 75%.

Predictions were made based on these two production cases, with three reinjection ratios: 0% (without reinjection), 40% and 75%. The production scenarios are presented in Table 6. The *LUMPFIT* program was used to predict the water level changes in SR-6 in response to production. The closed three-tank model and the open three-tank model were both used to predict water level drawdown for the next 20 years (from August 2006 to August 2026). The prediction results are presented in Figures 25-28.

In scenario I, the water level of SR-6 will decline as much as 200 m without reinjection and 100 m with 75% reinjection according to the closed model. According to the open model, the water level will decline to 60 m in about 15 years and stay stable after that without reinjection. The open model predicts that the water level will stay stable in the future with 75% reinjection.

TABLE 6: The production scenarios assumed for water level predictions for SR-6

Scenario	Production in non-heating season (l/s)	Production in heating season (l/s)	Ratio of reinjection (%)	Actual production in heating season (l/s)
I	**5**	20	0 40 75	**20** **12** **5**
II	**5**	40	0 40 75	**40** **24** **10**

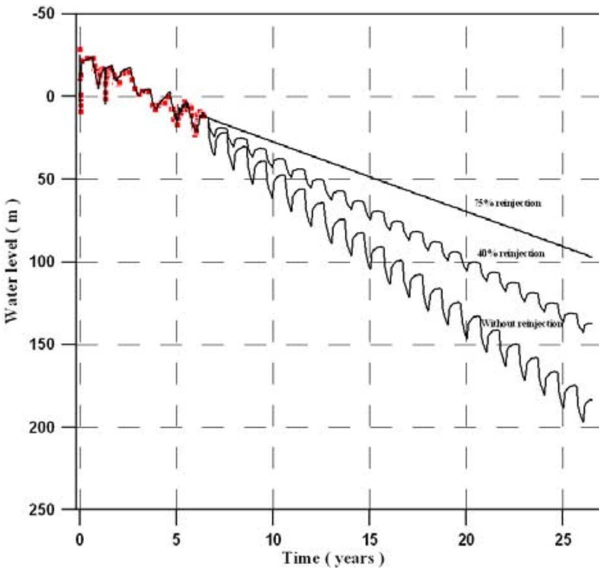

FIGURE 25: Water level drawdown predictions for well SR-6 for the next 20 years calculated by a three-tank closed model with 20 l/s production in the heating season

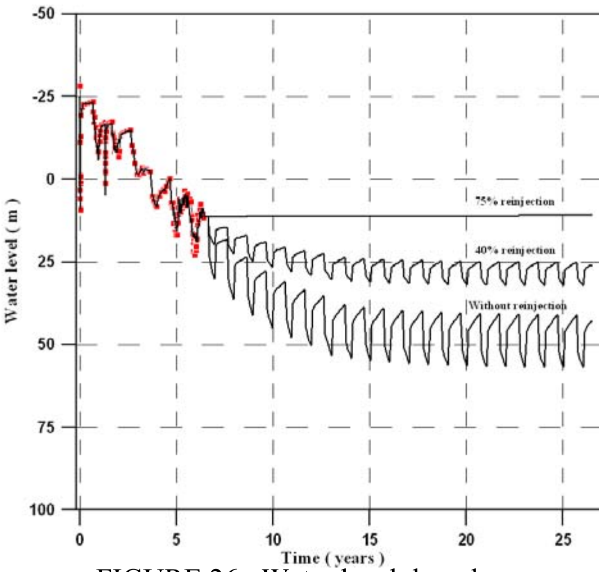

FIGURE 26: Water level drawdown predictions for well SR-6 for the next 20 years calculated by a three-tank open model with 20 l/s production in the heating season

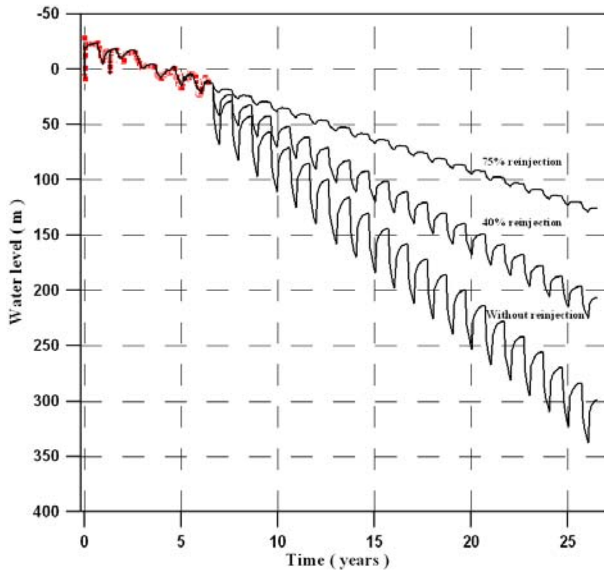

FIGURE 27: Water level draw-down predictions for well SR-6 for the next 20 years calculated by a three-tank closed model with 40 l/s production in the heating season

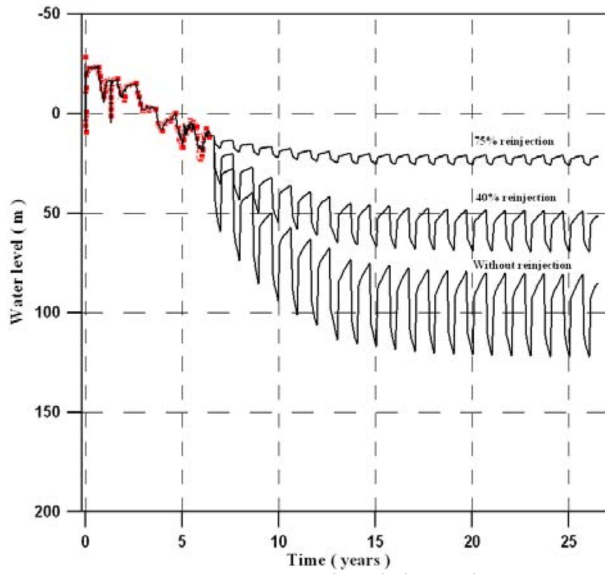

FIGURE 28: Water level draw-down predictions for well SR-6 for the next 20 years calculated by a three-tank open model with 40 l/s production in the heating season

In scenario II, the water level will drop as much as 340 m in 20 years without reinjection, according to the closed model, and to a depth of 130 m with 75% reinjection. According to the open model the water level will decline to 120 m in 10 years but remain stable after that even without reinjection. Similarly, according to the open model with 75% reinjection, the water level will decline to about 25 m in 10 years and stay relatively stable in the future for scenario II.

4.2 Temperature decline predictions

It is very beneficial to reinject geothermal waste water into the Beijing reservoirs, but possible temperature decline in production wells is one of the main potential problems associated with long-term reinjection. When a distance of 1–1.5 km between production and reinjection wells is maintained, the cooling should be fully avoidable. On the contrary, in cases where the distance between production and reinjection wells is small, and direct flow paths between the two wells exist, the fear of thermal breakthrough has been justified. We know the distance between wells SR-6 and SRG-1 is only 230 m, and the depths of the reservoir formations are similar. Despite the fact that most of the water is reinjected in winter and the temperature may recover in the non-heating season, if the reinjection rate with colder water is great enough, the thermal breakthrough, or cooling of production wells, will happen and the lifetime of the wells will be reduced.

Tracer tests are the most powerful tool for studying connections between injection and production wells, and hence the danger of thermal breakthrough. Their power lies in the fact that the thermal breakthrough time is usually some orders of magnitude (2-3) greater than the tracer breakthrough time (Axelsson, 2002).

Two methods can be used in calculating thermal breakthrough time. One is based on the theory of heat transport in liquid-phase porous media geothermal systems with radial flow. In this model, thermal breakthrough is induced after a long time. The other method is based on a one-dimensional fracture zone model in which thermal breakthrough is induced quickly, providing a kind of worst case situation. In this paper, we present temperature predictions by the second method through assuming different production and reinjection scenarios. The model presented in Figure 29 simulates a flowpath along a fracture zone, an interbed or permeable layer, such as in the case studied here. In the model, b indicates either the width of a fracture zone or the thickness of an interbed or layer, whereas h indicates the height of a flowpath inside a fracture zone or the sweeping width of flowlines along the interbed or layer. The flow channel cross-sectional area is then given by $A = h \times b$. To estimate h and b on basis of the main outcome of a tracer test interpretation, A and φ, one must make an assumption on the average flowpath porosity, which is often approximately known, and the ratio between h and b , which in contrast is normally poorly known.

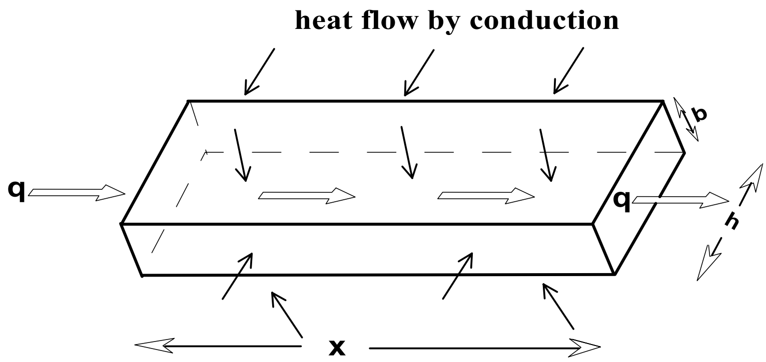

FIGURE 29: A model of a flow-channel, containing porous material, used to calculate the eventual cooling of a production well connected by a channel to a reinjection well

Here, a porosity of 5% is assumed for the reservoir layer incorporating the flow between the wells, as well as a production temperature of 70°C and a reinjection temperature of 40°C. In addition for *h,* which indicates the width of the flowpath, a constant value of 120 m is used here, and for *b,* indicating the thickness of the layer, three cases are studied, 35, 200 and 350 m. The same production scenarios as before are studied, 20 or 40 l/s in winter with two reinjection ratios (40% and 70%). The problem is simplified by using the average production and reinjection rates instead of variable rates. The scenarios considered are presented in Table 7.

TABLE 7: Model parameter assumed for the cooling prediction scenarios for SR-6 and SRG-1.

Cases	b (m)	Production rate in winter (l/s)	Average production (l/s)	Reinjection ratios (%)	Average reinjection (l/s)
1	35	20	**6.7**	40	**2.7**
2	200				
3	350				
4	35			75	**5**
5	200				
6	350				
7	35	40	**13.4**	40	**5.4**
8	200				
9	350				
10	35			75	**10**
11	200				
12	350				

The program TRCOOL (Arason et al., 2004) is used to predict temperature changes in well SR-6 for the next 50 years. Figures 30, 31, 32 and 33 show the results of these cases. It appears that when the thickness b equals 350 m and the reinjection ratio is 40%, the production temperature of well SR-6 is constant at 70°C, according to the calculations. For other cases with 40% reinjection, the production temperature will decline to about 60°C but the well can still be used for district heating in Beijing. When the reinjection ratio is 75%, the production temperature will decline well below 60°C (about 50°C) in the next 50 years. This is too much cooling for space-heating applications. In general, these results show that the danger of considerable cooling of well SR-6 due to reinjection into SRG-1 is quite significant due to the closeness of the wells. Therefore, it is advisable to select a reinjection well at a greater distance in the future.

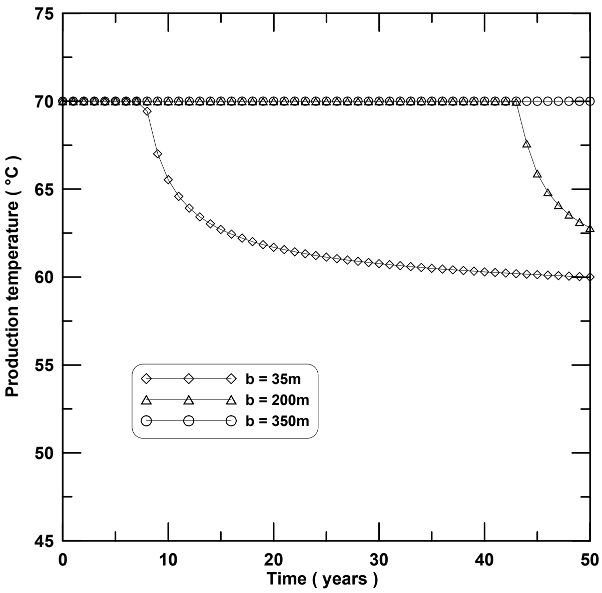

FIGURE 30: Estimated temperature decline of well SR-6 during reinjection into well SRG-1 for 6.7 l/s production and 2.7 l/s reinjection

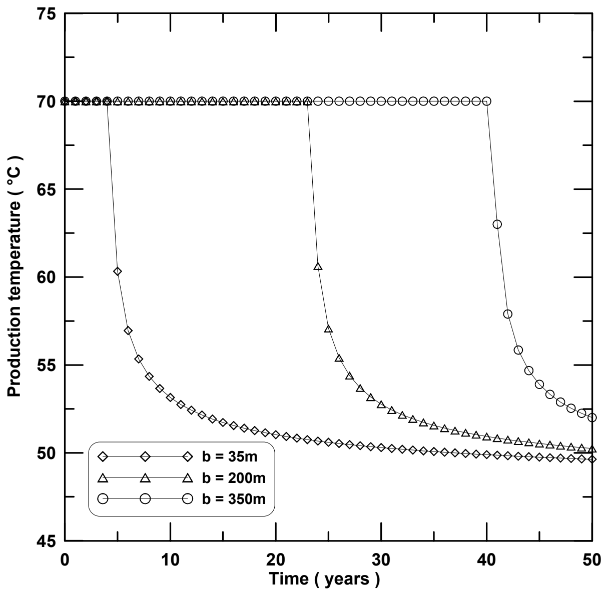

FIGURE 31: Estimated temperature decline of well SR-6 during reinjection into well SRG-1 for 6.7 l/s production and 5 l/s reinjection

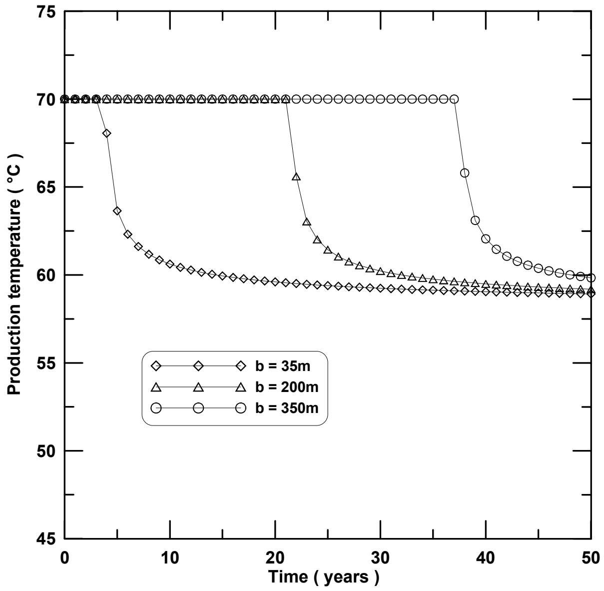

FIGURE 32: Estimated temperature decline of well SR-6 during reinjection into well SRG-1 for 13.4 l/s production and 5.4 l/s reinjection.

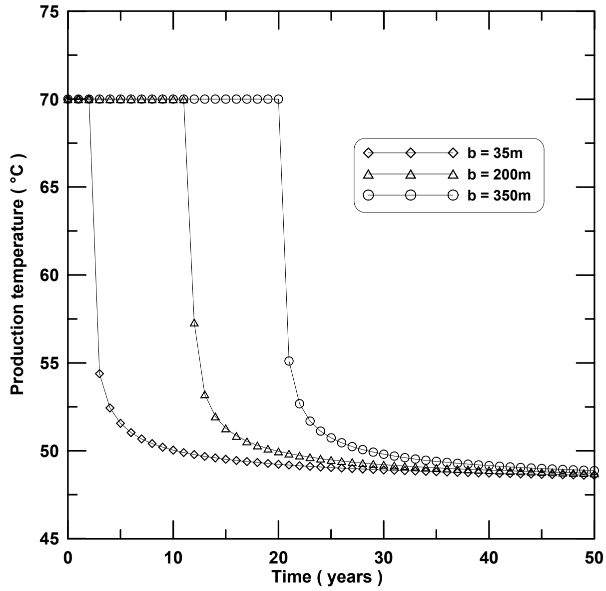

FIGURE 33: Estimated temperature decline of well SR-6 during reinjection into well SRG-1 for 13.4 l/s production and 10 l/s reinjection

If the distance between production and reinjection wells is changed from 230 to 1000 m and the width of *h* from 120 to 250 m, with other parameters kept the same, calculations give the results listed in Table 8.

TABLE 8: Results of cooling predictions for well SR-6 for an imaginary reinjection well at a distance of 1 km for the same scenarios as in Table 7

Number	Cases	Thickness *b* (m)	Temperature of production well in 50th year (°C)
1	1	35	70
	2	200	70
	3	350	70
2	4	35	68.7
	5	200	70
	6	350	70
3	7	35	68.7
	8	200	70
	9	350	70
4	10	35	58
	11	200	70
	12	350	70

The results show that the calculated production well temperature changes only for three cases, with only a minor change in two of these (cases 4 and 7). Only in case 10 is the temperature decline considerable, but actually only after 40 years. This shows undoubtedly that cooling due to reinjection is minimised by locating the reinjection well further away from the production well than well SRG-1 currently is.

5. LUMPED PARAMETER MODELLING FOR WELL BY-1 AND WATER LEVEL PREDICTIONS

Two lumped parameter models were set up to simulate the water level observed in well BY-1 during the one and half year production history of the well (December 2004 to July 2006). One of the models was a closed three-tank model, and the other an open two-tank model. The fit is very similar for the two models, so just one figure is presented, in Figure 34. The parameters of the models are presented in Table 4 in Appendix I.

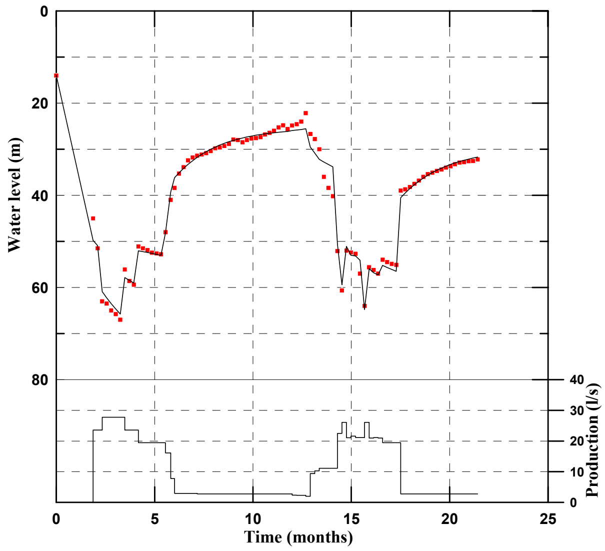

FIGURE 34: Water level variations in BY-1 during one and half year production simulated by a lumped parameter model

Using the models, the water level changes of well BY-1 with reinjection into well BY-3, can be estimated over the next 20 years. A 30 l/s production in the heating season is assumed and 3 l/s in the non-heating season. The following three reinjection scenarios were studied: 0% (no reinjection), 50% and 90% in the heating season. The results are presented in the graphs in Figures 35 and 36.

According to the three-tank closed model (Figure 35), the water level after 20 years will drop to 225 m depth without reinjection, but to 70 m with 90% reinjection. The two-tank open model predicts that the water level will decline to 115 m in about 15 years and stay stable after that. With the reinjection ratio at 90% the water level will stop declining and recover to 30 m depth after about 20 years.

It should be pointed out that these water level predictions for well BY-1 are not as accurate as the corresponding predictions for well SR-6. This is because the production history of the former well is only about a quarter of the production history of the latter.

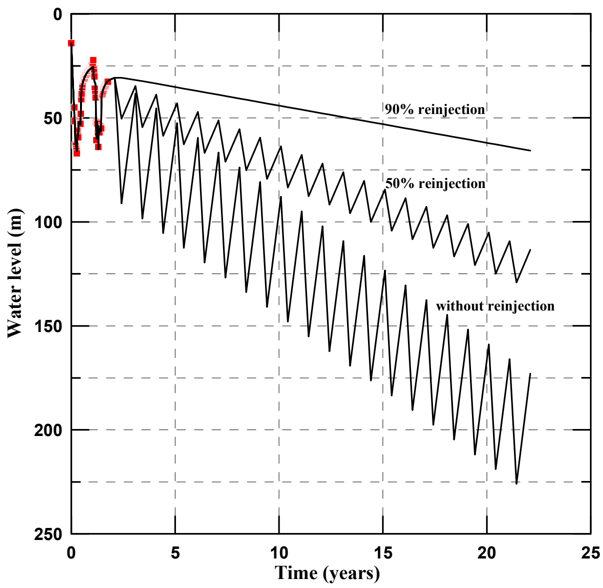

FIGURE 35: Water level drawdown predictions for well BY-1 during the next 20 years calculated by a closed three-tank lumped model

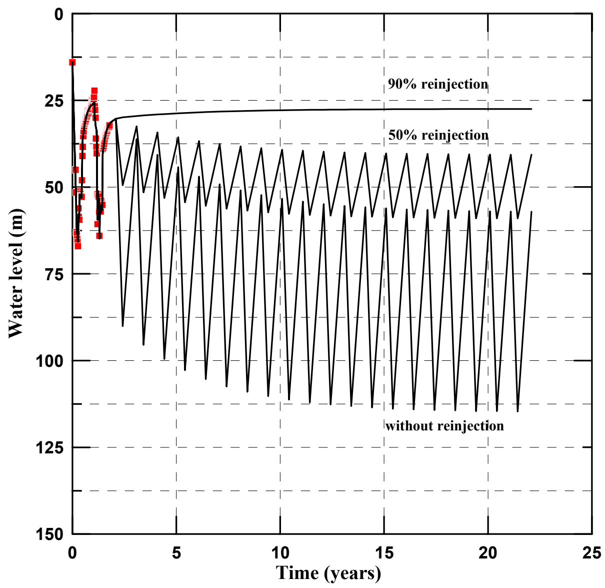

FIGURE 36: Water level drawdown predictions for well BY-1 during the next 20 years calculated by an open two-tank lumped model

6. CONCLUSIONS AND RECOMMENDATIONS

The main conclusions of this work may be summarized as follows:

1. According to lumped parameter modelling of the production and water level history of SR-6, the surface area of the geothermal reservoir is about 160 km^2. The estimated permeability thickness varies from 0.75 Dm to 83 Dm from the outskirts of the system to its centre.
2. Based on interpretation of interference data from four wells around SR-6, the average reservoir permeability thickness appears to be about 10 Dm. The distance from SR-6 to an apparent western impermeable boundary is estimated to be about 1.5 km.
3. The lumped parameter model for SR-6 was used to predict water level changes due to two long term production scenarios, in order to assess the production potential of Lishuiqiao-Beiyuan geothermal system. When production is 5 l/s in the non-heating season and 20 l/s in the heating season, the water level will decline to 200 m depth without reinjection, but with 75% reinjection to less than 100 m in 20 years time, according to model predictions. Conversely, the water level is predicted to drop to 350 m when production is 5 l/s in the non-heating season and 40 l/s in the heating season without reinjection, but to less than 130 m with 75% reinjection. This demonstrates very clearly the benefit of reinjection.
4. Production well cooling calculations show that, in 11 cases out of 12 involving reinjection into SRG-1 and production from SR-6, substantial cooling of SR-6 is predicted after 50 years of production/reinjection. This demonstrates that SRG-1 is too close to SR-6 to be used as a permanent, long-term, reinjection well.
5. The lumped parameter model for BY-1 is based on a one and a half year production history. When production is 3 l/s in the non-heating season and 30 l/s in the heating season, a three-tank closed model predicts the water level will drop to a 225 m depth without reinjection and to 70 m with 90% reinjection after 20 years. The two-tank open model predicts that the water level will decline to 115 m in about 15 years without reinjection and stay stable after that. When the reinjection ratio is 90%, the water level will stop declining and recover to 30 m depth after 20 years.

Based on the results of this study some recommendations are put forward:

1. Geothermal resources in Beijing are precious and the government must set up strict policies to control production and waste water reinjection.
2. The government should establish uniform monitoring criteria and set up a monitoring system for all geothermal wells, and every geothermal field/system. Certainly, the government can make some selected companies responsible for the monitoring.
3. The distance between production and reinjection wells should generally be greater than 1 km, which should prevent production well cooling. The distance between wells SR-6 and SRG-1 is only 230 m, and the distance between wells BY-2 and BY-3 is 560 m. Therefore, tracer tests should be conducted in the Lishuiqiao-Beiyuan area in order to investigate the flowpaths between reinjection and production wells and to estimate the danger of significant cooling due to reinjection.
4. Data on the Lishuiqiao-Beiyuan geothermal system (especially the Beiyuan Garden part) is limited at present. Careful monitoring must be carried out in the area and continuous water level, production rate, injection rate, water temperature and chemical content data for production wells must be ensured.
5. Reinjection is a very effective countermeasure for declining water levels in the Lishuiqiao-Beiyuan that are due to production and limited natural recharge. The government must ensure that more of the waste water from space heating be reinjected in the near future.
6. Special attention must be paid to interference between different production wells in the area (wells SR-6 and BY-1 in particular), as well as in Beijing as a whole, now that geothermal production

will likely be increasing. Such a study was beyond the scope of this work. The methods employed here (see section 3.3.2) can be used to estimate existing interference and predict interference due to future production. One problem with interference analysis is, however, the fact that it is difficult to distinguish interference from one production well to that of another production well nearby. This warrants a specific study devoted to interference in particular. The level of interference will, of course, decrease as the role of reinjection increases in the future.

ACKNOWLEDGEMENTS

I would like to thank Dr. Ingvar B. Fridleifsson, director of the UNU Geothermal Training Programme, and Mr. Lúdvík S. Georgsson, deputy director, for giving me the opportunity to come to Iceland and take part in the Geothermal Training Programme. I also thank Mrs. Gudrún Bjarnadóttir and Miss. Thórhildur Ísberg for their wonderful assistance and help. Special thanks to my supervisor Gudni Axelsson for his guidance and advice and for sharing his knowledge and time. I also want to thank all other teachers in Iceland for providing me with much special knowledge.

Deepest thanks to my leaders and colleagues in the Beijing Institute of Geo-Exploration and Technology; special thanks to engineer Xie Donghui for supplying the data presented here. Finally, I want to express my gratitude to my wife Wang Fang for her moral and emotional support during the six months.

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APPENDIX I: Parameters of lumped models for wells SR-6 and BY-1

TABLE 1: Parameters of lumped models for SR-6
based on the first part of the water level history of the well

Case	Without reinjection		With 40% reinjection	
Model number	1	2	3	4
Type of model	3-C	3-O	3-C	3-O
A_1	587.963	228.227	258.226	228.227
L_1	1220.64	928.421	846.313	928.421
A_2	0.807715	0.751956	0.596318	0.751956
L_2	2.08073	2.43716	1.06613	2.43716
A_3		0.118349		0.118349
L_3		0.00243716		0.00243716
B	0.132887		0.198392	
κ_1 (ms^2)	0.449122	1.15449	1.02111	1.15449
κ_2 (ms^2)	281.568	304.133	332.422	304.133
κ_3 (ms^2)	1708.32	1934.03	999.725	1934.03
σ_1 (10^{-4}ms)	2.11	4.12	3.32	4.12
σ_2 (10^{-4}ms)	1.94	2.48	1.03	2.48
σ_3 (10^{-6}ms		2.19		2.15
Root mean square misfit	1.80976	1.80353	1.80976	1.80353
Estimate of standard deviation	1.83225	1.83051	1.83225	1.83051
Coefficient of determination (%)	**87.248**	**87.336**	**87.248**	**87.336**

TABLE 2: Parameters of lumped models for SR-6
based on the third part of the water level history of the well

Case	Without reinjection		With 40% reinjection	
Model number	5	6	7	8
Type of model	2-C	2-O	2-C	2-O
A_1	0.1808	0.1808	0.89768	0.89774
L_1	0.08554	0.08554	1.31943	1.31954
A_2		0.02474		0.0792025
L_2		0.0008554		0.00131954
A_3				
L_3				
B	0.02474		0.0792	
κ_1 (ms^2)	1286.8	1286.8	270.748	270.732
κ_2 (ms^2)	9403.97	9621.19	3068.68	3075.37
κ_3 (ms^2)				
σ_1 (10^{-5}ms)	3.74	3.74	12.66	12.66
σ_2 (10^{-6}ms)		3.60		1.70
σ_3 (10^{-4}ms				
Root mean square misfit	2.55003	2.03826	2.57551	2.1478
Estimate of standard deviation	2.60621	2.09489	2.62862	2.20747
Coefficient of determination (%)	**62.049**	**75.753**	**70.394**	**79.088**

TABLE 3: Parameters of lumped models for SR-6 based on all the water level history of the well (water level estimated for missing data during the second part

Case	**Without reinjection**		**With 40% reinjection**	
Model number	9	10	11	12
Type of model	2-O	3-C	3-C	3-O
A_1	137	179	181	233
L_1	393	571	581	955
A_2	0.139	0.3163	0.322	0.711
L_2	0.0184	0.3676	0.356	2.31
A_3				0.143
L_3				0.0219
B		0.0703	0.0694	
κ_1 (ms^2)	1.92863	1.47441	1.45812	1.131
κ_2 (ms^2)	1901.05	683.39	674.977	309.829
κ_3 (ms^2)		3077.43	3134.65	1574.31
σ_1 (10^{-4}ms)	2.92123	3.24103	3.26134	4.1519
σ_2 (10^{-5}ms)	1.35088	7.94477	7.64156	23.0982
σ_3 (10^{-5}ms)				1.59439
Root mean square misfit	2.66902	2.66764	2.23924	1.84687
Estimate of standard deviation	2.68624	2.6892	2.25734	1.86483
Coefficient of determination (%)	**92.276**	**92.285**	**94.939**	**96.557**

TABLE 4: Parameters of lumped models for well BY-1 in Beiyuan Garden based on a one and a half year production history

Parameters	**2-O**	**3-C**
A_1	0.35	0.29
L_1	0.46	2.66
A_2	0.071	0.27
L_2	0.020	0.32
A_3		
L_3		
B		0.050
κ_1 (ms^2)	628.24	455.3
κ_2 (ms^2)	3444.88	598.90
κ_3 (ms^2)		4257.31
σ_1 (10^{-5}ms)	9.35	23.52
σ_2 (10^{-5}ms)	3.17	11.26
σ_3 (10^{-5}ms)		
Root mean square misfit	1.5055	2.66764
Estimate of standard deviation	1.5414	2.6892
Coefficient of determination (%)	**91.6**	**92.0**