The United Nations University

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

Reports 2002
Number 20

ASSESSMENT OF GEOTHERMAL RESOURCES IN XI'AN, CHINA

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ABSTRACT

The Xi'an geothermal field, where about 70 geothermal wells had been drilled by the end of 2001, is located in the province of Shaanxi in central China, The Xi'an geothermal reservoir is a low-temperature sandstone reservoir with conduction-dominated heat flow. Temperature of the hot water produced from the Xi'an geothermal system ranges from 40 to 104°C. The production rate has increased rapidly since large-scale exploitation began in 1994, and correspondingly the water level has declined rapidly, with an average annual drawdown of 10 m. The reservoir's main geological features are described, and the present utilization of the Xi'an geothermal field are reviewed. A simple lumped parameter model was used to simulate the water level of well XA-1, by using the LUMPFIT software, and to estimate the properties of the system based on the model parameters. LUMPFIT was also used to predict the potential of the system under various production scenarios with and without injection. Another program, VARFLOW, was also employed to simulate the existing data and to predict future performance of the system. The potential was determined by specifying a maximum allowable pump setting depth of 150 m. On this basis, the potential of the Xi'an geothermal system is estimated to be about 5 million tons per year until 2010. The possible risk of thermal breakthrough during reinjection, is evaluated in order to determine the minimum distance between production wells and reinjection wells. A tracer test is suggested to study the flow paths of the injected water.

1. INTRODUCTION

The Xi'an geothermal field is located in the province of Shaanxi in central China. The Xi'an geothermal field is one of many in the Guangzhong Basin that covers an area of 19,000 km^2. It is named after Xi'an, the capital city of Shaanxi province, located 1000 km southhwest of Beijing (Figure 1). Xi'an city is the starting point of the Silk Road and is a famous tourist city with approximately 3 million inhabitants. The field is a low-temperature, single-phase system. By the end of the year 2001, 70 geothermal wells had been drilled yielding water with temperature ranging from 40 to 104°C.

Geothermal surveys have been carried out since the 70's in order to locate geothermal anomalous areas.

In 1995-1998, a regional geothermal survey was conducted in which the primary characteristics of the geothermal system were obtained. The volumetric method was applied to assess the reservoir potential and the total resource in the Xi'an geothermal field was estimated to be about 12.87×10^{14} kcal (Wang et al., 1999).

First, this report presents a review of geothermal utilization in Xi'an and the main characteristics of the geothermal reservoirs that are being exploited. The emphasis of this report is placed on modelling with the aid of lumped parameter models, in order to estimate the long-term production potential. Water level recovery is predicted in a case of reinjection and a tracer test has been designed to identify the connections between production wells and reinjection wells.

2. THE GEOTHERMAL RESERVOIR IN XI'AN

2.1 Geological setting and reservoir features

The Xi'an geothermal field is located in the Guanzhong Basin, which penetrates the central part of the Shaanxi province as seen in Figure 1. It covers an area of 376 km^2 and is confined by faults on all sides, i.e. the Weihe fault to the north, the Bahe fault to the east, the Changan fault to the south and the Zhaohe fault to the west, as seen in Figure 2. All the faults are believed to function as hydrological barriers. Inside the Xi'an system, a minor fault is found parallel to Changan fault, with northeasterly direction.

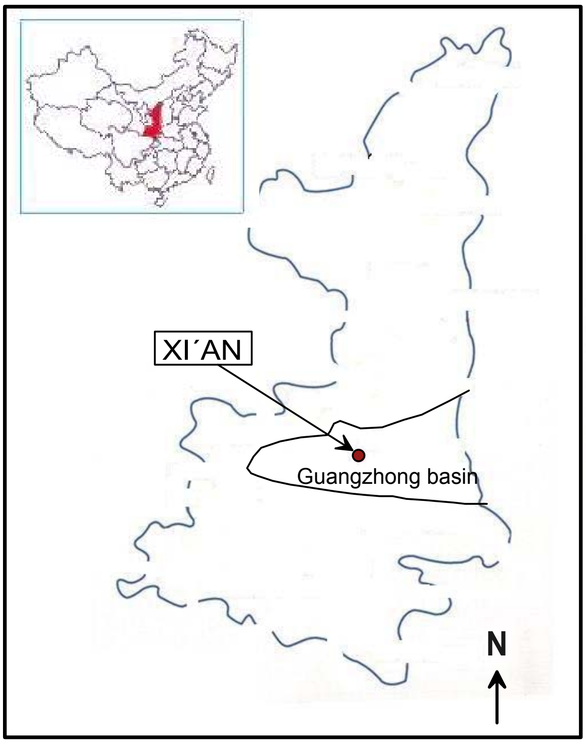

FIGURE 1: The location of the Xi'an geothermal field, China

There are 3 main reservoirs in the Xi'an geothermal system. The first reservoir, the Zhangjiapo formation, consists of alternative layers of sandstone and mudstone. Average thickness of the first reservoir is about 700 m, as shown in Figure 3. Wells tapping the first reservoir have an average temperature of about 54°C. The second reservoir is located in the Lantian-Bahe formation, which is composed of sandstone, conglomerate and mudstone with an average thickness of 700 m. Average temperature of a well drilled through the second reservoir is around 86°C. The third reservoir, which is in the Gaolingjun formation, is composed of mudstone and sandstone and its average thickness is 800 m, and stores geothermal fluid with the average temperature of 118°C (Wang et al., 1999). Initial wellhead pressure of the wells in the system was 1-3 bar. The formations dip slightly to the north as seen in Figure 3.

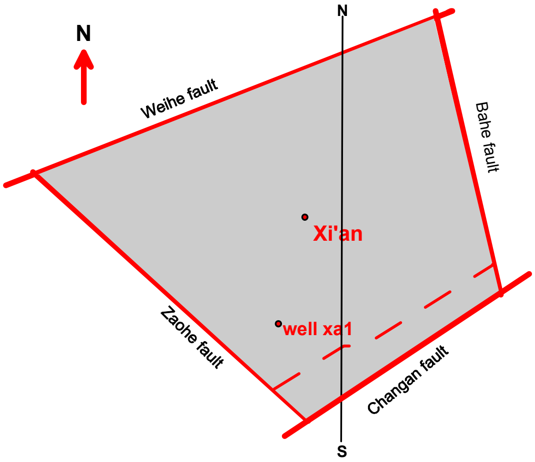

FIGURE 2: Geological setting of the Xi'an geothermal system

Chemical components in the geothermal fluid are controlled by the lithology of the host rock and its temperature. The total dissolved solids of the reservoir are in the range of 1-8 mg/l, and pH value varies from 7.5 to 8.8. The concentration of fluorine is relatively high, mostly between 5-8 mg/l (Wang et al., 1999).

Most wells in the Xi'an field are mining geothermal fluid from the second reservoir, the Lantian-Bahe, a Pliocene formation. A few abstract heat from the first reservoir Zhangjiapo, a Pliocene formation, as well as Gaolingjun formation of Miocene, the third reservoir.

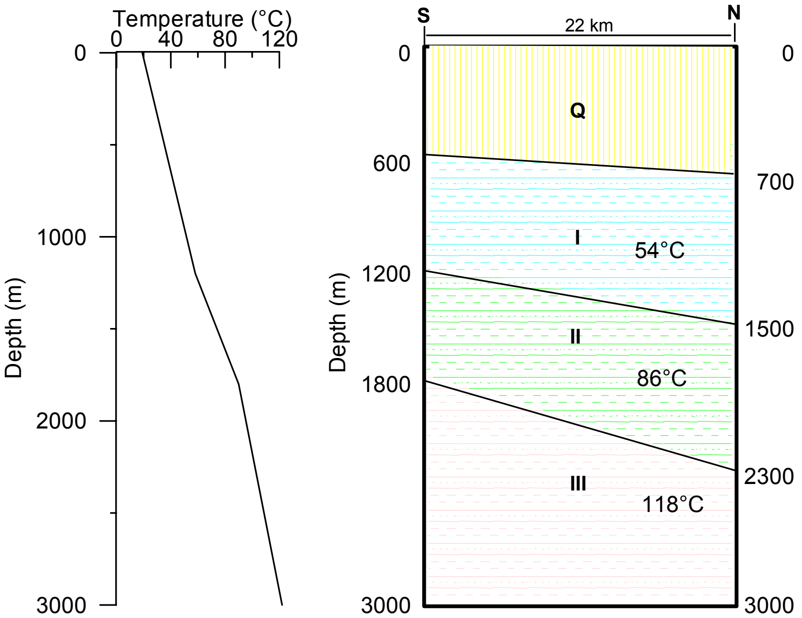

FIGURE 3: Temperature profile and geological section of the Xi'an geothermal system; Q: Quaternary formation; I: Zhangjiapo formation; II: Lantian-Bahe formation; III: Gaolingjun formation

2.2 Production history

Geothermal use in Xi'an can be traced back to the western Zhou Dynasty, more than 2000 years ago. During the imperial epoch, application of geothermal energy reached its summit 1000 years ago. The hot springs were mainly used by the imperial family for bathing. The Huaqing pool, the oldest geothermal pool in Xi'an, has long been the favourite place of visitors in Xi'an.

By the year 2001, around 70 geothermal wells had been drilled in the Xi'an urban area with varying capacities and temperatures. Wells are mainly located in the east and south parts. The main modes for use of geothermal water are shown in Figure 4. About 1/3 of the geothermal wells in Xi'an are producing hot water for space heating and some have already become the main sources for space heating in some communities. It is quite common to use geothermal water for aspects of medical bathing. The temperature required for bathing is relatively low and it is comparatively economical. Hot water from other wells is used for breeding tropical fish and grow flowers. Some wells are used for earthquake monitoring. The main existing problems include dense well distribution, which causes rapid drawdown of the water level, and reduces the long-term potential of the geothermal reservoir, non-cascaded and inefficient use of geothermal resources, as well as lack of monitoring through systematic measurements.

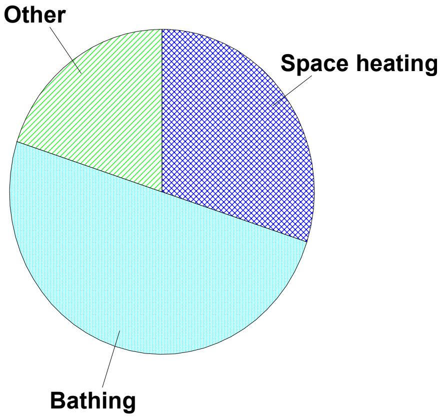

FIGURE 4: Pie chart of geothermal utilization in Xi'an

Large-scale geothermal production in Xi'an began in 1994 and has increased considerably year by year. The cumulative production amounted to 3.3 million tons in 2000 equalling 104 l/s annual average. The number of wells in the Xi'an geothermal field and estimated annual production can be found in Table 1. So far, no large-scale reinjection has been carried out; only a one month-long reinjection test was conducted in December, 2001. Unfortunately, so far no data is available on this reinjection.

TABLE 1: Number of wells in the Xi'an geothermal field and estimated annual production in the field from 1994 to 2000.

Year	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Number of wells	7	15	24	33	43	60	70
Production (10^4 m^3)	25	69	160	200	240	300	330

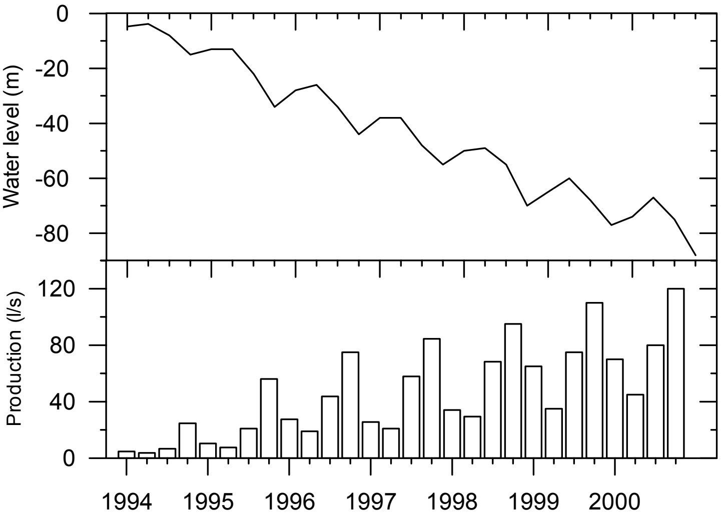

FIGURE 5: Production history of the Xi'an geothermal field and water level in well XA-1

Production in the field differs by season. The peak production during the winter season (January-March) is about two times larger than the lowest production in the summer season (June-August). Figure 5 shows the production history of the Xi'an geothermal field and annual water level change in well XA-1, which is located in the main well field. Well XA-1 is about 2000 m deep and is considered to produce from the second reservoir.

According to monitoring in well XA-1, the annual water level change in the Xi'an field is about 20 m, and the long term drawdown is about 10 m per year. Due to lack of other systematic monitoring, the water level in well XA-1 is assumed to reflect the general water level changes in the reservoir. Only the data from XA-1 are available for this study.

3. RESERVOIR MODELLING FOR THE XI'AN GEOTHERMAL SYSTEM

The main objective of modelling a geothermal system is to simulate pressure changes due to a given production in order to obtain information on the properties of the system and its nature. The models can then be used to assess the production potential by prediction of the future pressure response to different production scenarios.

Two simple reservoir modelling software, LUMPFIT and VARFLOW, were used to simulate the water level changes in well XA-1 in the Xi'an geothermal system. Due to lack of data, simple models are considered more appropriate than complex numerical models.

3.1 Conceptual model

A conceptual model is a descriptive model, which shows the essential features of a geothermal system. The main features of the Xi'an geothermal system are as follows: The Xi'an geothermal reservoir is a low-temperature sedimentary sandstone reservoir, with conduction-dominated heat flow. The system is confined by four faults, which are believed to be hydrological barriers. The reservoir temperature is between 50 and 120°C, depending on depth. In the natural state, geothermal wells discharge freely with average well head pressure at 1-3 bar. The caprock is believed to be mudstone, located between 700 and 900 m depth. The geothermal water is of meteoric origin with a relatively high concentration of fluorine.

3.2 Lumped parameter modelling

The method of lumped parameter modelling has been used successfully for simulating pressure response data from several low-temperature geothermal reservoirs in Iceland and elsewhere (Axelsson and Gunnlaugsson, 2000). The LUMPFIT simulator tackles the simulation problem as an inverse problem. It automatically matches analytical response functions of lumped models to the observed data by using a non-linear iterative least-squares technique for estimation of the parameters (Axelsson, 1989).

Figure 6 shows a schematic diagram of a three tank lumped parameter model. The model consists of three tanks (or fluid capacitors) and flow conductors (flow resistors). Each capacitor has the mass capacitance κ when it responds to a load of liquid mass m with pressure $p = m/\kappa$. The mass conductance of a conductor is σ when it delivers $q = \sigma\Delta p$ units of liquid mass per unit time at an impressed pressure differential Δp (Bödvarsson and Axelsson, 1986).

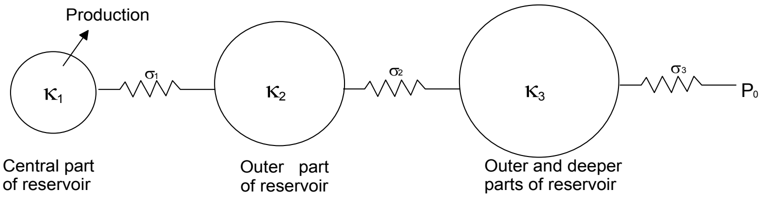

FIGURE 6: Schematic diagram of a lumped parameter model (Axelsson and Gunnlaugsson, 2000)

The first tank simulates the innermost (production) part of the geothermal reservoir, while the second and the third tanks simulate the outer parts of the system. The model can either be open or closed. In the open model the last tank is connected to a constant pressure recharge source. If the model is closed, then no recharge is to the last tank and $\sigma_3 = 0$. An open model may be optimistic, as equilibrium between production and recharge is eventually reached after long-time production. In contrast, a closed model is pessimistic, since no recharge is allowed and the water level declines steadily with time during long-term production.

The water level, or pressure in the tanks, simulates the water level or pressure in different parts of a geothermal system. The pressure response, p, of a general open lumped model with N tanks to a constant production, Q, since time $t = 0$, is given as (Bödvarsson and Axelsson, 1986)

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

and the pressure response of an equivalent N tank closed model is expressed by the following equation:

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

The coefficients A_j, L_j and B are functions of the model parameters κ_j and σ_j.

The simulations are conducted automatically by the LUMPFIT simulator. A first guess of the lumped model parameters is made and then the parameters are changed by the iterative process until a satisfactory fit is obtained.

3.3 Simulation results by LUMPFIT

The resulting water level changes in the Xi'an reservoir, due to production since 1994, were simulated with a two-tank closed model. The match between the observed and the calculated water level is

TABLE 2: Parameters of the closed two-tank lumped model of the Xi'an geothermal system (κ = Capacitance; σ = Conductivity)

Parameter	Value
κ_1 (ms^2)	2,462
κ_2 (ms^2)	115,000
σ_1 (10^{-4} ms)	1.04
Coefficient of determination: 98.8%	

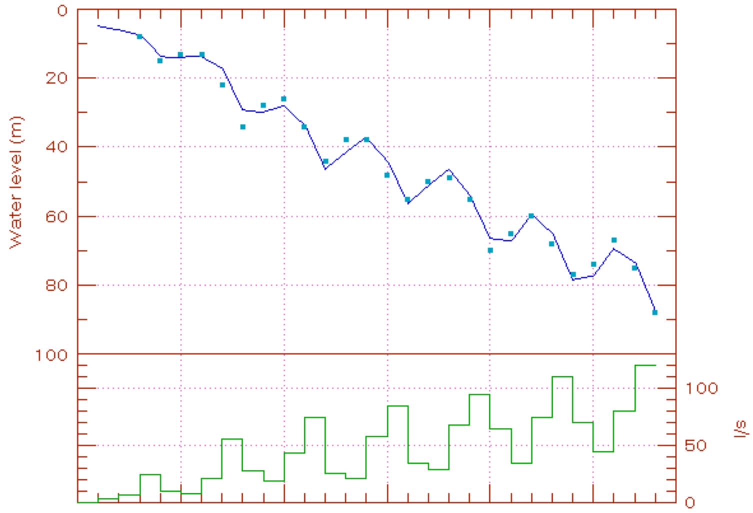

FIGURE 7: Observed and simulated water level by LUMPFIT

considered satisfactory and can be seen in Figure 7. The model parameters are presented in Table 2. The model parameters can be used to estimate some of the reservoir properties, such as volume, area and permeability by assuming a given reservoir geometry.

Capacitance, or storage, in a liquid-dominated geothermal system may be affected by two types of storage mechanisms. One is controlled by liquid/rock compressibility and the other is dominated by free surface mobility (Axelsson, 1989). In the former case, the following formula is used:

$$\kappa = V\rho c_t \tag{3}$$

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

The total compressibility is given by equation

$$C_t = \phi c_w + (1-\phi)c_r \tag{4}$$

where c_w and c_r are the compressibility of the water and rock, respectively. In the latter case, the capacitance may be controlled by the mobility of a free surface.

$$\kappa = \frac{A\phi}{g} \tag{5}$$

where A = Surface area of that part of the reservoir (m^2);
ϕ = Its porosity; and
g = Acceleration of gravity (m/s^2).

The volume of the first tank derived from Equation 3 is 37.3 km^3. The surface area is 47 km^2, assuming a reservoir thickness of 800 m, which corresponds to the thickness of the Lantian-Bahe formation. The second tank occupies a volume of 1740 km^3 and covers an area of 2175 km^2 based on the same assumptions. Assuming horizontal and radial flow between the cylindrical tanks, the permeability between them is 15 mD. The reservoir parameters are summarized in Table 3. As mentioned above, the resulting reservoir parameters depend on the assumed model geometry. If, on the other hand, a reservoir thickness of 200 m is assumed, then the first tank covers 187 km^2 and the second 8700 km^2. This assumption also gives considerably higher permeability, 60 mD.

TABLE 3: Parameters from LUMPFIT simulation

Name of the tank	**Volume of the tank (km^3)**	**Surface area (km^2)**
T_1	37.3	47
T_2		2175
Permeability: 15 mD		
Transmissivity: 3.3×10^{-8} m^3 / Pa s		

3.4 Modelling with VARFLOW

The distributed parameter computer code VARFLOW (EG&G Idaho Inc. and Lawrence Berkeley Laboratory, 1982) calculates pressure changes in response to fluid production/injection from/into an idealized reservoir system, on the basis of the Theis model as follows:

$$\Delta p(t) = \frac{\mu}{4\pi kh} \int_{\tau_n}^{\tau_{n+1}} \frac{q(\tau)}{t-\tau} \exp\left[\frac{-r^2}{4\eta(t-\tau)}\right] d\tau \tag{6}$$

where $\Delta p(t)$ = Pressure change at a time t due to the flow rate $q(\tau)$ (bar);
μ = Dynamic viscosity of the fluid (kg/m/s);
k = Permeability (m^2);
h = Reservoir thickness (m);
τ_n = Time at which the flow starts (s);
τ_{n+1} = Time at which the flow stops (s);
$q(\tau)$ = Volumetric flow rate at time τ (l/s);
r = Distance between the observation well and the production/injection well (m);
η = The hydraulic diffusivity ($k/\mu c_t$) (m^2/s);
C_t = Total compressibility of water-saturated formation (1/Pa);
c_w = Compressibility of water (1/Pa);
c_r = Compressibility of rock matrix (1/Pa).

At most, the program can calculate pressure changes in 10 observation wells at the same time. The model properties are changed until a good agreement between the calculated response and the observed data is obtained. These properties are the transmissivities in the X and Y-coordinates, T_x and T_y, respectively, defined by $T_j=k_jh/\mu$ and the storage C_th.

3.5 Simulation results by VARFLOW

The whole system was divided into 3 blocks. Production in each block was assigned by multiplying average well production with number of wells in each block. Figure 8 shows measured and simulated water level drawdown with VARFLOW in the Xi'an geothermal system, due to the production since 1994. The model fits the water level drawdown during winter production but not during summer production. The reason may be that the production obtained by the above-mentioned method is not suitable for

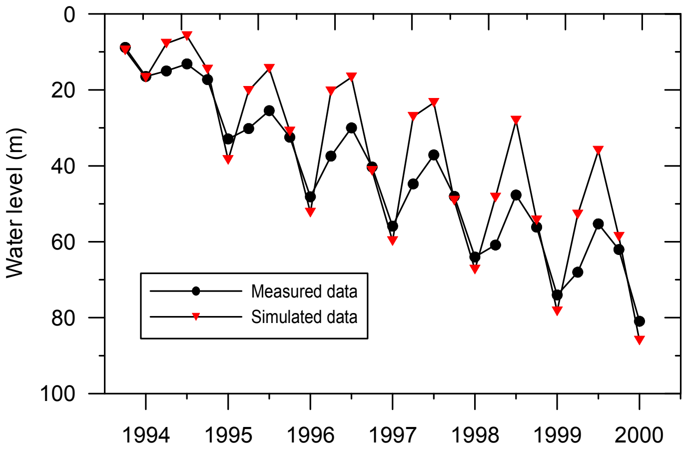

FIGURE 8: Simulated and measured water level by VARFLOW

VARFLOW simulation. The properties of the model are as follows:

$$
\begin{aligned}
k_x h / \mu &= 3.7 \times 10^{-10} \text{ m}^3 / \text{Pa s}\\
k_y h / \mu &= 3.7 \times 10^{-10} \text{ m}^3 / \text{Pa s}\\
C_\tau h &= 1 \times 10^{-8} \text{ m / Pas}
\end{aligned}
$$

The permeability anisotropy presumably reflects the NE-SW fault direction in the system (see Figure 2). But the permeability of the system calculated from the above properties is quite small, 0.15 mD, which may be influenced by the impermeable boundaries.

3.6 Future predictions with LUMPFIT

The main objective of modelling a geothermal system is to assess its production potential, by calculating its future water level for different future production scenarios. Three scenarios are set to predict future well performance. Two are based on assuming constant production rates, 100% and 150% of the production in the year 2000, respectively, which corresponds to an annual production of 3.3 million tons and 5 million tons. The third scenario is for a dynamic production rate, i.e. 10% increase in production year by year. The closed two-tank model was used to predict the water level changes in the Xi'an reservoir for the three production scenarios until the year 2010. Figure 9 shows the results.

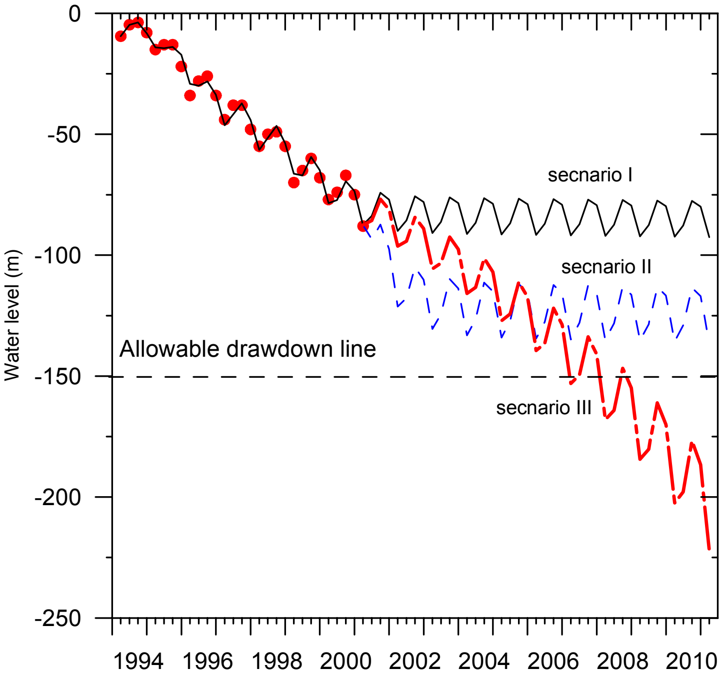

FIGURE 9: Predicted water level up to year 2010 under three different production scenarios

3.7 Future prediction with VARFLOW

VARFLOW was used to predict the water level in winter time 2010 under scenario II. The water level predicted by VARFLOW is in a relatively good agreement with the water level derived from LUMPFIT at the same time. The water level drawdown according to VARFLOW is 141 m, but according to LUMPFIT it is 135 m.

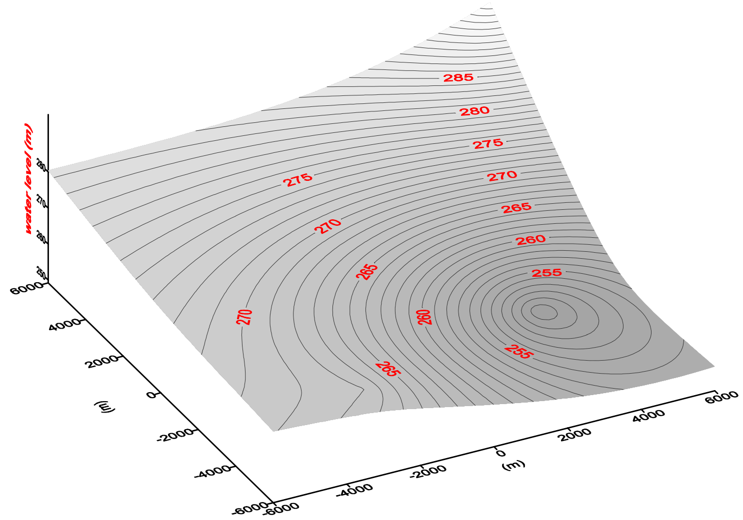

FIGURE 10: Predicted water level in winter time of 2010 in m a.s.l.

Figure 10 shows calculated water level (above sea level) by VARFLOW in wintertime 2010 during constant 5 million ton annual production, since year 2000. Three imagined observa-tion wells were put into the system, coinciding with the above-mentioned three blocks, in order to calculate the contours presented in Figure 10. The depression centre of the Xi'an geothermal system occurs in the eastern part, where the number of wells is highest, while the water level in the north part is 30-40 m higher.

Further performance of the system may follow the behaviour predicted. In the eastern and southern parts, where most of the highly productive wells are concentrated, the water level drawdown is predicted to be greatest.

3.8 Production potential

Based on the predictions produced by LUMPFIT, the water level in the geothermal system will stay above 85-92 m in scenario I in 2010, whereas the water level in the production wells will stay above 125-135 m in scenario II. In the third scenario, the water level drops dramatically. Water level drawdown in the first scenario is on the order of 0.6 m/year on average, compared to 5 and 13 m/year in the second and third scenarios, respectively.

Based on the predictions, production should be set at a certain amount, since too great production can not be maintained for long, such as in the third scenario where the water level will drop below 200 m in the year 2010. Such a water level is regarded as beyond economic pumping depth. The maximum potential production is determined by specifying a maximum allowable pump setting depth of 150 m. On this basis, the potential of the Xi'an geothermal system is estimated to be about 5 million tons per year, i.e. 158 l/s on the average, until the year 2010.

4. REINJECTION IN XI'AN

4.1 Background

According to the predictions for the Xi'an geothermal system, the water level draw-down will be large, so reinjection is suggested in future in an effort to reduce water level draw-down. Reinjection started purely as a disposal method, but has more recently been recognised as an essential and important part of reservoir management (Stefánsson, 1997). Both theoretical and practical studies have shown that reinjection is a powerful method for increasing the life of geothermal resources and the amount of energy that can be mined from a given reservoir.

Reinjection will help maintain reservoir pressure, thereby sustaining flow rates from production wells as shown in the Ahuachapan geothermal field in El Salvador. The locations of injection wells must balance the effects of pressure maintenance and thermal breakthrough in order to maximize production while minimizing thermal breakthrough potential (Bödvarsson and Witherspoon, 1989).

4.2 Water level recovery predictions

LUMPFIT was used here again to estimate water level recovery during long-term reinjection. Two cases were estimated.

Case I: Two reinjection wells, each with a constant reinjection rate of 10 l/s lasting 3 months during each year's wintertime. The injection rate is 8% of the production rate during wintertime of the year 2000, and no reinjection is carried out for the rest of the year. The calculated water level recovery is shown in Figure 11.

Case II: Four reinjection wells, instead of two as in case I, with a constant 10 l/s injection rate lasting 3 months during each year's wintertime. The injection rate is 15% of the production rate during wintertime of the year 2000. Figure 11 shows the water level recovery calculated by LUMPFIT.

The results indicate that, with 2 reinjection wells, the water level in the system will rise about 7 m maximum and 2 m minimum with 5 m in average, long-term. With 4 reinjection wells, the average water level recovery will be 8 m, and the minimum and maximum water level recovery will be 5 and 14 m, respectively. There is no doubt that the production potential and lifetime of the reservoir will improve accordingly.

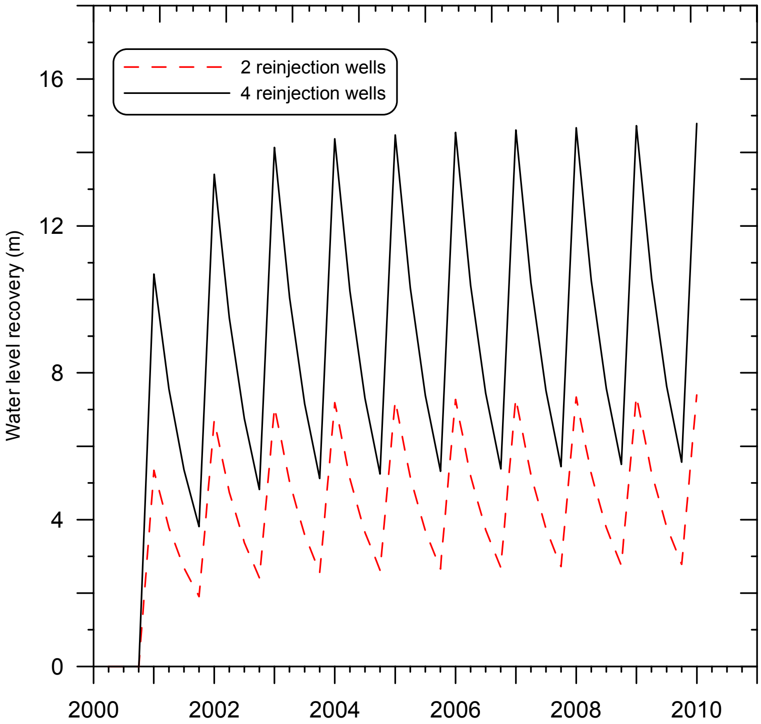

FIGURE 11: Predicted water level recovery with 2 and 4 reinjection wells

4.3 Thermal breakthrough calculations

All methods, regardless of how promising they may be, have their positive and negative sides. Besides cost consideration, thermal breakthrough is the most serious problem facing injection. Even though thermal breakthrough and cooling of reservoir fluid have not been major problems in any geothermal fields, it is necessary to predict thermal breakthrough time for different injection-production well spacing, i.e. the time from initial injection until a significant cooling is observed in a production well (Stefánsson, 1997).

Consider one reinjection well without a production well nearby. The injected water diffuses radially away from the injection well through the porous rock matrix. If an intergranular flow is assumed, then the rock and the fluid have the same temperature at any point. The differential equation that describes this heat transport is

$$\frac{\partial T}{\partial t} + \frac{\beta_w}{\langle \rho\beta \rangle} \bar{q} \cdot \nabla T = 0 \tag{7}$$

where T = Temperature (°C);
β_w = Heat capacity of water (J/kg/°C);
$<\rho\beta>$ = Wet rock heat capacity (J/°Cm^3);
$\bar{q}$ = (q_x, q_y, q_z) the mass flux vector (kg/m^2/s);
∇T = The temperature gradient vector.

An infinite horizontal reservoir of constant thickness H is assumed. Injection of Q kg/s of cold water is assumed to start at time $t = 0$. The cold front moves away from the injection well, and the radial distance from the well to the temperature front is given as follows:

$$r_T = \left[\frac{\beta_w Q t}{\pi H \langle \rho\beta \rangle} \right]^{\frac{1}{2}} \tag{8}$$

This formulation indicates that the radial distance is closely related to injection rate and time passed. Then changing the equation to an equation giving cold front break-through time as a function of the distance between reinjection and production wells, results in:

$$t = \frac{r_0^2 \pi H \langle \rho\beta \rangle}{\beta_w Q} \tag{9}$$

Three different injection rates, 10, 20 and 30 kg/s of 10°C cold water, were applied to predict the breakthrough time. The results calculated by the above formulation are presented in Figure 12. It should be noted that the thickness of the reservoir used in the above equation is 175 m, one fourth of the actual thickness of the second formation, since most wells are located in that part of the reservoir.

Based on the calculation, the distance between a production well and a reinjection well should be longer than 1000 m in order to prevent potential thermal breakthrough for a very long time. Because the reservoir is composed of alternate layers of sandstone and mudstone, it is quite possible that the injected water might travel along a thin sandstone layer with abnormal permeability, reducing cooling time dramatically.

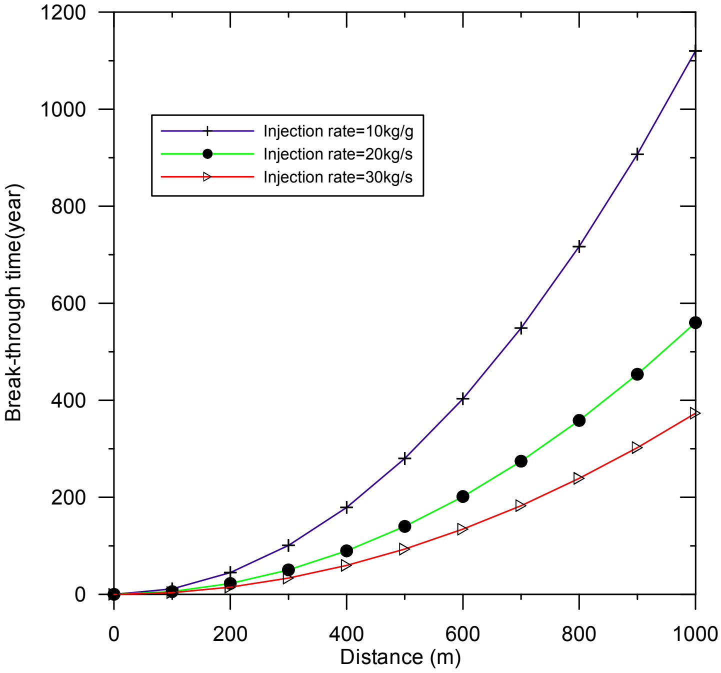

FIGURE 12: Estimated cold front breakthrough time as a function of distance between reinjection and production well

5. RECOMMENDED DESIGN OF A TRACER TEST

5.1 Tracer test

The thermal breakthrough time estimated earlier depends on the channel geometry of the channels connecting the production and the reinjection wells. The most common method of monitoring fluid communication between the reinjection site and the production area is a tracer test (Stefánsson, 1997). This method involves injection of a chemical material (tracer) into the reservoir and measurements of tracer concentration in nearby production wells. A tracer test was designed for the Xi'an geothermal system in order to predict potential cooling.

A constant mass flow rate, q, is injected down the injection well and a constant mass flow rate, Q, is produced from the production well, with $Q > q$. We assume that the flow channel, which connects the injection well and the production well, is along a narrow fracture zone and the mass flow is, therefore, one-dimensional. The cross-section of the flow channel is $A = h \times b$, where h and b refer to the height and width of the flow channel. The porosity of the flow channel is ϕ and its longitudinal dispersivity is denoted by α_L. The differential equation describing the tracer concentration, C, in the channel is as follows:

$$D\frac{\partial^2 C}{\partial x^2} = u\frac{\partial C}{\partial x} + \frac{\partial C}{\partial t} \tag{10}$$

At zero time, a mass M of tracer is injected instantaneously into the injection well and the solute subsequently transported along the flow channel to the production well. The tracer concentration in the produced fluid, c, is correlated to the fracture zone concentration by using the conservation of mass, i.e. $cQ = Cq$. The concentration in the produced fluid can be written as a function of the distance between the wells, time and fluid flow velocity as follows (Axelsson et al., 1995):

$$c(t) = \frac{uM}{Q}\frac{1}{2\sqrt{\pi D t}}e^{-(x-ut)^2/4Dt} \tag{11}$$

where x = Distance from the injection well (m);
t = Time (s);
u = Mean velocity, $u = q / \rho A \phi$ (m/s);
D = Dispersion coefficient of the flow channel, $D = \alpha_L\, u$ (m^2/s);
A = Cross-sectional area of the flow channel (m^2);
Q = Production flow rate (kg/s);
α_L = Dispersivity of channel (m).

There are several preconditions for tracer selection. It should not be present in reservoirs, should not react with or be absorbed by surrounding rocks and should be easy to measure. Sodium-fluorescein was selected as the tracer for this test. Some have argued about the stability of sodium-fluorescein, but the results of two laboratory experiments in Iceland for the Laugaland tracer test indicated that sodium-fluorescein is stable at the relevant time scale (up to 230 days) and at a temperature of around 90-100°C (Axelsson et al., 2001).

Assume that a tracer test is conducted between production well A and injection well B, with a constant production of 20 kg/s from well A and a stable reinjection rate of 10 kg/s injection into well B. During the test, 10 kg sodium-fluorescein is injected into well B. The sampling frequency in the production well should be quite high initially, several samples per week, but fewer after the breakthrough and as the test progresses, since the flow velocity is unknown in the flow channel.

Three different flowpaths, with cross-sectional areas of 100, 200 and 400 m^2, were chosen to calculate three tracer recovery curves, presented in Figure 13. According to the recovery curves, the tracer

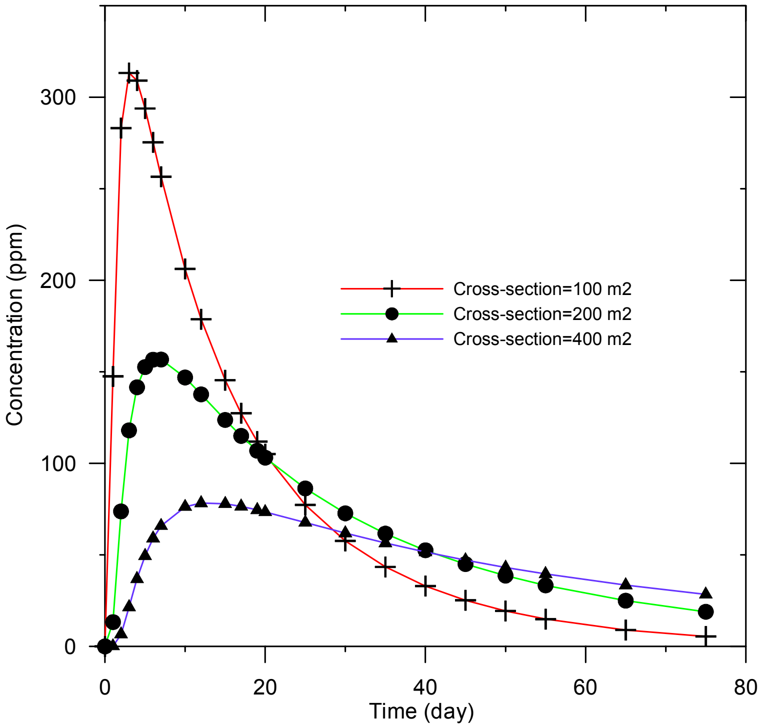

FIGURE 13: Calculated tracer recovery curves for different cross-section area

breakthrough time is shorter and the recovery faster as the cross-sectional area decreases. Note that the designed tracer test is based on the assumption of one production well and one injection well pair. If there is more than one production well, each producing a portion of the injected water, the tracer concentration will be lower, accordingly.

5.2 Predicted water temperature changes

The purpose of the tracer test designed above was to estimate the tracer breakthrough time and study the geometry of the flowpath between the injection/production well pair. The cooling rate of the water produced during long-term injection may be expected to be inversely related to the volumes involved, since the heat mining by the injected water depends on the contact area between the injected water and the rock-matrix.

A simple one-dimensional fracture-zone model was used to carry out long-term cooling predictions of the production water due to reinjection. The temperature of the injected fluid at any distance x along the flow channel can be estimated from the flow channel geometry and the initial temperature of the injected water and the undisturbed reservoir rock. This is based on a formulation, which considers a 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 fluid temperature $T_q(x,t)$ is:

$$T_q(x,t) = T_i + (T_0 - T_i) erf\left[\frac{Kxh}{c_w q\sqrt{k(t - x/\beta)}}\right] \tag{12}$$

This equation is valid at times $t > x/\beta$, where β is defined as $\beta = q\rho_w/(\rho c)_f hb$, and

K = Thermal conductivity of the reservoir rock (J/°C/s);
q = Reinjection flow rate (kg/s);
$(\rho c)_f$ = Wet rock heat capacity (J/°Cm^3);
c_w = Heat capacity of water (J/Kg/°C).

The temperature of the produced fluid is expressed as follows, assuming a constant temperature T_0 of all feedzones in the production well:

$$T(t) = T_0 - \frac{q}{Q}\left[T_0 - T_q\right] \tag{13}$$

Two reinjection rates, 5 and 10 kg/s, were used to predict the temperature of the produced water during long-term constant 15 kg/s production. The flow channel cross-section was assumed as 400 m^2 (h = 200 m and b = 2 m) with 10% porosity, and the distance between the reinjection and production wells is assumed 1000 m in the predictions. The results are shown in Figure 14.

As can be seen, there is a large difference in the calculated cooling of the production well. In the case of 5 kg/s injection rate, the temperature drop is 3°C after 20 years of continuous reinjection, but 17°C in the case of 10 kg/s. The thermal breakthrough time is also shorter for the higher injection rate, 1 year, but 3 years for the lower rate.

It should be pointed out that the realistic situation should be better than the situations predicted above, as the reinjection is only carried out for 3 months during the winter time, resulting in a lower temperature drop. Based on the predictions, it is recommended that the reinjection well should be located about 1000 m away from the production wells and the reinjection rate be less than 10 kg/s, in order to prevent cooling of the production water. The above predictions are based on a single production-injection pair; if, on the other hand, there are several wells around the injection well, the temperature drop will be lower than that predicted in Figure 14.

Although potential cooling is a disadvantage of reinjection, it is beneficial from the view of long-term management of the Xi'an geothermal system. If the reinjection rate is 5 kg/s lasting 3 months during the wintertime, the increase in annual energy production amounts to 3.8 GWh, assuming a production increase equal to the reinjection.

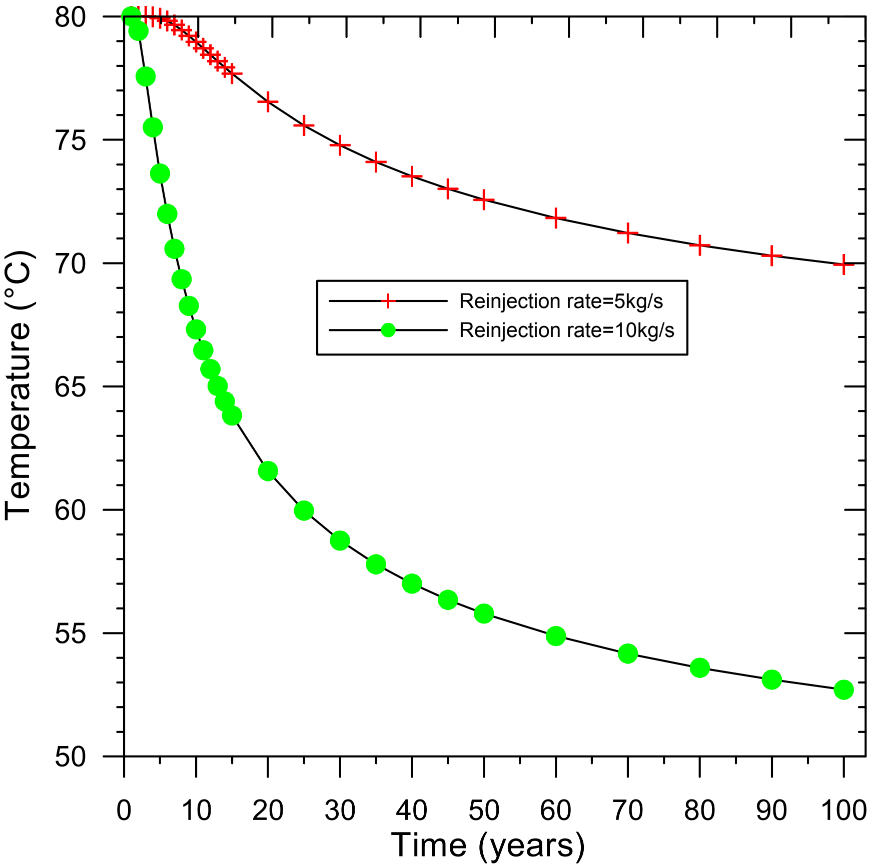

FIGURE 14: Calculated temperature changes in the produced water when the production well is 1000 m away from reinjection well

6. SUMMARY AND RECOMMENDATIONS

The main conclusions of this report are summarized as follows:

1. The Xi'an geothermal reservoir is a low-temperature sandstone reservoir, with a conduction-dominated heat flow. It is bounded on all sides by four faults, considered to be flow-barriers. The area of the Xi'an field is about 376 km^2. The Lantian-Bahe formation, at a depth between 1000 and 1900 m, is widely exploited and has an average temperature of 86°C.

2. Hot water production for bathing and space heating has increased dramatically from year to year since 1994, from 250,000 tons per year up to 3.3 million tons in the year 2000. This results in an increasing long-term water level drawdown of 10 m per year.

3. A simple lumped parameter model, using the software LUMPFIT, was used to simulate water level changes in well XA-1 from 1994 to 2000. According to the model, the volume of the Xi'an reservoir is estimated at 37 km^2 and it is connected to another hydrological system with a much larger volume. The estimated permeability of the system is 15 mD assuming radial flow, but by assuming different model geometry, higher permeability is obtained.

4. The lumped parameter model was used to predict water level changes due to three long term production scenarios in order to assess the production potential of the Xi'an geothermal system. According to the model, the system is capable of sustaining constant 158 l/s production, or 5 million tons annually, until the year 2010, with water level drawdown less than 150 m.

5. The effect of reinjection in the Xi'an reservoir was estimated with the lumped parameter model. If 10 l/s are injected into two reinjection wells each, the water level will increase about 5 m on average until 2010, but the increase will be about 8 m on average if four reinjection wells are used.

Some recommendations are put forward:

1. A coordinated action is needed to improve geothermal management in general in Xi'an. Monitoring is an essential part of geothermal management. Long-term monitoring of the Xi'an geothermal system must be continued and improved. The main parameters to monitor include production rate, water level and water temperature for each production well. Collection of water samples for chemical analysis is also recommended to provide information on chemical changes, which may indicate recharge change or temperature change. It is important to update existing models as the production history proceeds.

2. The Xi'an geothermal system should be considered a single reservoir and rapid production increase should be avoided.

3. Results of the modelling in this report indicate that reinjection will increase the production potential of the reservoir. It is, therefore, quite important to carry out tracer tests before a reinjection project is launched. In that way, the potential of premature cooling in the production wells can be estimated.

4. Numerical modelling is recommended in order to simulate both the whole system and individual wells, when considerable data has been collected.

5. Due to the existence of a poisonous element, fluorine, in the geothermal water, monitoring of wastewater is required to prevent soil and groundwater pollution.

ACKNOWLEDGEMENTS

I would like to take this opportunity to thank the director, Dr. Ingvar B. Fridleifsson, and the deputy director, Mr. Lúdvík S. Georgsson for giving me the opportunity to participate in the UNU Geothermal Training Programme, and to Mrs. Gudrún Bjarnadóttir for her kind help. I am deeply indebted to my supervisors, Dr. Gudni Axelsson and Mr. Arnar Hjartarson, for giving me excellent guidance and help with the English. I am grateful to staff members at Orkustofnun for their valuable lectures and I am deeply grateful to Mr. Wang Deqian and Mr. Liu Zuzhi for providing the data used in my report.

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