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ASSESSMENT OF GEOTHERMAL RESOURCES IN THE LISHUIQIAO AREA, BEIJING, CHINA

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ABSTRACT

The Lishuiqiao geothermal system is a low-temperature sedimentary system, with conduction dominated heat flow and a reservoir temperature of about 80°C. The first geothermal well in the area, SR-6, was successfully drilled during the winter of 1999-2000. It has been used for space heating since November 2000. In order to reduce air pollution resulting from the use of coal boilers, the Beijing Government encourages the use of environmentally friendly energy to heat houses. A plan has been made to develop the geothermal resources in the Lishuiqiao area to provide heating and domestic hot water for some inhabitants in the area. Three more geothermal wells have been drilled successfully, but have not been utilized yet. Available data from well SR-6, including well test data and 2 years for production and waterlevel data, provide the basis of model development and calculations. Two lumped parameter models have been set up and used to estimate the properties of the Lishuiqiao geothermal system and to calculate predictions for different production scenarios. Based on the models, the system acts like a closed geothermal reservoir with a surface area of about 110 km^2, a volume of about 55 km^3 and a reservoir permeability-thickness varying between 20 and 68 Darcy-m. According to conservative water level predictions of a closed three-tank model, the production potential of the system is about 14 l/s without reinjection, 28 l/s with 50% reinjection and 56 l/s with 75% reinjection, on the average for the next 10 years. Reinjection will, in fact, be essential for sustainable development, exploitation and management of the Lishuiqiao resource. Preliminary calculations indicate that a minimum distance between reinjection and production wells of about 1000 m should be maintained. Further testing, such as interference and tracer testing, is required. The present results are uncertain because of the short production history of SR-6 as well as being model dependent. Model calculations should be updated as exploitation of the reservoir continues.

1. INTRODUCTION

The Lishuiqiao geothermal system is about 6 km north of the Asian Sports Village in Beijing, China, and about 15 km north of the centre of Beijing. It is near the village planned for the 2008 Olympics. It is also

FIGURE 1: Location of the Lishuiqiao geothermal system in Beijing

near the Xiaotangshan geothermal field, which has more than 700 years history of geothermal utilization. Figure 1 shows the location of the Lishuiqiao geothermal system.

There are 10 main geothermal fields in Beijing, with a total surface area of about 2370 km^2. Figure 2 shows the distribution of these geothermal fields. Field number II is the so-called Shahe geothermal field. The Lishuiqiao geothermal area is part of the Shahe geothermal field, located in the southeastern part of the field. More than 200 geothermal wells had been drilled by the end of 1999 in Beijing, thereof 126 geothermal wells that were utilized (including 3 injection wells). The total production from all the fields is about 10,000,000 m^3/year, which corresponds to about 317 l/s on average. Newly drilled geothermal wells have been increasing at a rate of more than 10 wells per year in the last three years, most of which are used for space heating and bathing. Geothermal wells are being drilled deeper and deeper as drilling technique improves and deeper wells become economically acceptable. The deepest well drilled so far is about 4000 m. Most of the wells were drilled in the Urban (V) and Xiaotangshan (III) geothermal fields, which have been utilized on a large scale since the 1980s. Some higher risk exploration, including deep drilling, has been conducted in some of the other Beijing geothermal fields in recent years. Beijing Geological Survey and Technical Institute in Lishuiqiao successfully drilled one geothermal well, SR-6, in its backyard in the winter of 1999-2000. It is the first successful geothermal well in this area. Utilization of this well for space heating started in November 2000. It has not been used at full capacity yet, but only to provide heat for the offices and staff apartments of the Institute with a total heating area of about 25,000 m^2.

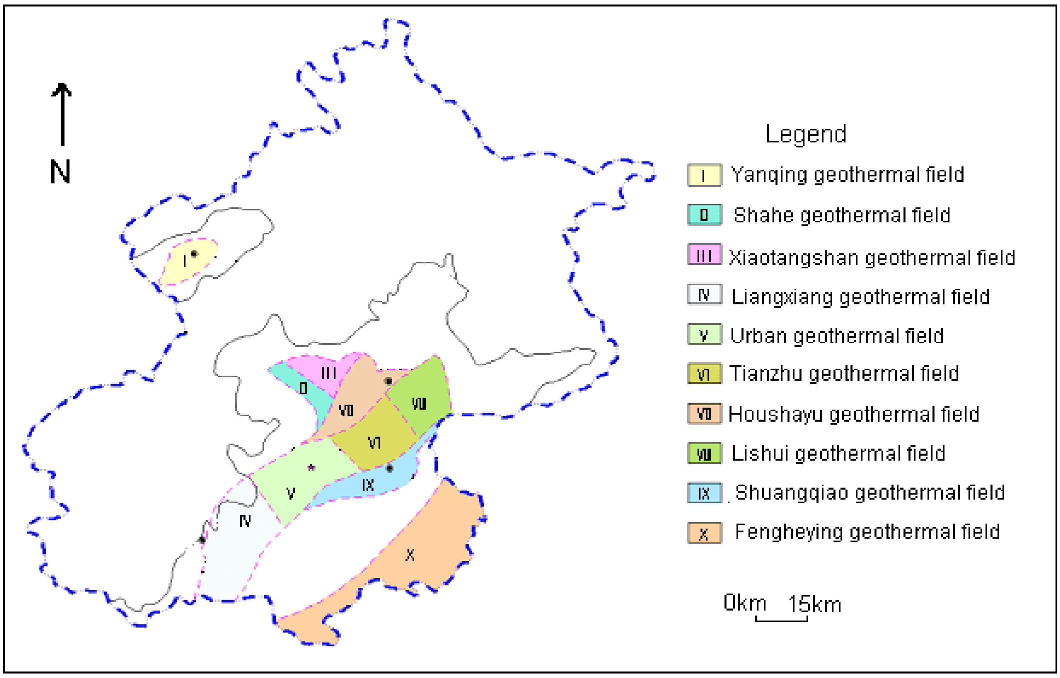

FIGURE 2: Distribution of geothermal fields in Beijing

Based on the successful drilling of well SR-6 and the results of an extensive geophysical exploration survey, Beijing City Tianyin Geothermal Development Co. decided to develop further the geothermal resources in Lishuiqiao and provide heating and domestic hot water for some inhabitants in this area. Four geothermal wells SR-6, JR-126, JR-94 and SRG-1(both production and reinjection wells) had been successfully drilled in the Lishuiqiao geothermal area by June 2002. A continuous water level record is also available from one seismic observation well in this area.

Careful production and reinjection monitoring is the basis of successful reservoir modelling. An appropriate model can be set up based on the monitoring data and the geological characteristics of the reservoir. A good model is a powerful tool for reservoir management. It provides the field operator with information about how the reservoir should be managed, how much water can be extracted from the reservoir, and what is the best reservoir management strategy. Therefore, it is very important to set up an appropriate model for reservoir management. The purpose of this report is to set up such a model for SR-6 and the Lishuiqiao geothermal system. The model is based on available well test data and production history data, including flow rate and wellhead pressure (or the water level) and water temperature. Well test data for well JR-126 is also used to try to understand the nature and behaviour of the system as well as assess its production potential. The following are the main items to be addressed:

1. To set up an appropriate model for the Lishuiqiao geothermal system;
2. To assess the properties and nature of the geothermal system;
3. To predict the water level drawdown due to production for different future utilization scenarios;
4. To assess the system's production potential with, or without reinjection;
5. To estimate the danger of thermal breakthrough due to reinjection, and the optimal distance between production and reinjection wells;
6. To make other relevant recommendations regarding management of the system.

This work is comparable to the sedimentary reservoir assessments by Axelsson and Dong (1998), Wang (1998) and Kang (2000).

2. THE LISHUIQIAO GEOTHERMAL SYSTEM

2.1 Geological background

The city of Beijing is located in the north part of the China-Korea geological quasi-platform. It is crossed by the Yanshan platform fold belt (often called WE-Beijing uplift) and the Huabei depression. The Beijing plain is divided into three geological parts, the NW-Beijing uplift, the Beijing depression and the Daxing uplift. The Shahe geothermal field is situated within the Beijing depression, and the Lishuiqiao geothermal system is part of the Shahe geothermal field. The rock formations in the Lishuiqiao geothermal system are controlled by complicated geological structures. A Quaternary formation covers all of the area, consisting of sand and clay, with a thickness varying from 100 to 350 m (Beijing Geological Survey and Technical Institute, 2001). Figure 3 shows a simplified structural map of the area, while Table 1 provides information on the wells in this area.

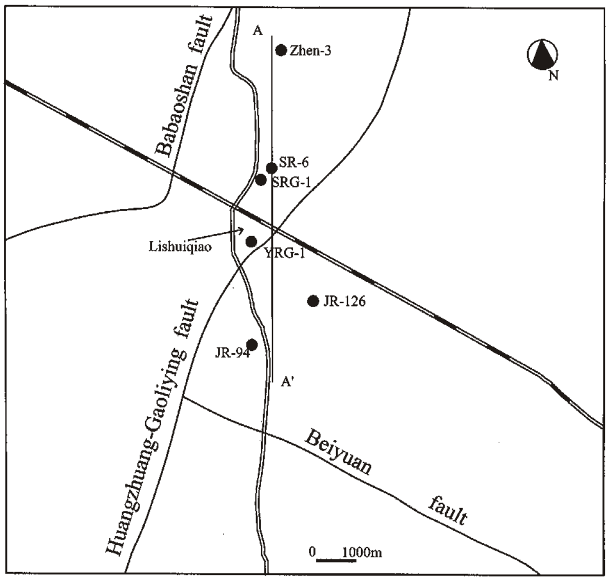

FIGURE 3: A simplified structural map of the Lishuiqiao area, location of cross-section AA' in Figure 4 is also shown

TABLE 1: Geothermal wells in the Lishuiqiao area

Well no.	Completion date (year)	Depth (m)	Aquifer formation	Aquifer depth (m)	Flow rate (l/s)	Temperature (˚C)
SR-6	2000	2418	Cambrian	2250-2418	~46	~72
JR-94	2001	3610	Ordovician	2898-3610	~19	~72
JR-126	2002	3648	Ordovician-Cambrian	2676-3648	~30	~74
SRG-1	2002	2898	Information not available			

2.1.1 Faults

There are three main faults crossing the Lishuiqiao area, the Huangzhuang-Gaoliying fault, the Babaoshan fault and the Beiyuan fault, all of which play an important role in the geothermal system.

- The Huangzhuang-Gaoliying fault is a normal fault, striking NE50° and dipping to the southeast at an angle of 70-80°. The fault is believed to be permeable and to extend to a great depth, perhaps as deep as 50 km, i.e. all the way down to the mantle. It is believed to provide a path for heat and water from depth, thus playing a very important role for the geothermal resources of the Lishuiqiao area. The fault crosses right through the centre of the area.
- The Babaoshan fault is an inverse fault, located to the west of the Lishuiqiao area. It strikes NE40-50° and dips to the southeast at an angle of about 30°.
- The Beiyuan fault is a normal fault to the south of the area.

The roles of the two last faults are not clearly understood now. For example, the Babaoshan fault may act as a kind of barrier.

2.1.2 Formation lithology

The information presently available on the lithology of the Lishuiqiao geothermal system is presented in Table 2 and Figure 4. It is based on results of geophysical prospecting and borehole geology. A Quaternary formation covers all of the area, but Tertiary and Cretaceous formations may be missing in some areas. Figure 4 shows a lithological cross-section through the Lishuiqiao geothermal system directed N-S, based on stratigraphic data from available boreholes. The location of the cross-section is shown in Figure 3.

TABLE 2: The lithological structure in the Lishuiqiao region

Stratum	Thickness (m)	Lithology
Quaternary - Q	100-350	Sandy cohesive soil, fine sand
Tertiary - T	240-370	Mudstone, sandstone and sandy conglomerate
Cretaceous - K	~1300	Andesite, rhyolite, tuff and volcano-clastic sedimentary rock
Jurassic - J	700-2200	Volcanic rock, andesitic pyroclastic rock, sandstone, etc.
Permian-Carboniferous - P-C	295-532	Sandstone, conglomerate and mudstone intercalated with coal
Ordocician - O	688-700	Limestone and dolomitic limestone
Cambrian - ∈	~500	Limestone, mudstone and siltstone
Qingbaikou Sys. - Qn	~500	Shale, sandstone and micritic limestone
Jixianxi Sys. - Jx	2000-3000	Dolomitic limestone, shale and dolomite

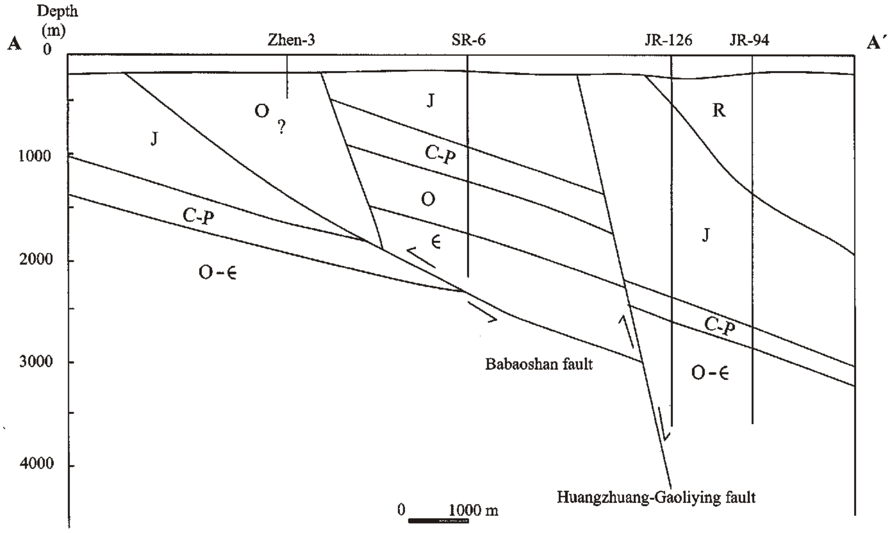

FIGURE 4: Lithological cross-section A-A' through the Lishuiqiao system; geological units are defined in Table 2

2.2 Reservoir features

Thermal conditions in the Lishuiqiao geothermal system are mostly controlled by heat conduction. Therefore, the reservoir temperature varies with depth according to the thermal gradient, which varies within the limits of 2-3.5°C/100 m. The reservoir temperature is 74-80°C according to temperature logs and discharge water temperature. According to the chalcedony geothermometer, the reservoir temperature is about 92°C ($T = 1032 /(4.69 - \log S) - 273.15$, (Fournier, 1977)). A reservoir temperature of about 80°C is assumed in the following.

It is believed that the Huangzhuang–Gaoliying fault plays an important role in the existence of the geothermal resource. Greater permeability near the fault creates an important path for heat and water. 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-∈), which consist of quite permeable limestone and dolomitic limestone. Another formation, the Jixian system (Chinese classification), which belongs to the Proterozoic, consisting of limestone, shale and dolomite, also hosts permeable aquifers. The latter is the main geothermal formation in Beijing. It is not considered economical to drill to this aquifer to the east of the Huangzhuang-Gaoliying fault because of the great depth. But it may be possible to the west of the fault. The Ordovician and Cambrian formations (O-∈) are considered the main reservoir rocks in this evaluation of the Lishuiquao system.

2.3 Production history of SR-6

Two of the geothermal wells drilled in the Lishuiqiao area have been utilized until now, wells SR-6 and JR-94. JR-94 was completed in the summer of 2001, and has been used to supply domestic hot water since the winter of 2001. Unfortunately no monitoring data, such as water level and production data are available for it. Well SR-6 was completed in March 2000, and it has been used for space heating during the two heating seasons since then. According to a completion well test, this well is quite productive compared to other wells in Beijing. Figure 5 shows the two-year production history of SR-6 since March 2000. It also includes data from two well tests, one during completion in March 2000 and the other in July 2001. Positive water level indicates wellhead pressure. By now, the total production is about 280,000 m^3, corresponding to an average winter-time production of about 13 l/s. It must be kept in mind that water level changes are not only induced by production, but also by water temperature. During limited, or no discharge, the water column in the well is cooled down, which causes it to contract.

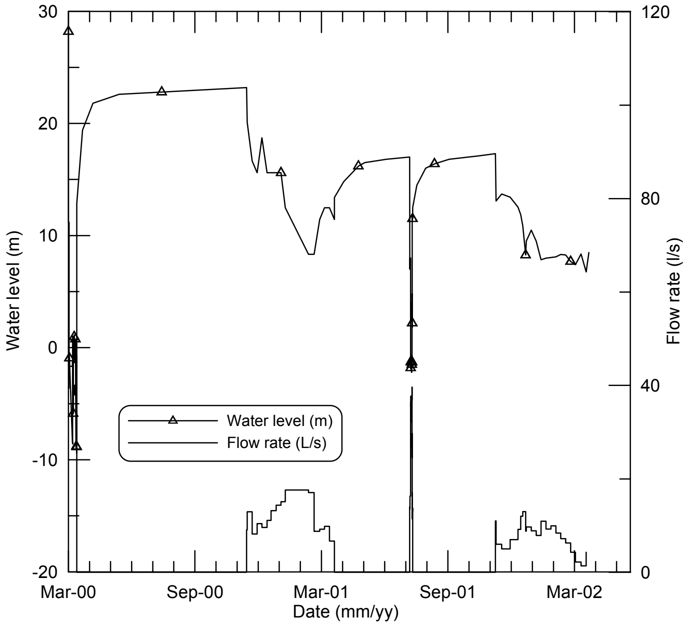

FIGURE 5: Production and water level history of well SR-6

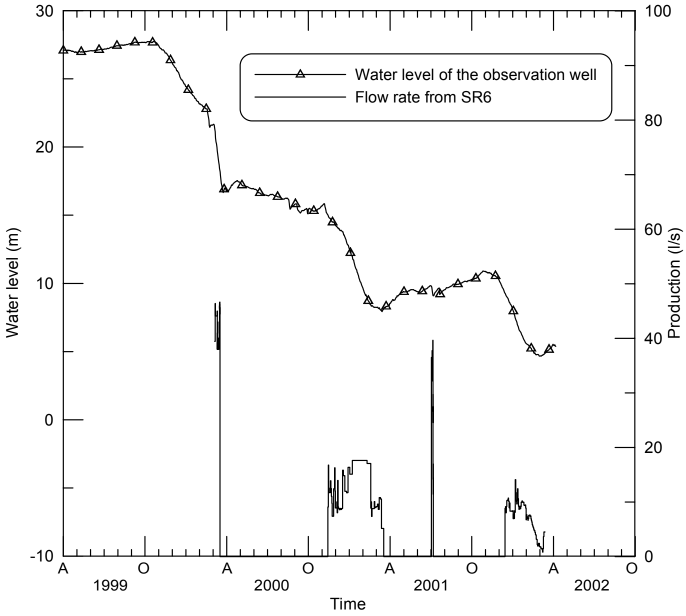

FIGURE 6: Water level changes in earthquake observation well Zhen-3 and flowrate of well SR-6

Figure 6 shows the water level changes in the earthquake observation well Zhen-3 and the flow rate of well SR-6 for comparison. Great water level changes are seen in well Zhen-3 some of which appear to be caused by production from SR-6. Figure 5 shows that the water level difference in SR-6 between the winter of 2001 and the winter of 2000 is about 1.5 m. Figure 6 shows that the lowest water level drop in Zhen-3 is about 5 m between these two time-points. Therefore, it is likely that the water level changes in the observation well are not only affected by well SR-6, but possibly also by other production wells. This could either be other geothermal wells or deep groundwater wells. It is noteworthy that the water level in Zhen-3 dropped drastically 10 m during the winter of 1999/2000 before SR-6 was completed. It is also worth noting that the well test in July 2001 caused a small water level change compared to the well test in March 2000.

2.4 Pressure transient data

The water level drawdown in a production well reflects not only the pressure change caused by laminar flow in the reservoir, but also an additional pressure drop, which is associated with turbulent flow caused by flow through narrow feed-zones, flow through the well screen and flow inside the well to the pump intake. So the water level, or pressure, measured in a production well is a combination of these factors. Before using the measured water level and pressure to simulate changes in a reservoir, these data need to be corrected. In order to estimate turbulence pressure changes, a step rate-pumping test is required. Figures 7 and 8 show water levels versus flowrate plots for step-rate well tests of SR-6 and JR-126, respectively. The curves deviate from linear behaviour to second order behaviour, implying turbulence. This situation is expressed by the polynomial regression equation:

$$H = H_o + BQ + CQ^2 \tag{1}$$

where Q = Production flow rate [l/s];
H_o = Water level in the production well at zero flow [m];
BQ = Linear drawdown in the reservoir, caused by Darcy flow [m];
CQ^2 = Pressure loss caused by turbulent flow at the location of inflow into the well and in the well itself [m];

The factor BQ increases with time while the factor CQ^2 is constant.

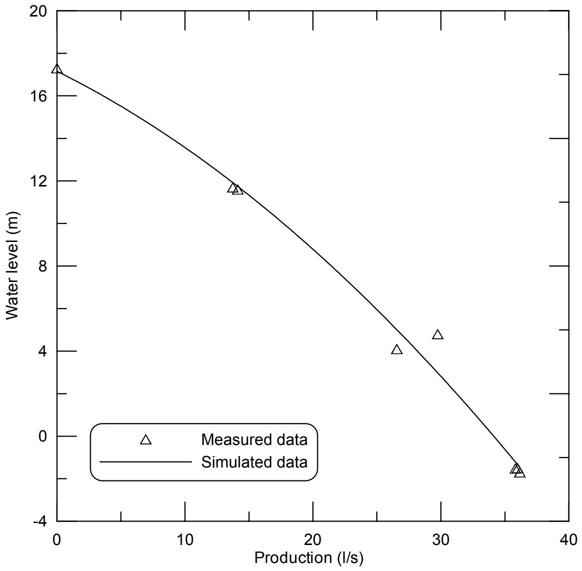

FIGURE 7: Production characteristics of well SR-6 based on the July 2001 step rate well test

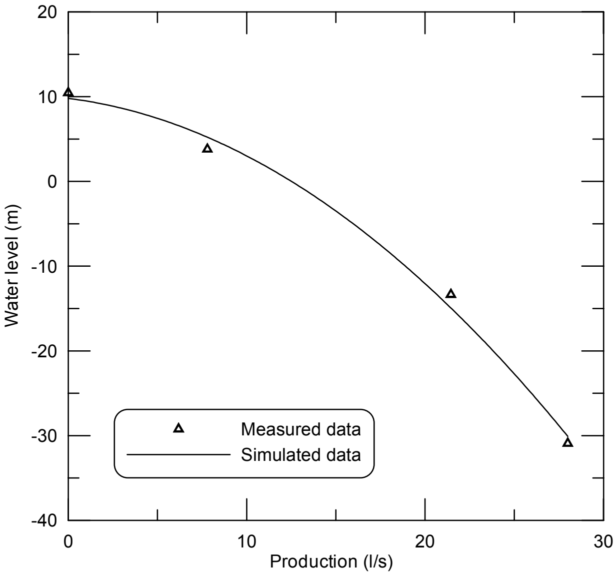

FIGURE 8: Production characteristics of well JR-126 based on a step-rate completion test

The best fitting equation for the pumping test data for SR-6, presented in Figure 7, is

$$H = 17.16 - 0.229 \times Q - 0.006 \times Q^2 \quad \textit{(Coefficient of determination = 0.988)} \qquad (2)$$

The best fitting equation for the pumping test data for JR-126, presented in Figure 8, is

$$H = 9.80 - 0.264 \times Q - 0.0414 \times Q^2 \quad \textit{(Coefficient of determination = 0.995)} \qquad (3)$$

These equations show that turbulent pressure losses are much greater in JR-126 than in SR-6. This can be seen more clearly in Table 3. The measured water level, or pressure, in the production wells should be corrected by using the above equations before further analysis is undertaken.

TABLE 3: Calculated turbulent pressure losses in wells SR-6 and JR-126

Flow rate (l/s)	**Pressure loss (m)**	
	SR-6	**JR-126**
10	0.6	4.1
20	2.4	17
30	5.4	37

Fluid density changes with fluid temperature, so water level data is affected by fluid temperature as already mentioned. Thus, water level data should be revised to the water level corresponding to the same fixed temperature. This can be done through using the program PREDYP in the ICEBOX software package or by using the following equation:

$$(h_s)_{corr} = H_o + (H_o - h_s)\frac{\rho_s}{\rho_f} \qquad (4)$$

where H_o = Feed-zone depth (m);
$(h_s)_{corr}$ = Corrected water level (m);
h_s = Measured water level (m);
ρ_s = Average water column density at time of measurement (kg/m^3);
ρ_f = Water density at correction temperatures (kg/m^3).

The above equation is used here to correct the water level measured in SR-6 during summer to correspond to values measured during winter, when the well is flowing at maximum temperature.

3. RESERVOIR MODELLING OF THE LISHUIQIAO GEOTHERMAL SYSTEM

Modelling of geothermal systems, as well as other hydrological reservoirs, is used extensively as a tool for resource assessment. During different development phases, conceptual models, natural state models and exploitation models are developed. Considering the information available on a geothermal system as well as the time available and cost, different modelling approaches may be chosen. These include simple analytical models, lumped parameter models and detailed numerical models. These models are based on appropriate conservation- and transport equations. The basic method of modelling involves matching the collected data, using any of these simulators, then predicting the response of the reservoir to future production and estimating the production potential of the system. The model can also be used to estimate the outcome of different management actions. Models are very important tools for geothermal reservoir management.

In this report the simulation programs LUMPFIT and VARFLOW are used. LUMPFIT is a powerful lumped parameter simulator, which integrates all of the properties into lumped values, but does not consider reservoir geometry. It can neither simulate the behavior of, nor the interference between individual wells distributed over a large area. VARFLOW is based on a Theis model of an infinite horizontal reservoir. It can take individual wells into account, but is based on a fixed geometry, which is not always in agreement with reality.

3.1 Conceptual model

A conceptual model is the fundamental basis of successful reservoir modelling. It describes what are believed to be the main factors in the structure and nature of a geothermal system. A sketch of the current conceptual model of the Lishuiqiao geothermal system is shown in Figure 9. It is based on available geological, geophysical and borehole data.

The main factors may be summarized as follows:

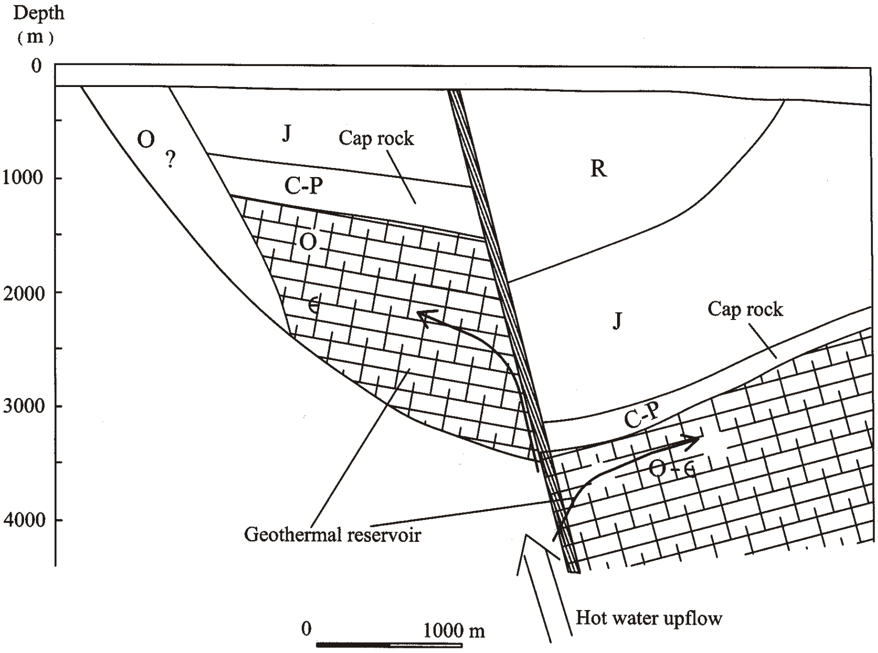

FIGURE 9: Schematic figure of the conceptual model of the Lishuiqiao geothermal system

- The reservoir is a low-temperature sedimentary reservoir, with conduction-dominated heat-flow, reservoir temperature is about 80°C;
- The production reservoir is in a Cambrian and Ordovician limestone formation, with an effective thickness of 500 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;
- The recharge water is of meteoric origin from the hills and mountains in NW-Beijing.

3.2 Lumped parameter models

Lumped parameter models have been extensively used to simulate data on water level and pressure changes in geothermal systems in Iceland and other parts of the world (Axelsson and Gunnlaugsson, 2000). Such models ignore reservoir geometry, and integrate reservoir properties into a few lumped values. Here the program LUMPFIT, based on appropriate analytical functions, is used to set up some models to simulate the water level response (SR-6) to production in the Lishuiqiao geothermal system. The program LUMPFIT was developed by Axelsson and Arason (1992). This computer program tackles the simulation problem as an inverse problem. It automatically fits analytical response functions of lumped models to the observed data by using a non-linear iterative least-squares technique for estimating the model parameters (Axelsson, 1989).

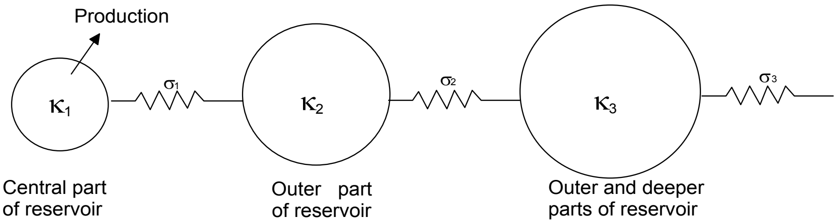

FIGURE 10: General open three-tank lumped parameter model (Axelsson, 2002a)

Lumped models consist of a few capacitors or tanks that are connected by conductors or resistors. A general open three-tank lumped model is shown in Figure 10. The tanks simulate the storage of different parts of the reservoir in question, whereas the resistors simulate permeability. A tank in a lumped model has mass storage coefficient κ when it responds to a load of liquid mass m with a pressure increase given by $p = m/\kappa$. The mass conductance of a resistor in a lumped model is σ when it transfers $q = \sigma \Delta p$ units of liquid mass per unit time at the impressed pressure difference Δp. The pressure (water level) in the tanks simulates the pressure in different parts of the reservoir, whereas production from the reservoir is simulated by withdrawal of water from one of the tanks.

Lumped models can either be open or closed. When open, they are connected by a resistor to an infinitely large imaginary reservoir, which maintains a constant pressure. When closed, lumped models are isolated from any external reservoirs. Actual reservoirs may be represented by a few tank lumped parameter models, closed or open, a one-tank closed model being the simplest.

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:

$$p(t) = -\sum_{j=1}^{N} Q \frac{A_j}{L_j}\left[1 - e^{-L_j t}\right] \tag{5}$$

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

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

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

Two lumped models are set up here to simulate the water level response to production by using LUMPFIT; one is a closed three-tank model, and the other is an open three-tank model. These models give the best fit obtained. The simu-lated and measured water levels over the period from March 2000 to March 2002, combined with flow rates in well SR-6, are shown in Figure 11. The fit is very similar for these two different models, so just one figure is presented.

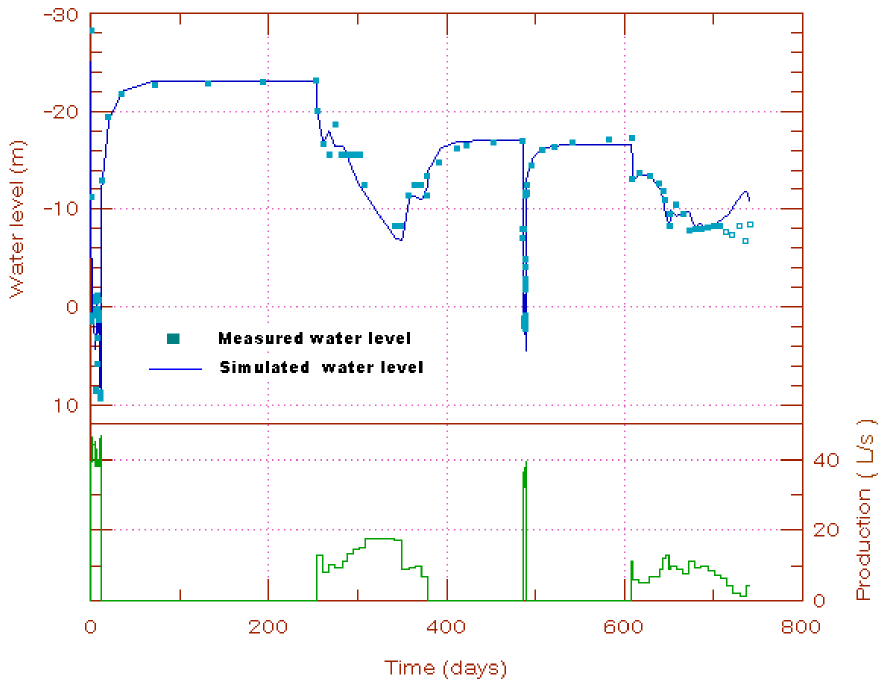

FIGURE 11: Water level variations in SR-6 during the two years production history simulated by program LUMPFIT

It should be mentioned that it was not possible to simulate part of the data set because of discrepancy between flow-rate and water level. These are the last few data points (shown as open squares in Figure 11) where water level declines even though production decreases. The explanation for this is not known, but it might be interference from other wells (JR-126 or SRG-1?).

The parameters of the two models are presented in Table 4. These can be used to estimate properties of the reservoir, such as the reservoir volume, surface area and permeability or permeability-thickness. Furthermore, after the best fit is obtained by LUMPFIT, the model can be used to predict the reservoirs' future water level responses for given production scenarios.

TABLE 4: Parameters of the two three-tank lumped models for well SR-6 in the Lishuiqiao geothermal system

Parameters	**Closed model**	**Open model**
A_1	7.33	7.37
L_1	29.3	29.5
A_2	0.0248	0.0248
L_2	0.0844	0.0851
A_3		0.00392
L_3		0.000127
B	0.0038	
κ_1 (ms^2)	1.20	1.19
κ_2 (ms^2)	308	307
κ_3 (ms^2)	2020	1950
σ_1 (10^{-4}ms)	4.04	4.06
σ_2 (10^{-4}ms)	2.62	2.62
σ_3 (10^{-4}ms)		0.0329
Coefficient of determination	88%	88%
Remarks	κ : Capacitance (storage) σ : Conductivity (permeability)	

By assuming a reservoir thickness of 500 m, an average porosity of 5% and confined and two-dimensional flow, the parameters in Table 4 can be used to estimate properties of the reservoir (Axelsson, 2002a). The results for the two different models are presented in Table 5.

TABLE 5: Estimates of reservoir properties based on lumped parameters

Model	Parameters	First tank	Second tank	Third tank	Total
Closed three-tank model	Surface area	5.6×10^4 m^2	1.4×10^7 m^2	9.4×10^7 m^2	110 km^2
	Volume	2.8×10^7 m^3	7.3×10^9 m^3	4.7×10^{10} m^3	55 km^2
	Permeability-thickness	68 Dm	20 Dm		
Open three-tank model	Surface area	5.6×10^4 m^2	1.4×10^7 m^2	9.1×10^7 m^2	105 km^2
	Volume	2.8×10^7 m^3	7.1×10^9 m^3	4.5×10^{10} m^3	53 km^2
	Permeability-thickness	68 Dm	19 Dm	0.13 Dm	

The properties of the two models are almost the same, caused by the fact that the open model is almost closed as the permeability-thickness between the third tank and the outside is very low, only 0.13 Dm. This is an important result concerning long term utilization of the reservoir, which indicates that natural recharge will be very small. The estimated reservoir area is about 110 km^2, which may be compared to the area of Shahe geothermal field. The permeability-thickness between the first tank and the second tank is 68 Dm, and it is 19.3 Dm between the second tank and the third tank, reflecting good permeability.

It should be pointed out that some assumptions are inherent when LUMPFIT is used to fit and calculate. Some of these don't agree with the actual situation. Furthermore, well SR-6 has operated for only two years, and only at a fraction of its capacity, so a lot of information on the reservoir has not been revealed. As exploitation from the reservoir increases, and more data become available, the model can be updated and refined by matching the longer production history, to make the model as accurate as possible. Consequently, this would result in more reliable calculations and predictions for the reservoir.

3.3 Distributed parameter model

The distributed parameter computer code VARFLOW (EG&G Idaho Inc., and Lawrence Berkeley Laboratory, 1982) was used to calculate pressure changes in response to fluid production or injection into an idealized reservoir system. It is based on the Theis model, which is based on assumptions described as follows:

a. The reservoir is of infinite areal extent, or bounded on one side by a linear constant potential or barrier boundary.
b. The reservoir is completely saturated with slightly compressible single-phase water.
c. The reservoir is isothermal.
d. The reservoir is horizontal and has a constant thickness H.
e. The flow of fluid in the reservoir is described by Darcy's law.
f. The reservoir is homogeneous and bounded above and below by impermeable layers.
g. The reservoir permeability can be anisotropic in a horizontal plane.

It should be noted here that these assumptions are rather restrictive, in particular the geometrical constraints (*a, d* and *f*). In this model, pressure changes caused by production or reinjection from or into a single well, with a variable flowrate, can be calculated by using the following equation:

$$\Delta p(t) = \frac{1}{4\pi}\left(\frac{\mu}{kh}\right)_e \int_{\tau_n}^{\tau_{n+1}} \frac{q(\tau)}{t-\tau} \exp\left[\frac{-r^2}{4\eta_\theta (t-\tau)}\right] d\tau \tag{7}$$

where $\Delta p(t)$ = Pressure change at time t due to the flow rate, $q(\tau)$, $\tau_n < t < \tau_{n+1}$;
μ = Dynamic viscosity of the fluid;
k = Permeability;
h = Reservoir thickness;
τ_n = Time at which the flow starts;
τ_{n+1} = Time at which the flow stops;
$q(\tau)$ = Volumetric flow rate at time;
r = Distance between the observation well and the production/reinjection well;
kh/μ = Effective transmissivity = $\sqrt{((kh/\mu)_x \times (kh/\mu)_y)}$
θ = The angle between the line adjoining the observation well and the production / reinjection well as measured counter-clockwise from a line parallel to the x-axis;
η_θ = Hydraulic diffusivity ($\eta_\theta = (kh/\mu)_\theta / \phi ch$); and

$$(kh/\mu)_\theta = \frac{(kh/\mu)_x}{\cos^2\theta + \dfrac{(kh/\mu)_x}{(kh/\mu)_y}\sin^2\theta}$$

The pressure response, caused by production/reinjection from more than one well, is calculated by summing up the responses due to each production/reinjection well.

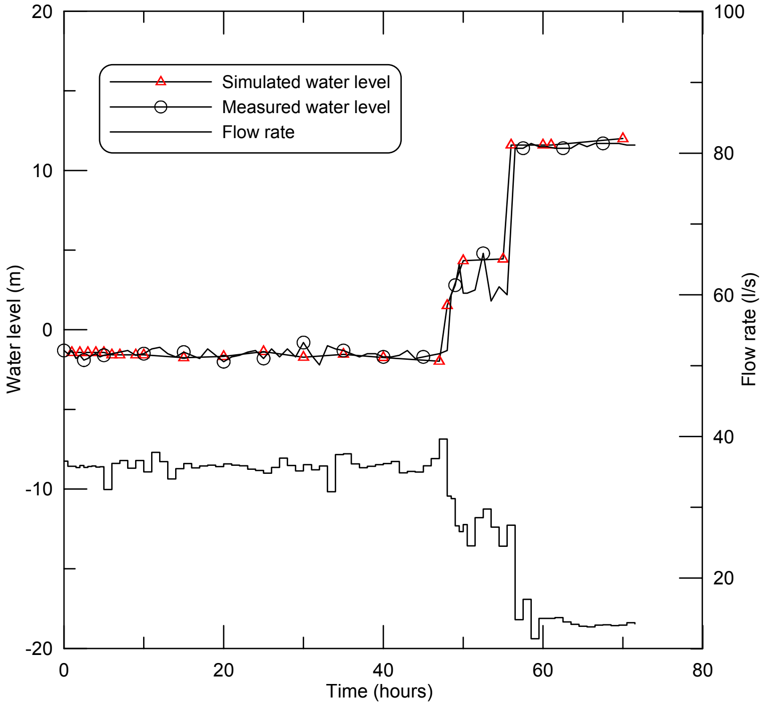

FIGURE 12: Water level variations in SR-6 during the short term well test in July 2001 simulated by program VARFLOW

Based on the conditions believed to prevail in the Lishuiqiao geothermal reservoir, anisotropic permeability is assumed. The Huangzhuang-Gaoliying fault is assumed parallel to the Y-axis, and well SR-6 is chosen as the origin. Figure 12 shows the match results between the observed and simulated water level in well SR-6 for the short-term well test conducted in July 2001. According to the simulation results, the estimated reservoir parameters are as follows:

X-direction transmissivity:
$T_x = 5.5\times10^{-8}$ m^3/Pa s

Y-direction transmissivity:
$T_y = 4.9\times10^{-6}$ m^3/Pa s

Storage coefficient:
$S = 9.28\times10^{-8}$ m/Pa s

The anisotropy, $Ty/T_x = 89$, is assumed quite high reflecting the fact that permeability along the Huangzhuang-Gaoliying fault is very big. The hydraulic connection in that direction is assumed to be good, in agreement with the water level changes in observation well Zhen-3. It should be pointed out that the anisotropy is based on an assumption; it cannot be determined uniquely on the basis of well test data from a single well. From the above results, the average transmissivity and permeability of the reservoir are estimated as follows (assuming $h = 500$ m and $s = 3.6\times10^{-4}$ kg/ms):

$$T = \sqrt{T_x \times T_y} = 5.19 \times 10^{-7} \; m^3 / Pa\,s \tag{8}$$

$$\langle k \rangle = \sqrt{(\mu T_x / h) \times (\mu T_y / h)} = 0.37 \; D \tag{9}$$

$$kh = 185 \, Dm \tag{10}$$

This value is considerably greater than that estimated on the basis of the lumped parameter model, but only reflects permeability next to SR-6.

The pressure distribution in the reservoir can also be calculated by using the distributed parameter model (VARFLOW), and hence water level contour maps may be plotted at any time during the well test. Figure 13 shows calculated water level contours around well SR-6 at the end of the well test in July 2001.

When using VARFLOW, several reinjection wells, production wells and observation wells may be included in the calculation. The program can be used to predict the water level changes in production wells due to reinjection at some distance from the production well, and to predict interference between production wells. Therefore, a VARFLOW distributed parameter model based on long term well test data may be used as a tool when production and reinjection wells are to be located.

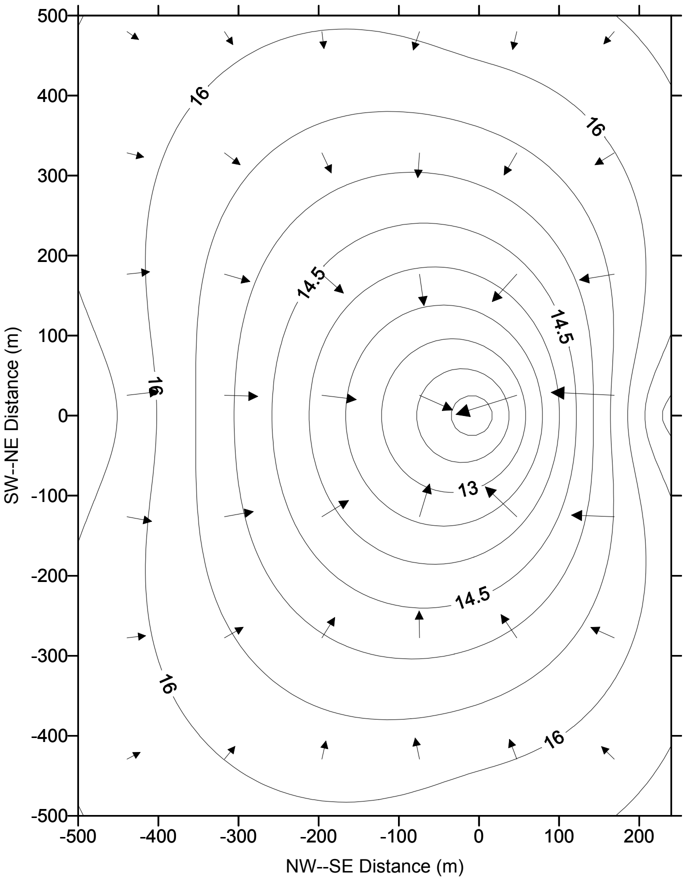

FIGURE 13: Water level contour map around well SR-6 at the end of the well test in July 2001 according to VARFLOW

It turned out that VARFLOW could not be used to simulate the two-year production history of SR-6, probably because the reservoir behaves like a closed system. Thus, simulation by a more complex detailed numerical model is recommended sometime in the near future.

4. PRODUCTION POTENTIAL OF THE LISHUIQIAO GEOTHERMAL RESERVOIR

It has long been recognized that the basic tasks and main objectives of reservoir engineering are the assessment of production potential and response predictions for long-term behaviour of wells and reservoirs. This should be based on all available information of the reservoir's nature and properties. The lumped parameter model was here used to estimate the production potential of the Lishuiqiao geothermal reservoir, by calculating water level forecasts for different future production scenarios, since the production response of the reservoir is chiefly manifested by water level drawdown. The distributed parameter model (VARFLOW) will not be used to assess the production potential of Lishuiqiao geothermal reservoir for reasons mentioned above.

The program LUMPFIT was used to predict the water level changes in response to production. The production potential is assessed on the basis of long-term predictions and maximum water level drawdown, determined from the setting depth of submerging pumps. Here, the maximum allowable water level drawdown is assumed as 200 m. The production scenarios for SR-6 are as follows:

Scenario I:
Production in heating season (125 days): 30 l/s;
Production in non-heating season (240 days): 0 l/s
Annual average production: 315,000 m^3/year (10 l/s);

Scenario II:
Production in heating season (125 days): 30 l/s;
Production in non-heating season (240 days): 15 l/s
Annual average production: 630,000 m^3/year (20 l/s);

The closed three-tank and open three-tank models were both used to predict water level drawdown in SR-6 for the next 10 years. The more pessimistic model, the closed three-tank model was consequently used to assess production potential. Figures 14 and 15 show the prediction results. The figures show that for scenario I, the water level in the production well will stay above 150 m for the next 10 years according to the models. For scenario II, the water level in the production well will go as deep as 275 m after 10 years, and drawdown will reach about 200 m in about 7 years. It should be mentioned that the predictions of the open and closed models may be looked upon as upper and lower bounds, and that reality will most likely lie somewhere in between them. The open and closed predictions also give an indication of the uncertainty in the predictions.

Based on these results, the production potential of the Lishuiqiao geothermal area is estimated to be about 440,000 m^3/year, or an average 14 l/s, for the next 10 years. The estimated production potential of the Lishuiqiao geothermal reservoir is based on predictions for the next 10 years only, and is based on two years of monitoring data from one production well only. So it should be looked upon as rather uncertain. The reservoir potential estimate should be revised on a regular basis in the future, as geothermal resource development in this area continues.

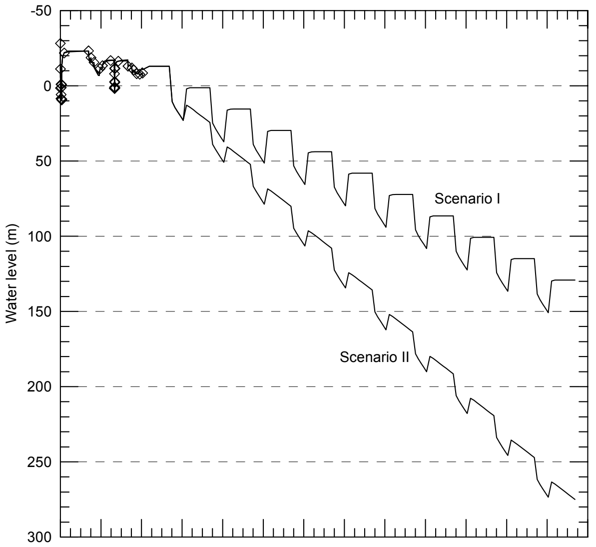

FIGURE 14: Predictions of water level draw-down in well SR-6 for the next 10 years calculated by a closed three-tank lumped model

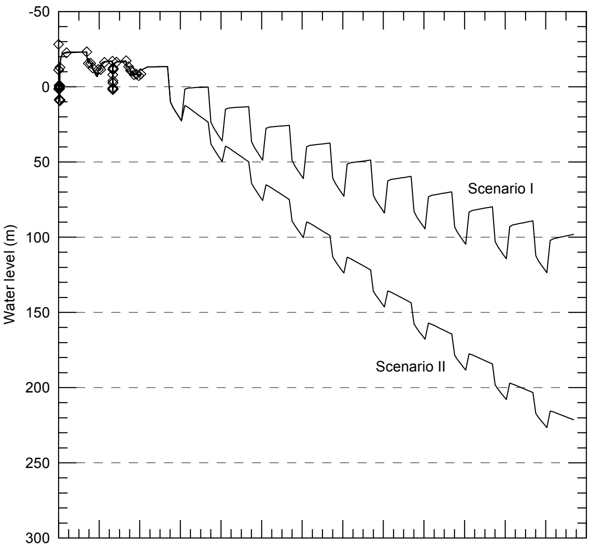

FIGURE 15: Predictions of water level draw-down in well SR-6 for the next 10 years calculated by an open three-tank lumped model

5. REINJECTION

According to the results of the lumped parameter simulation, the geothermal system is closed and water level drawdown will continue to increase rapidly in the coming years. The natural recharge to the system is, therefore, limited, which is also reflected in the water level drawdown in well Zhen-3. It is, therefore, essential to reinject the return geothermal water into the reservoir in order to enable sustainable utilization and to increase reservoir longevity.

5.1 Background

Fluid reinjection is currently used in many geothermal fields around the world. The primary purpose has been the disposal of wastewater for environmental reasons, but has more recently been recognized as an essential and important part of reservoir management (Stefánsson, 1997). It is a powerful method for increasing the longevity of geothermal resources and the amount of energy that can be extracted from a given reservoir. Yet, reinjection is one of the most complex methods used in the exploitation of geothermal resources. It is a multi-parameter method where a good knowledge of (i) the chemistry of the geothermal fluid, (ii) water-rock interaction, (iii) geothermal reservoir engineering, and (iv) mechanical engineering is essential to success (Stefánsson, 1997).

But all methods have their positive and negative sides. Reinjection can maintain the geothermal reservoir pressure and increase a reservoirs' longevity. At the same time, there are some problems associated with reinjection. It adds to the cost of operating a geothermal field, such as the extra cost of drilling reinjection wells and for surface piping to transport the geothermal return water to the reinjection wells. And if the distance between the reinjection well and production well is too short, reinjection can also cool down the production well (thermal breakthrough). It can also cause scaling in surface equipment and reinjection wells. Careful studies must be made before a decision is taken to execute reinjection in a geothermal reservoir, such as through tracer tests. Careful monitoring should be employed during reinjection.

According to the lumped parameter model, recharge to the Lishuiqiao reservoir is very limited. Therefore, reinjection should be a very important part of the management of the reservoir. Figures 16 and 17 show predictions calculated by the closed three-tank model and the open three-tank model, with and without

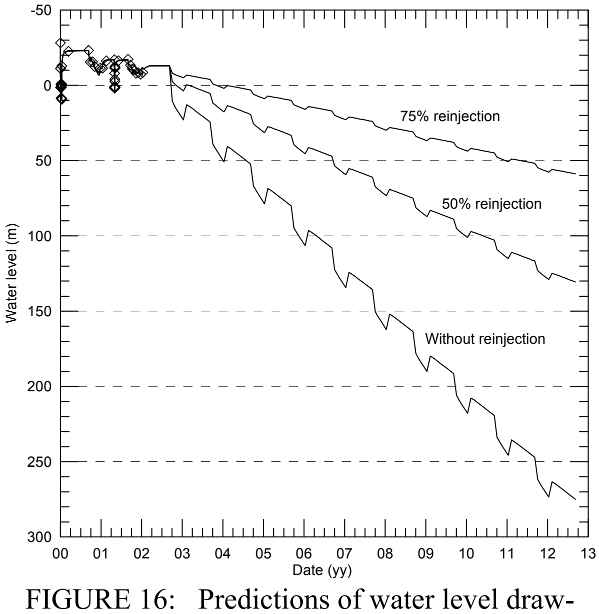

FIGURE 16: Predictions of water level drawdown in well SR-6 for the next 10 years with and without reinjection based on the closed three-tank lumped model

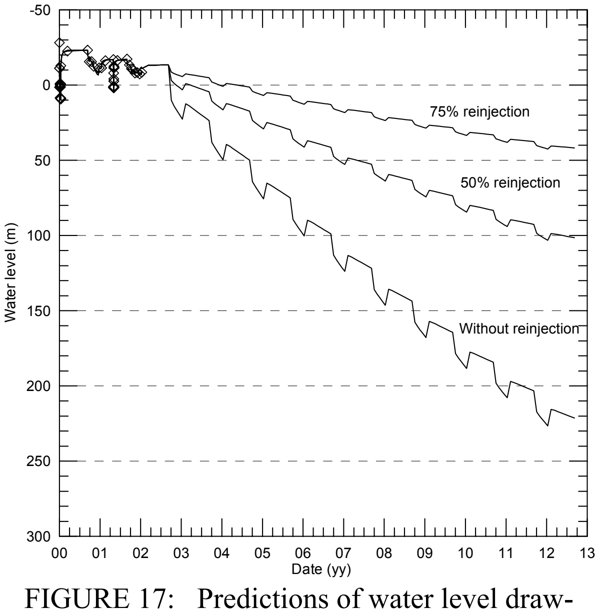

FIGURE 17: Predictions of water level drawdown in well SR-6 for the next 10 years with and without reinjection based on the open three-tank lumped model

reinjection. Here, only scenario II is considered with 50 and 75% reinjection compared to no reinjection. The figures clearly show that reinjection will be essential for sustainable utilization of this reservoir.

5.2 Reservoir potential involving reinjection

According to the closed three-tank model, the water level will stay above 130 m with 50% reinjection and above 60 m with 75% reinjection, during the next 10 years. According to the open three-tank model, the water level will stay above 100 m with 50% reinjection and above 40 m with 75% reinjection, over the next 10 years.

According to the closed three-tank model, it will take about 14 years for the water level to reach 200 m depth with 50% reinjection, and it will take about 30 years for the water level to reach 200 m with 75% reinjection. Calculations by the closed three-tank model indicate that production potential will be about 880,000 m^3/year and 1,890,000 m^3/year with 50% and 75% reinjection, respectively. These estimates indicate, in fact, the maximum benefit from reinjection since the lumped model calculations are based on net production. In the actual situation, the effect of reinjection is not well known; it depends on the interference between reinjection and production wells. Therefore, the effect of reinjection must be studied carefully before it becomes part of the management of the Lishuiqiao reservoir.

5.3 Thermal breakthrough time

Thermal breakthrough time is defined as the time it takes a production well to start cooling down after reinjection starts in a nearby well. It is some orders of magnitude longer than the time it takes the reinjection water to travel this distance. There are different methods available to estimate thermal breakthrough time as a function of reinjection-production well spacing. Each of the methods is based on specific assumptions on geometry and other conditions. Two methods will be used here to calculate 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 this model, thermal breakthrough is induced quickly, providing a kind of worst case situation. These two methods can be assumed to represent the two possible extremes with actual thermal breakthrough occurring between the two calculation results.

First, consider the theory of heat transport in porous media liquid-phase geothermal systems to estimate the thermal breakthrough time. One reinjection well is considered with no production nearby. It is assumed that heat transport is by intergranular fluid flow and rock grains are so small that rock and fluid are at the same temperature at any point. The approximate differential equation describing this is as follows:

$$\frac{\partial T}{\partial t} + \frac{\beta_w}{\langle \rho\beta \rangle} \vec{\mathbf{q}} \cdot \nabla T = 0 \tag{11}$$

where T = Temperature (°C);
β_w = Heat capacity of water (J/kg°C);
$<\rho\beta>$ = Volumetric heat capacity of the reservoir (J/m^3/°C);
$\vec{\mathbf{q}}$ = (q_x, q_y, q_z) the mass flux vector (kg/m^3/s);
∇T = $(\partial T/\partial x, \partial T/\partial y, \partial T/\partial z)$, the temperature gradient vector.

Different models are available to simulate heat transport in porous media. Here, an infinite horizontal reservoir model with two-dimensional flow and constant reservoir thickness H is considered. It is assumed that q kg/s of cold water ($T = 0°C$) are injected since time $t = 0$. The cold fronts consequently move away from the reinjection well with time. The time it takes the temperature front to move from the reinjection well to a given radial distance is expressed by the following equation:

$$t = \frac{\pi H \langle \rho\beta \rangle r_T^2}{\beta_w q} \tag{12}$$

Here the following parameters are used in the calculations. The reservoir average thickness is $H = 500$ m, injection flow rate is $q = 20$ kg/s, density of water is $\rho_w = 1000$ kg/m^3, heat capacity of water is $\beta_w = 4200$ J/kg°C, porosity is $\phi = 0.05$, density of wet rock is $\rho_r = 2750$ kg/m^3, heat capacity of wet rock is $\beta_r = 921$ J/kg°C. According to the model, it takes 560 years for the cold front to move 600 m and 1500 years to move 1000 m. However, most of the reinjected water may travel through specific flow channels in the reservoir. This may be accounted for by changing the thickness to 50 m only; other parameters don't change. Then it takes 56 years for the cold front to move 600 m and 150 years to move 1000 m according to the model.

The other method is based on a one-dimensional fracture-zone flow channel model to predict the water temperature (see Figure 18). The cross-sectional area $A = h \times b$ is estimated by analysing the tracer recovery data, if that is available, and, hence, the total contact area between the reservoir rock and the flow channel; otherwise, this area is assumed. Given the flow channel inlet temperature T_i, channel height h, length L and width b as well as undisturbed rock temperature T_o, we can estimate the temperature of the injected fluid at any distance x along the flow channel. This is based on a formulation that considers coupling between the heat convected along the flow channel and the heat conducted from the reservoir rock to the channel fluid (Axelsson et al., 1995). The analytical solution for the fluid temperature is as follows:

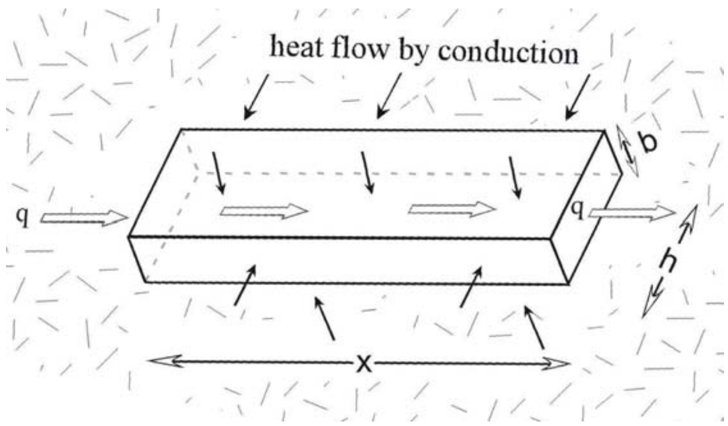

FIGURE 18: One-dimensional fracture-zone model (Axelsson et al., 2002b)

$$T_q = T_i + \left(T_o - T_i\right) erf\left[\frac{Kxh}{\beta_w q \sqrt{\kappa (t - x/\alpha)}}\right] \tag{13}$$

This equation is valid at times $t > x/\alpha$ with α defined as $\alpha = q\rho_w / <\rho\beta> hb$, and

K = Thermal conductivity of the reservoir rock (J/°C/m/s);
κ = Thermal diffusivity of the reservoir rock (m^2/s);
q = Reinjection flow rate (kg/s);
β_w = Heat capacity of water (J/kg°C);
$<\rho\beta>$ = Volumetric heat capacity of the wet fracture zone-material (J/m^3/°C).

The temperature of the produced fluid, assuming a constant temperature, T_o, for all feedzones in a production well except the one connected to the flow channel, is finally given by (assuming $Q > q$ where Q is the production rate)

$$T(t) = T_o - \frac{q}{Q}\left[T_o - T_q\right] \tag{14}$$

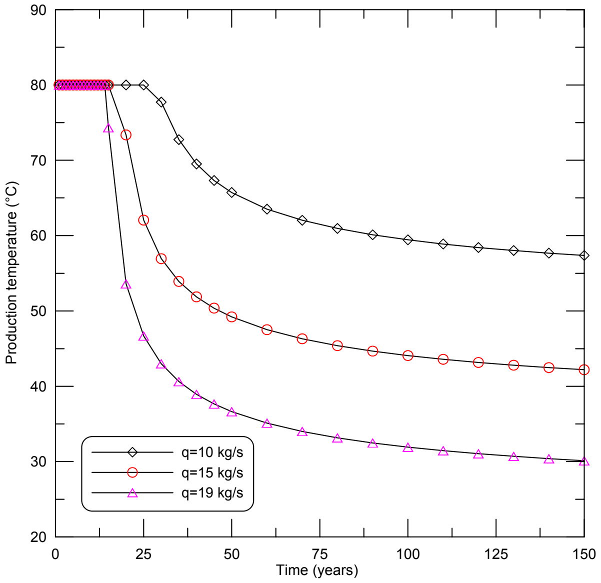

FIGURE 19: Calculated temperature changes in a production well during reinjection into a well at a distance of 500 m assuming a fracture zone connection

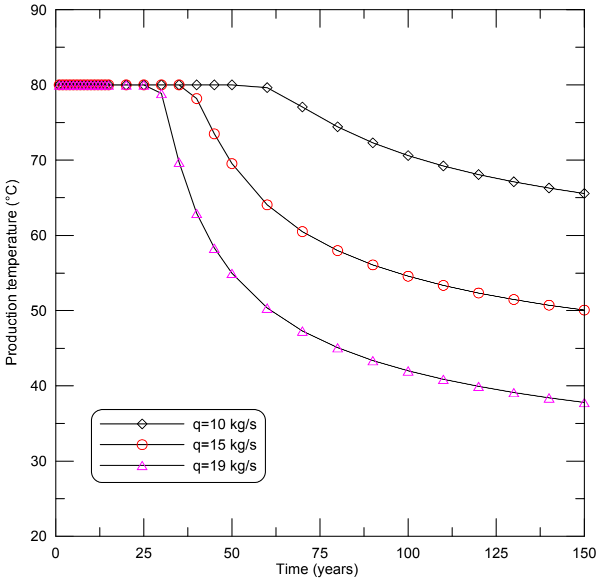

FIGURE 20: Calculated temperature changes in a production well during reinjection into a well at a distance of 1000 m assuming a fracture zone connection

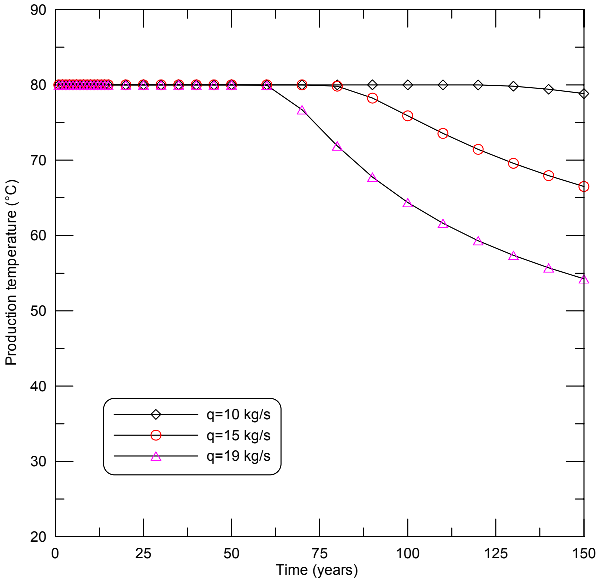

FIGURE 21: Calculated temperature changes in a production well during reinjection into a well at a distance of 2000 m assuming a fracture zone connection

Program TRCOOL in the ICEBOX package can be used to predict the temperature changes in a production well during reinjection according to this model. Here, three different situations are considered, L = 500, 1000 and 2000 m as well as reinjection rates of q = 10, 15 and 19 kg/s, with porosity of 0.05, reservoir thickness of 500 m, reservoir temperature of 80°C, reinjection temperature of 20°C, flow channel height, h = 500 m and flow channel width, b = 50 m and Q = 20 kg/s. Figures 19, 20 and 21 show the results of these calculations.

It appears from these plots that a safe distance between production and reinjection wells should be about 1000 m. For that distance, thermal breakthrough should not occur in less than 30 years, even if 100% reinjection is applied. Maximum production may also be expected to have some effects on the thermal breakthrough time. The larger the production, the faster the thermal breakthrough. However, it should be kept in mind that these results are highly uncertain because the flow channel dimensions are unknown; they are just calculated based on some likely assumptions. A tracer test will provide very important information on the calculations between wells and flow-path dimensions.

5.4 Location of reinjection wells and reinjection strategy

Reinjection has become an important aspect of geothermal field development and operation. But, at the same time, there are problems that may be associated with reinjection, such as: i) cooling of the produced fluid, ii) excessive injection pressure, iii) ground water contamination, iv) adverse impact on the chemistry of the produced fluid, v) induced seismic activity, etc. Most of these problems can be avoided by means of careful siting and design of injection wells and by adjusting reinjection strategies to results of exploration, well testing and conceptual modelling of the reservoir as well as through prudent field operation.

The locations selected for reinjection wells are variable. Generally, there are three main kinds of configuration selected for reinjection wells: i) Reinjection distributed in-between production wells, or the intermixed configuration. ii) Reinjection near the boundaries of the reservoir, the so-called peripheral configuration. iii) Reinjection in a certain area of the reservoir with production from another distinct area, often called the dipole configuration (Sigurdsson et al., 1995). The peripheral configuration is currently the most common reinjection configuration used in the world (Stefánsson, 1997). The location of injection wells is addressed by Sigurdsson et al. (1995). Their conclusion is that the maximum thermal sweep is of greater importance than pressure maintenance for liquid-dominated and two-phase reservoirs. Peripheral or dipole well configurations appear to be more suitable than the intermixed configuration if maximum energy extraction is the objective of a reinjection strategy.

James (1979) has discussed some of the factors involved in reinjection strategies for geothermal reservoirs. He concludes that the first law on reinjection is as follows: production wells and reinjection wells are interchangeable. According to this law, there are neither production wells nor reinjection wells, only wells. This can be termed the intermixed configuration. There are some problems associated with this configuration. When a reinjection well is changed into a production well, the water around the production well is cold, and it requires a long time to recover to the reservoir temperature. But changing a production well into a reinjection well is not problematic, as reservoir pressure near a production well will have declined because of hot water production from the reservoir.

At present, there is no universally accepted rule for the proper location of reinjection wells. It should be carefully studied in the case of each individual geothermal system according to the reinjection objectives and reservoir conditions and properties. A tracer test is a powerful tool for studying the connections between production wells and reinjection wells. In the Lishuiqiao geothermal system, the intermixed configuration is considered to be the best one. According to the results above concerning thermal breakthrough, the distance between reinjection well and production well should not be less than 1000 m.

5.5 Suggested tracer test design

A tracer test is a very powerful tool for studying connections between reinjection and production wells. Tracer tests involve injecting a chemical tracer into a hydrological system and monitoring its recovery, through time, at various observation points. The results are, consequently, used to study flow-paths and quantify fluid-flow. The main purpose in employing tracer tests in geothermal studies is to predict possible cooling of production wells, due to long-term reinjection of colder fluid, through studying connections between injection wells and production wells (Axelsson, 2002b). Rapid tracer velocities are sometimes interpreted as indicators of potentially rapid cooling of the reservoir when reinjection is applied. In general, there is a relationship between the chemical front velocity and the thermal front velocity in a geothermal reservoir (Stefánsson, 1997). Thermal breakthrough time is at least 1 or 2 orders of magnitude greater than the chemical tracer breakthrough time.

A simple one-dimensional flow-channel tracer transport model has turned out to be quite powerful in simulating return data from tracer tests in geothermal systems. It assumes the flow between injection and production wells may be approximated by one-dimensional flow in a flow-channel such as in Figure 18 (Axelsson, 2002b). Concentration is initially zero everywhere in the channel. At time $t = 0$, a mass M of the tracer is injected instantaneously into the reinjection well, and consequently transported along the flow-channel to the production well. The governing equation for the concentration distribution $C(x, t)$ is as follows:

$$D\frac{\partial^2 C}{\partial x^2} = u\frac{\partial C}{\partial x} + \frac{\partial C}{\partial t} \tag{15}$$

The initial and boundary conditions are $C(x, 0) = 0$, and $C(x, t) = 0$ when $x \rightarrow \infty$. The solution for tracer concentration $c(t)$ in the produced fluid for an injection-production well pair is as follows:

$$c(t) = \frac{um}{Q}\frac{1}{2\sqrt{Dt\pi}}e^{-\frac{(x-ut)^2}{4Dt}} \tag{16}$$

where x = Distance from the reinjection well (m);
u = $q/(\rho A\phi)$, average fluid velocity in the channel (m/s);
A = Cross-sectional area of the flow channel (m^2);
q = Reinjection flow rate (kg/s);
Q = Production flow rate (kg/s);
D = $\sigma_L u$, dispersion coefficient of the flow channel (m^2/s);
σ_L = Dispersivity of the channel (m).

Before a tracer test is conducted in a geothermal field, several aspects must be carefully planned: i) what kind of tracer should be selected, ii) the amount of tracer to inject, iii) the sampling plan to follow (sampling points and frequency), and iv) how to analyze the recovery data.

Several different tracers can be used. The following are the tracers most commonly used in geothermal applications (Axelsson, 2002b):

a) Radioactive tracers like iodide-125, iodide-131, tritium, etc.
b) Fluorescent dyes such as sodium-fluorescein and rhodamin WT.
c) Chemical tracers such as iodide, bromide, etc.

Sodium-fluorescein has been used successfully in numerous geothermal fields, in both low-temperature and higher-temperature systems.

The required mass may be estimated very roughly through mass-balance calculations, wherein injection- and production rates are taken into account, as well as the expected recovery time-span. This time-span depends on the distance involved, but also on how directly the wells involved are connected. In general, tracer tests should be designed such that tracer concentrations reach 5-10 times the detection limit. The amount of sodium-fluorescein injected is usually in the range of 10-100 kg, while the mass of potassium iodide must be an order of magnitude greater (100-1000 kg). The radioactive tracers iodide-125 and iodide-131 are normally injected with an initial activity of 0.5 and 2 Ci, respectively (Axelsson, 2002b).

The length of a tracer test depends on local reservoir conditions and distances between wells involved, the factors that control the fluid flow-pattern in the reservoir. They usually last from a few weeks to months or even years. It cannot be determined beforehand, but once a sufficiently good data set has been obtained, a tracer test may be terminated. Sampling frequency is case specific, but should, in general, be quite high initially (a few samples per day), and then reduced as a test progresses (a few samples per week) (Axelsson, 2002b).

As the geological structure of the Lishuiqiao geothermal system is very complicated, the nature of the connections between production and reinjection wells is not well known. Therefore, it is very important for the studies of these connections to conduct tracer tests. The results may be used to evaluate possible reservoir cooling and to plan reasonable management of the reservoir. Assume that a tracer test is conducted in this area and consider three different scenarios: 1) q = 10 kg/s, $A\phi$ = 10000 m^2; 2) q = 10 kg/s, $A\phi$ = 5000 m^2; 3) q = 10 kg/s, $A\phi$ = 1000 m^2, with x = 1000 m, M = 10 kg, Q = 20 kg/s, ϕ = 5%, ρ = 1000 kg/m^3, $D = 6\times10^{-3}$ m^2/s, α_L = 300 m. Program TRCURV, included in the ICEBOX software package, was used to calculate theoretical recovery curves, which are shown in Figure 22. It shows the concentration for different flow path cross-sectional areas.

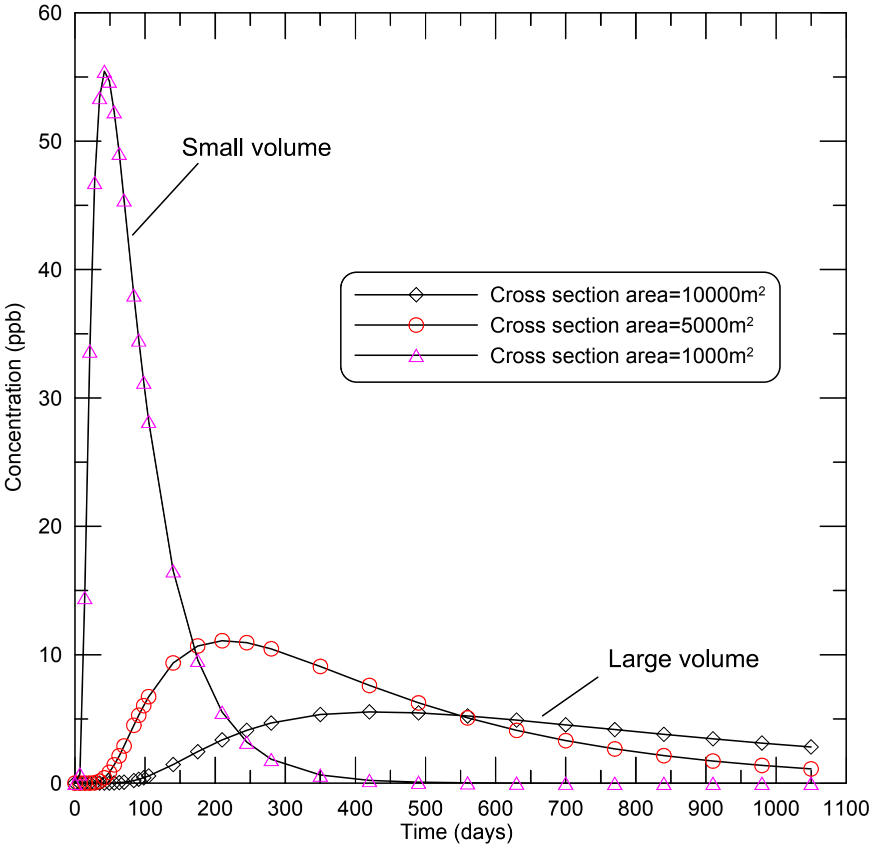

FIGURE 22: Theoretical tracer concentration curves for different flow channel cross-section areas

The detection limit of sodium-fluorescein is 0.1-1 ppb. Based on the above calculations, if the flow channel is similar to the last two situations, the tracer will not be detected or will be only slightly detected. As the flow channel is unknown, a larger mass of sodium-fluorescein should be used in order to make the tracer detectable, 50 kg for example. Radioactive iodide is an excellent tracer, detectable at extremely low concentrations. But, due to safety restrictions and the high cost of using this kind of tracer, it is an unrealistic choice for tracer inside the city of Beijing.

6. SUMMARY AND RECOMMENDATIONS

The principal results of this report may be summarized as follows:

- The Lishuiqiao geothermal reservoir is a low-temperature sedimentary reservoir, with conduction dominated heat flow. The main aquifer is a Cambrian and Ordovician limestone formation with Permian and Carboniferous formation caprock. The Huangzhuang-Gaoliying fault plays a major role in the geothermal activity. It is believed to be the main path for fluid and thermal energy flow from depth into the system. In its initial state, the reservoir pressure is artesian (above the surface). The reservoir temperature is about 80°C.

- The Lishuiqiao geothermal reservoir is still in its natural state. Only two wells have extracted energy from the system for up to two years, each with limited production. Information on the properties and nature of the reservoir has only been revealed to a limited extent during the beginning of the production history and from a few short-term well tests.

- According to a lumped parameter model developed to simulate the water-level history of well SR-6, the surface area of the reservoir is about 110 km^2 and the reservoir permeability-thickness varies from 0.13 to 68 Dm from the outskirts of the system to the inside, respectively, with the average being about 19 Dm. The model indicates that the reservoir acts like an almost closed system.

- The model should be updated and refined as new production and response data become available, to make it more reliable.

- Based on water-level predictions of the lumped parameters model for different production scenarios, the production potential of the reservoir is about 440,000 m^3/year without reinjection. It is estimated to be about 880,000 m^3/year and 1,890,000 m^3/year with 50% and 75% reinjection, respectively.

In view of the work presented in this report, the author would like to conclude with the following recommendations:

- Reinjection is a very effective countermeasure for declining water levels due to limited recharge. It is essential for sustainable development of geothermal reservoirs, such as the Lishuiqiao reservoir, in order to maintain reservoir pressure, counteract water level drawdown, extract more thermal energy from the reservoir rocks, improve efficiency of utilization and increase longevity of a resource. Therefore, one of the main priorities of comprehensive management of the Lishuiqiao reservoir, and other comparable reservoirs, is reinjection.

- A tracer test should be conducted between geothermal wells in Lishuiqiao in order to investigate the flow paths between injection and production wells with the aim of estimating possible cooling resulting from reinjection.

- Interference tests should be conducted between wells in Lishuiqiao. Such tests can be used to study connections between wells, and the influence of production/reinjection in one well on the water level in another well. Of particular interest is studying the interference between different depth-levels in the geothermal system. The results may be helpful in locating reinjection and production wells.

- Considering both the positive (pressure maintenance) and negative (cooling) effects, the distance between production and reinjection wells should not be less than 1000 m, according to calculated thermal breakthrough time. The configuration of the reinjection wells is suggested as an intermixed configuration, making the production wells and reinjection wells interchangeable.

- Numerical modelling, i.e. with the TOUGH2 program, should be considered because of the complex nature of the Lishuiqiao geothermal system. The effects of the complex geometry, and the various faults, can only be simulated accurately with a detailed numerical model. Such modelling will become relevant once more detailed data on the nature and response of the system become available.

- Careful monitoring must be accomplished for all wells in the area. The production rate, water level changes and water temperature need to be recorded on a regular basis for each production well, preferably continuously. Monitoring should be an intergral part of any efficient geothermal management, partly because it enables more accurate modelling and more reliable predictions. Collection of water samples for chemical analysis is also recommended in order to provide information on changes in the reservoir, such as reservoir cooling due to reinjection and cold water infiltration due to lowered reservoir pressure.

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