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Production Potential Assessment of the Low-Temperature Sedimentary Geothermal Reservoir in Lishuiqiao, Beijing, P.R. of China, Based on a 3-D Numerical Simulation Study

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ABSTRACT

The paper describes the development of a detailed numerical reservoir model of the geothermal system underlying the Lishuiqiao area in Beijing, P.R. of China. The purpose of the modeling was, firstly, to simulate the nature and response of the geothermal system and, secondly, calculate predictions on it's response to future production for different production scenarios in order to estimate it's production potential, which is mainly controlled by water-level-decline resulting from the hot water extraction. The model consists of about 4500 elements and covers the whole Beijing sedimentary Basin. It was developed using the TOUGH2 simulator and the inverse modeling capabilities of the iTOUGH2 code was applied for parameter estimation during the work. The predictions indicate drastic water-level draw-down in all the production wells, when reinjection is not applied. Based on the predictions the production potential of this geothermal region in Beijing is not likely to be much greater than 40 l/s on the average, with a maximum production of about 100 l/s during the heating period. With reinjection, the production potential, is much higher, perhaps of the order of 60-70 l/s on the average with 50 % reinjection.

1. INTRODUCTION

This paper describes the development of a detailed numerical reservoir model of the geothermal system underlying the Lishuiqiao area in Beijing, P.R. of China. The model was developed according to contract between Tianyin Co., Beijing, and Enex-China Ltd., Reykjavik in Iceland. According to this contract Enex-China Ltd. carried out a conceptual design for a geothermal district heating system in Beiyuan Garden, which was completed in May 2003 (Enex-China, 2003). The modeling part of the project can be looked upon as a continuation of a feasibility study conducted in 2001 (Axelsson, 2001). The purpose of the model development is threefold: (1) To simulate the nature and response of the geothermal system, (2) to calculate predictions on it's response to future production for different production scenarios and (3) to estimate it's production potential, which is mainly controlled by the water-level decline resulting from the hot water extraction. Without a reliable reservoir model, the future of geothermal utilization in the Beiyuan garden in Lishuiqiao is extremely uncertain, and intense investment in wells and surface equipment not at all justified. A reliable reservoir model is, therefore, a key element in sustainable geothermal utilization (Axelsson *et al.*, 2002).

The detailed numerical model described here was developed using the TOUGH2 simulation software and the inverse modeling capabilities of the iTOUGH2 code was applied for the model parameter estimation. It was deemed necessary to have the model extend over the whole Beijing since the long-term hydrological response of the system below the Lishuiqiao area is certainly influenced by the whole basin. First, a general background of the work is given in the paper, then, available data and information is described. After reviewing the conceptual model of the geothermal system in Lishuiqiao the numerical model design and simulation results are described. Finally, the future predictions are then reviled and the production potential of the system is estimated.

2. BACKGROUND

2.1 Beijing's Geothermal Fields

Beijing City is situated on top of a large and deep sedimentary basin where geothermal resources have been found at depth (Bin *et al.*, 2002; Qilong *et al.*, 1986). These resources owe their existence to sufficient permeability at great depth (1-4 km) where the rocks are hot enough to heat water to exploitable temperatures. The sedimentary basin is characterized by a series of grabens and horsts, which are bounded by faults and fractures, mainly directed SW-NE. The most prominent feature in the geological complex is the Beijing Graben, which is 3,5 km deep, 15-20 km wide and 80 km long in SW-NE direction with center under the Beijing city. Major faults and fractures play an important role in sustaining the geothermal activity through providing the main flow paths for circulating water as well as acting as aquicludes. The water recharge to the basin is believed to be precipitation falling in the hills and mountains on the outskirts of the basin, which percolates to great depth and, consequently, rises as hot water through some of the permeable faults and fractures.

The Beijing Basin has been divided into about ten geothermal fields on the basis of geological and geothermal conditions. At present, there are about 200 wells in and around the Beijing city producing about 10 Mm^3/a of geothermal water, averaging to 300 l/s, with temperature in the range of 44 to 88 °C (Liu, 2003a). The two best-known areas are the Urban and Xiaotangshan fields, which have been utilized since the 70's. The reservoir rocks in the Urban and Xiaotangshan systems are mostly limestone and dolomite of the so-called Wumishan and Tieling formations. The yearly production from the Urban and Xiaotangshan fields corresponds to an average production of about 110 and 120 l/s, respectively. This has resulted in a water level draw-down of the order of 1.5 m/year in the two fields. The water level has declined at an apparently constant rate in spite of the average production remaining relatively constant (Axelsson *et al.*, 2002). This clearly indicates that the underlying reservoirs have limited recharge and, in fact, act as nearly closed hydrological systems.

Figure 1 shows a simplified map of the Beijing geothermal areas discussed here. It shows both the Urban and Xiaotangshan geothermal areas as well as the focus of this study, the Lishuiqiao area. The geothermal system under study here is located at the SE-boundary of the so-called Shahe geothermal field, which is also shown on the map (Figure 1). The Shahe field is located in the north part of Beijing, south of the Xiaotangshan field. It has an area of about 100 km^2 elongated NW-SE.

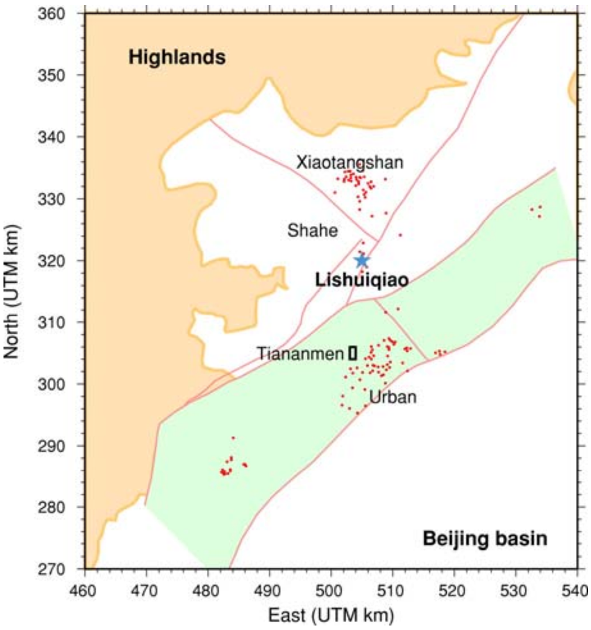

Figure 1. A simplified map of the Beijing Basin showing the geothermal field under discussion here. The Beijing Graben is outlined with light green color. Geothermal wells are presented with red dots and major faults with red lines. The wellfield in Lishuiqiao is marked with blue star.

2.2 Previous Studies

The nature and potential of the Lishuiqiao part of the Shahe field have recently been assessed by Axelsson (2001) and Xu (2002). The main results of these assessments are reviewed below:

Only a few wells have been drilled in the Shahe field, compared with the great number of wells drilled in the Urban and Xiaotangshan fields, most of them poorly productive. A well drilled in 1999-2000 in the Lishuiqiao area in the easternmost part of the field, SR-6 (ShaRe-6), turned out to be quite productive, however. It is drilled to a depth of 2418 m, in-between two major faults, which obviously play a major role in the wells' productivity (see later). It produces from a Cambrian formation, which is mostly composed of limestone. The well has been utilized since late 2000 with a careful monitoring program in place for most of its utilization history. The monitoring data collected form the basis for both assessments and have been accurately simulated by lumped parameter models. Such models have been successfully used to simulate the pressure response of numerous geothermal systems world-wide (Axelsson and Gunnlaugsson, 2000).

The simulation results of both studies show clearly that the Shahe reservoir is an almost closed system (with limited recharge). According to the model developed by Xu (2002) the surface area of the reservoir is of the order of 110 km^2. The model also indicates an average permeability-thickness of about 19 Darcy-m ($19\cdot10^{-12}m^2$). This corresponds to an average permeability of about 0.04 Darcy, assuming a reservoir thickness of 500 m.

Water level predictions for well SR-6 have been calculated by the lumped parameter models for several different future production scenarios. The predictions are, of course, rather uncertain because of the short production history. Yet it is clear that a considerable, constantly increasing, water-level draw-down may be expected in the reservoir. For example a prediction based on an average yearly production of 20 l/s shows that the water level draw-down in the well will have reached about 200 m at the end of an 8 year prediction period. Predictions with reinjection (into a nearby imaginary well) show that reinjection will be essential for sustainable utilization of this reservoir. Without reinjection its potential appears to be quite limited. The Shahe reservoir suffers, in fact, from a lack of water. More than sufficient thermal energy is in-place in the geothermal reservoir, however, and reinjection will, therefore, provide a kind of artificial recharge (Axelsson *et al.*, 2002).

3. AVAILABLE DATA AND INFORMATION

In this section the information and data used in the development of the numerical model of the geothermal system underlying the Lishuiqiao area, will be reviewed. This may be divided into (a) general geological information, (b) information on particular wells and (c) monitoring data from production and observation wells. Unfortunately, not as much data turned out to be available as had been anticipated. In particular, no specific testing of new wells involved, drilled by Tianyin Co., was conducted. This has reduced the reliability of the model development considerably. The following information and data were used:

3.1 Study Area

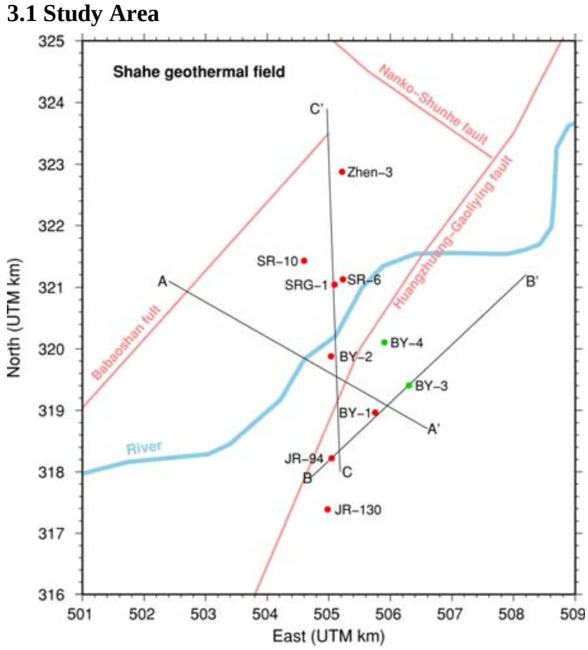

Figure 2. A simplified map of the Lishuiqiao area in Beijing showing the locations of wells and major landmarks. Wells still to be drilled are presented as green dots. Also shown are locations of geological cross-sections available to the study.

This study focuses on the geothermal system under the Lishuiqiao area, which is located near the SE-boundary of the Shahe geothermal field, as already mentioned. It focuses, in particular, on wells BY-1 and BY-2 drilled in the area by Tianyin Co., and a few additional wells still to be drilled. These wells will supply a geothermal district heating system in Beiyuan Garden with hot water. Well SR-6, already discussed, also plays a key role being the only well in the area, which has been utilized for any length of time. Figure 2 shows a simplified map of this area with well locations relative to major landmarks. The figure also shows a few other wells, which have been drilled in surrounding areas by other companies and institutions.

3.2 General Geological Information

Some information on the geological structure of the Lishuiqiao area is presented by Axelsson (2001) and Xu (2002). Some more detailed information has been provided by Tianyin Co., partly in the form of geological cross-sections and partly in the form of a detailed text description (Tianyin Co., 2003). This information is based on the few wells drilled in the area, general geological information and geophysical data. The locations of the cross-sections available to the study, and not presented here, are shown on Figure 2. General geological information for the whole Beijing Basin, with particular emphasis on the geological nature of the Beijing geothermal fields, is presented by Bin *et al.* (2002), Liu (2003a) and Hochstein and Keyan (2002). Additional information has been provided by Liu (2003b).

3.3 Well Information

Detailed information is available for wells SR-6, BY-1, BY-2 and SRG-1. This includes well design information, lithological information, some limited temperature data and production characteristics data from short well tests conducted at the end of drilling. This information is summarized in Table 1 below. Some limited information has also been provided for a few other wells in the area, which also is presented in the table. These are wells SR-10, JR-94 and JR-130.

Table 1. Information on wells SR-6, BY-1, BY-2 and SRG-1 in the Lishuiqiao area and well SR-10, JR-94 and JR-130 in surrounding areas (see Figure 2 for locations).

Well	Drilled	Depth (m)	Casing interval (m)	Reservoir temp. (°C)	Productivity (l/s/m)
SR-6	1999/2000	2418	0-2250	~71	2.3
BY-1	2001	3648	0-2701	64-74	0.65
BY-2	2002	3349	0-2383	65-68	0.22
SRG-1	2001/2002	2898	0-1460	~59	0.22
SR-10	2001/2002	2750	-	~65	0.08
JR-94	2000/2001	3610	-	69-79	0.30
JR-130	2002	3700	-	75-85	0.16

It should be mentioned that limited data are available on temperature conditions of these wells, since very limited temperature logging has been conducted in the wells. This is unfortunate since temperature logging is relatively simple and provides some of the most important information on conditions in geothermal systems and on the characteristics of particular wells (feed zones etc.)

Very limited production testing has, furthermore, been conducted in these wells, which also is unfortunate. The only testing conducted in wells BY-1, BY-2 and SRG-1 is some step-rate production testing at the end of drilling, lasting only a few days. The production characteristics of the wells in the area, based on such testing are presented in Figure 3 below.

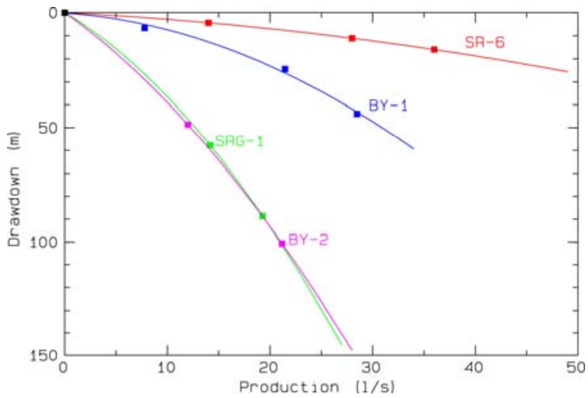

Figure 3. Production characteristics of wells SR-6, BY-1, BY-2 and SRG-1 based on short (few days) well tests at the end of drilling.

Figure 3, and Table 1, show that well SR-6 is by far the most productive well in this area of Beijing, during short-term (few days) production. It yields close to 40 l/s with a draw-down about 20 m. Well SR-6 is about an order of magnitude more productive than wells SRG-1 and BY-2. It must have intersected some highly permeable structure, the other wells did not intersect. Well BY-1 is fairly productive, yet its short term productivity is less than 1/3 of the productivity of well SR-6. It yields about 30 l/s with a draw-down of about 50 m. The production characteristics of wells BY-2 and SRG-1 are very similar. They are poorly productive, yielding about 20 l/s with a draw-down of more than 100 m. It should also be mentioned, even though the wells cited are outside the scope of this study, that well JR-94 appears to be slightly more productive than wells BY-2 and SRG-1, well JR-103 appears to be slightly less productive than wells BY-2 and SRG-1, and that well SR-10 appears to be the least productive well in the area.

3.4 Monitoring Data

The monitoring data available for the modeling effort are the following:

1. Production history of well SR-6; including well test at the end of drilling in March 2000, production history from November 2000 through March 2003 and well test in July 2001. These data are shown in Figure 4.

2. Water level history of well SR-6 for the same period. Data is not available for the 2002/2003 heating period, however, due to failure of the water-level monitoring device used. These data are also shown in Figure 4.

3. Water level interference data from wells SRG-1, SR-10, BY-1 and BY-2 (see Figure 2 and Table 1) measured during the 2002/2003 heating season. These data are shown in Figure 5.

4. Water level interference data from the shallow earthquake monitoring well Zhen-3 (Figure 2) from January 2000 through March 2003. These data are shown in Figure 6.

5. Average production data from the Xiaotangshan and Urban geothermal fields based on Liu *et al.* (2002) and Pan (1998). These data are shown in figures 7 and 8.

6. Average water level draw-down data from the Xiaotangshan and Urban geothermal fields based on Liu *et al.* (2002) and Pan (1998). These data are shown in figures 7 and 8.

It should be emphasized that the monitoring data presented here are the most important data in the model development. The model development revolves around simulating these data as accurately as possible and, hence, obtaining fairly reliable predictions on future water-level changes, etc.

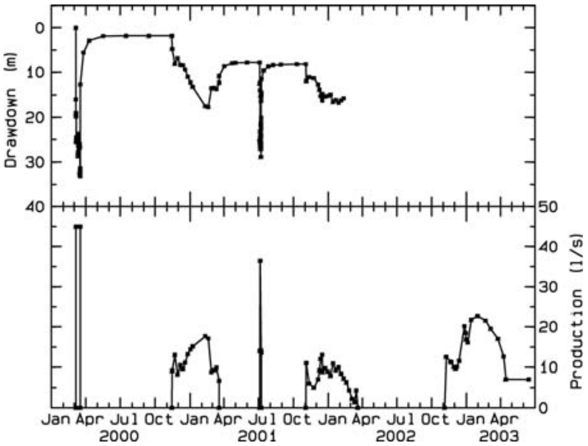

Figure 4. Production and water level history of well SR-6, since the end of drilling in March 2000 through March 2003. Water level data for April 2002 through March 2003 is not available.

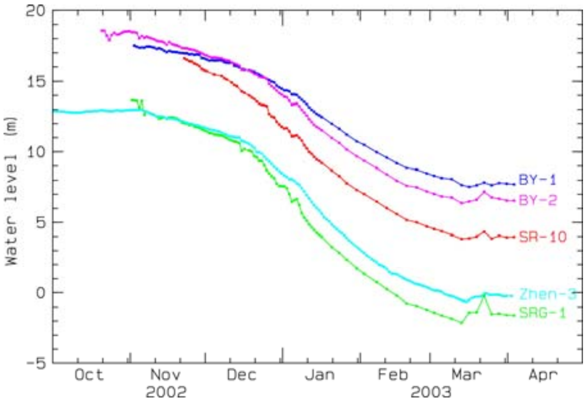

Figure 5. Water level interference data from wells SRG-1, SR-10, BY-1, BY-2 and Zhen-3 measured during the 2002/2003 heating season.

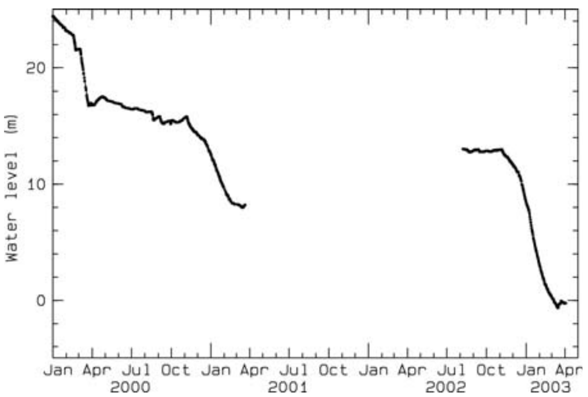

Figure 6. Water level interference data from the earthquake monitoring well Zhen-3, since January 2000 through March 2003.

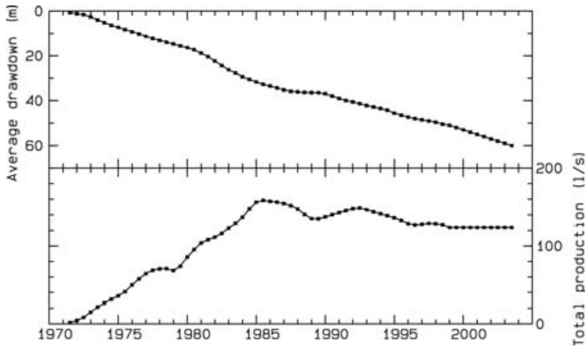

Figure 7. Six-month average production and water-level draw-down data from the Urban geothermal field in Beijing, since 1971.

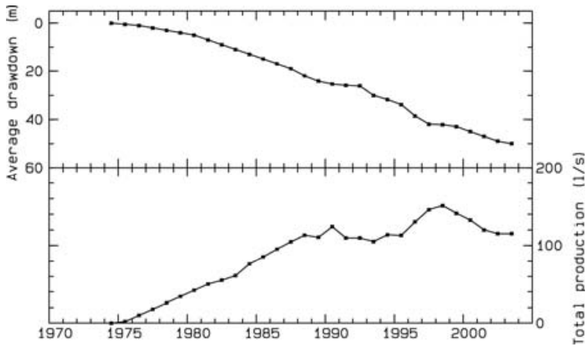

Figure 8. Average production and water-level draw-down data from the Xiaotangshan geothermal field in Beijing, since 1974.

4. CONCEPTUAL MODEL

Xu (2002) describes the current conceptual model of the geothermal system under the Lishuiqiao area and presents the simplified sketch replicated in Figure 9. Up to now the conceptual model has not changed, since limited additional data has become available. The main features of the conceptual model of Xu (2002) are the following:

The reservoir is a low-temperature sedimentary reservoir, with conduction dominated heat-flow and reservoir temperature about 80°C. The production reservoir is in a Cambrian and Ordovician limestone formations, with an effective thickness of 500 m. The caprock is a Permian and Carboniferious 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.

This conceptual model is the foundation for the model described in next chapter. That model extends over a much larger area, however. It may, for example, be mentioned that in the numerical model recharge to the whole Beijing Basin is assumed to come from depth in the NW and in the SW.

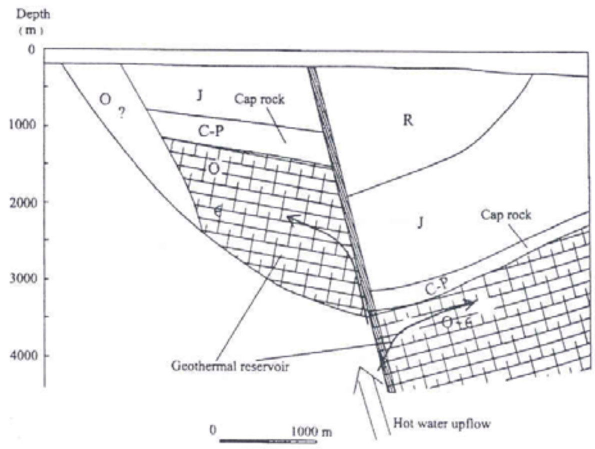

Figure 9. A simplified sketch of the conceptual model of the geothermal system below the Lishuiqiao part of the Shahe geothermal field as presented by Xu (2002).

5. NUMERICAL MODEL DESIGN

In this section the numerical model used for the production potential assessment of the geothermal system in Lishuiqiao is described. First are the principles of the TOUGH2 and iTOUGH2 computer programs described that were used for the modeling. Then the model architecture and development is presented followed by the simulation results.

5.1 Numerical Modeling with TOUGH2 and iTOUGH2

In the modeling effort presented here the TOUGH2 numerical simulation program (Pruess *et.al,* 1999) was applied for the modeling. In such detailed numerical reservoir modeling, the total reservoir volume is divided into many small sub-volumes, or grid blocks. TOUGH2 solves the mass and energy conservation equations for each grid block in multi-dimensional fluid flow systems of multi-phase, multi-component fluid mixtures in porous media. Each grid block has given a number of model parameters: permeability, porosity, heat conductivity etc. Initial temperature and pressure conditions have to be given in the model with appropriate boundary conditions. Sinks and sources simulate feed zones in boreholes, recharge or a hot spring for example. Then the model is run and adjusted until a steady state is obtained, which, simulates the natural state of the geothermal system, as indicated by initial temperatures and pressures in boreholes. The natural state is usually used as initial conditions for the transient simulations i.e. matching the calculated pressure or temperature response to the observed as resulted according to the production history. A good model simulates both the natural state and the transient history.

Simply put, the main goal is to adjust the model parameters until observation data is simulated. In large models the number of parameters controlling the model output can be in hundreds. Finding the solution to the forward problem is therefore very time consuming. iTOUGH2 is a computer program that provides inverse modeling capabilities for the TOUGH2 code (Finsterle, 1999). This means iTOUGH2 solves the inverse problem for determining the TOUGH2 input model parameters based on any type of data for which a corresponding TOUGH2 output variable can be calculated. By using iTOUGH2 the modeler can focus more on the model identification and parameter sensitivity instead of performing forward modeling.

The model developed in this work was done with the iTOUGH2 code on a Linux Networx cluster computer, made up of 52 processors.

5.2 The Numerical Model

5.2.1 Model design

The three-dimensional model grid was generated by the Amesh code (Haukwa, 1998). It is made of 8 identical and horizontal layers. The model area extent is 80x100 km and covers the Beijing Basin. The layout of the full mesh projected on a map of the Beijing area can be seen on Figure 10 along with important landmarks and geothermal fields.

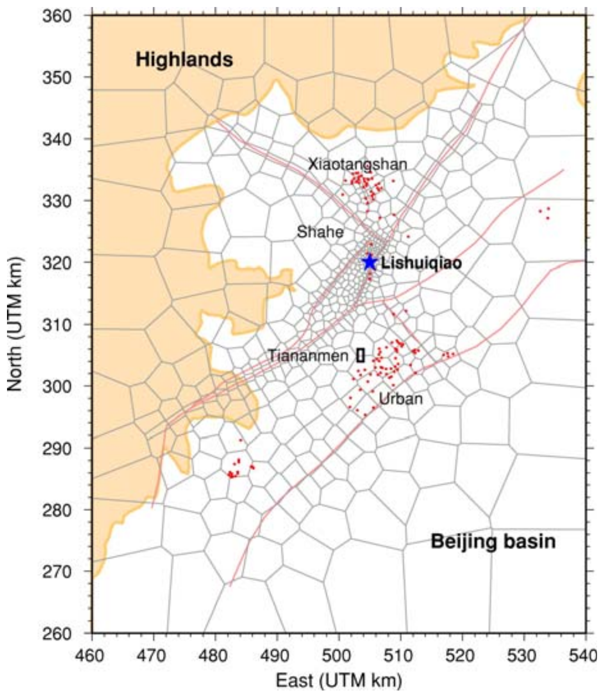

Figure 10. The model grid layout, in reference to the map. Major faults are presented in light red color and wells in dark red color. The Lishuiqiao area is marked with blue star.

The element distribution is based on the conceptual model. Elements are big where geological knowledge is poor and small where more information is available. Important faults have also fine element distribution. Figure 11 zooms in to the center of the map, to the Lishuiqiao area. The model grid axes are oriented in parallel with N and E directions.

The model consists of 4584 elements whereof 3428 are active. The number of connections between elements exceeds 17,000. The model is generated and modified with homemade Unix shell scripts. The model is therefore flexible in use, which keeps the model simple to update and revise as more data becomes available. The numerical model is made of 8 identical horizontal layers as mentioned before. Figure 12 shows the thickness and center location of each layer. The thickness of each layer represents different formations in the Lishuiqiao area. The top layer is 200 m thick and represents the Quaternary formations. It is inactive and has therefore constant pressure and temperature. Layer B presents the cap rock of the geothermal system. The main production layers in the model are C, D, E and F layers, which are all 500 m thick. Layer G represents the base under the production layers.

The bottom layer H is also inactive with constant pressure and temperature.

The model reaches to the depth of 4500 m but the maximum exploitable depth is 3750 m. This was considered appropriate depth since boreholes do not generally penetrate deeper. Geological data is also not available at such depths and a deeper model would not give as conservative result. It does, therefore, not serve the purpose of this modeling study of having it reaching greater depths.

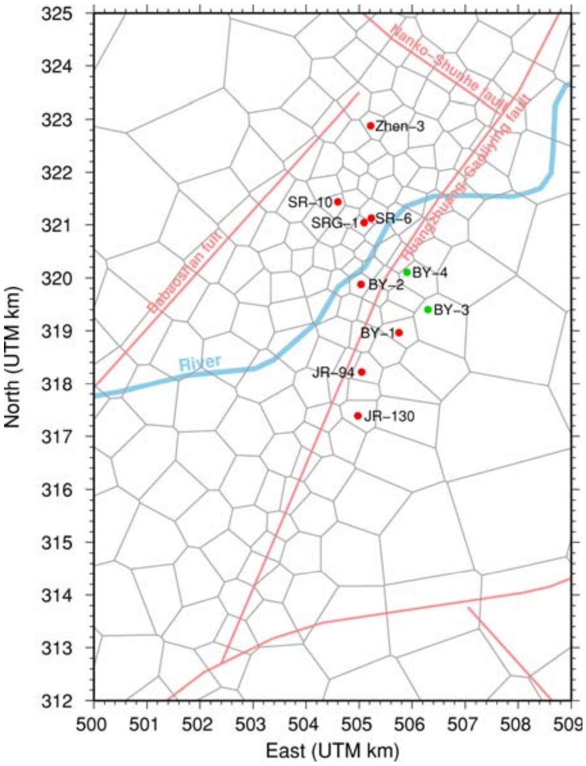

Figure 11. Layout of the model grid in the Lishuiqiao area. Wells are marked with red dots and wells under construction with green dots. Major faults are presented in red.

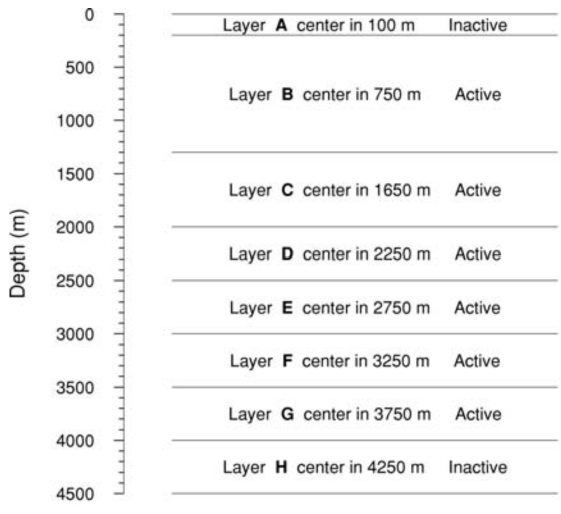

Figure 12. Horizontal layering of the model.

<u>5.2.2 Initial and boundary conditions</u>

An important part of the modeling is the definition of the boundary conditions. Layer A and H are inactive and have therefore constant pressure and temperature, acting as top and bottom boundaries. The temperature and pressure in the center of layer A, at 100 m depth, is 16.6°C and 12.7 bars (absolute). In layer H at 3750 m depth the temperature is 81°C and the pressure 419 bars. When executed, the model will obtain geothermal gradient around 15.5°C/km and pressure gradient according to the temperature profile. The gradient is different between areas where there are different formations with different thermal conductivity. The permeability in the two inactive layers is close to zero to ensure no recharge to the hydrodynamic system.

The sides of the model are no-flow boundaries so there are no fluid or heat flows out of the model, except through feed zones in boreholes, simulated with sinks and sources. The model is deliberately kept large so the remote side boundaries do not significantly affect the performance of the model during the simulation time. It was also considered necessary to simulate the 30-year production histories in Urban and Xiaotangshan field since such a long histories obviously affects large reservoir volumes. This turned out to be quite valuable when estimating the permeabilities far away from the Lishuiqiao area, since they control the long-term draw-down in the field.

According to the conceptual model, the recharge water of the geothermal systems in the Beijing Basin is originated as precipitation in the highlands N, W and SW of the Basin travels along faults and fractures. This natural recharge was simulated with few large elements with constant pressure and temperature in layer G north of Xiaotangshan and SW of Urban geothermal field. This means, as the pressure gets lower in the model, these elements turn into flow boundaries and give recharge to the system.

5.3 Model Calibration and Simulation Results

No reliable temperature measurements in wells were available and only limited data on the initial pressure distribution outside the Lishuiqiao area. Simulating the natural state of the area has therefore no meaning. The model simulates, therefore, only the transient changes observed during the production histories in the three geothermal fields discussed here.

To obtain initial conditions the model was run until a steady state condition, lasting for 10,000 years, was obtained. The initial pressure and temperature distribution depend only on the rock properties in the model. According to the model, the steady state thermal conditions in the model show similar character as observed in the fields. The geothermal gradient is lower where the impermeable sediments are thick, for example in the Beijing Graben, and higher over shallower permeable formations.

The inverse modeling technique of iTOUGH2 and the parallel capability of the Linux cluster resulted in a relatively fast model calibrations process. The model was rather simple in the beginning but became more complex with time since the focus was on the model identification and parameter estimation rather than on the forward modeling. Forward modeling was, however, important help for the modeler to understand some important aspects of the model.

The final model has 35 rock types with different horizontal and vertical permeabilities. The inverse modeling technique was used to find the best permeability values for the different rock types. The rock parameters and permeability distribution will not be described here in detail but the main points are as follows.

- The permeabilities in the Lishuiqiao area are on the order of 10-100 mDarcy.

- The permeabilities of the caprock sediments are on the order of 0.05-0.1 mDarcy.

- The permeability in and around the Urban and Xiaotangshan fields is rather high, up to 600 mDarcy in the Urban field. This is maybe not representative for the true reservoir rock, but considering that the fields are only simulated on a large scale and large faults and fractures are not simulated especially, this is not considered to invalidate the simulation of the Lishuiqiao area.

- The porosity is between 5 and 10 %. This is justified with the fact when the porosities are small the rock compressibility becomes dominant in the storage of the reservoirs, and has the same effect as higher pore volume. The model is not sensitive to the pore volume.

- The density of all formations is always the same, 2650 kg/m^3.

- The formation heat conductivity is between 1.9 to 3.6 J/(kg°C).

Figure 13 show a sample of the permeability distribution in the Lishuiqiao area in layer D at 2250 m depth.

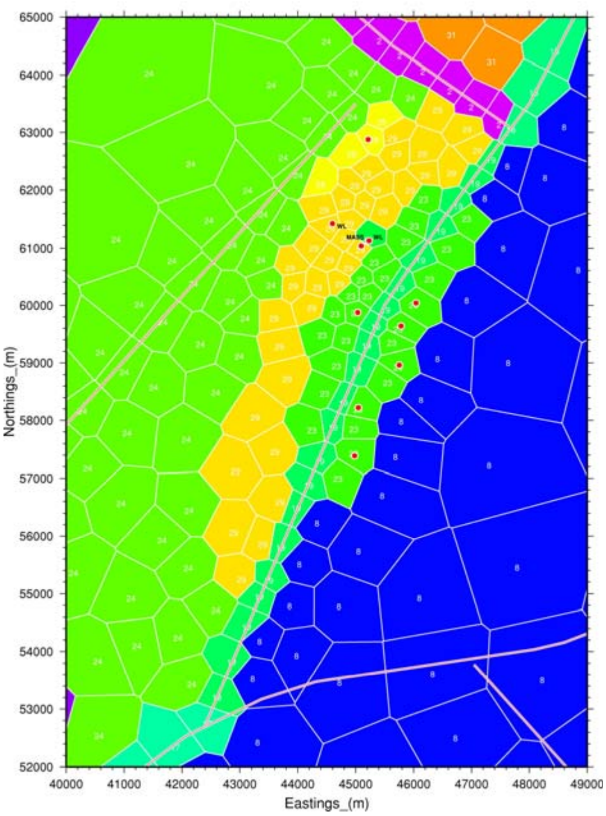

Figure 13. Example of permeability distribution in layer D at 2250 m depth in Lishuiqiao. The color ramp is from blue (low permeability) to red (high permeability), also indicated with higher number in the blocks. Wells in the field are marked with red dots and major faults with red lines.

Figure 14 shows the simulation results. The black dots show the measured data while the calculated data is presented with red lines. The numerical model simulates all available draw-down, in general quite well. The long draw-down histories in Urban and Xiaotangshan geothermal fields are simulated successfully as the two years production history of well SR-6. When looked at the shallow well Zhen-3 one can see that the simulation of the interference data in the 2002/2003 heating season is good but the data in the 2000/2001 season does not reflect the production in SR-6. Possibly are other factors responsible for that, for example other production wells or deep groundwater wells. The fit in the interference wells is good especially in well SR-10. The model calculates little more draw-down in wells BY-1 and BY-2.

It must be iterated here that the data are rather limited due to the short production history in the Lishuiqiao area. So one must be careful to interpret the model results in order to update the conceptual model of the system.

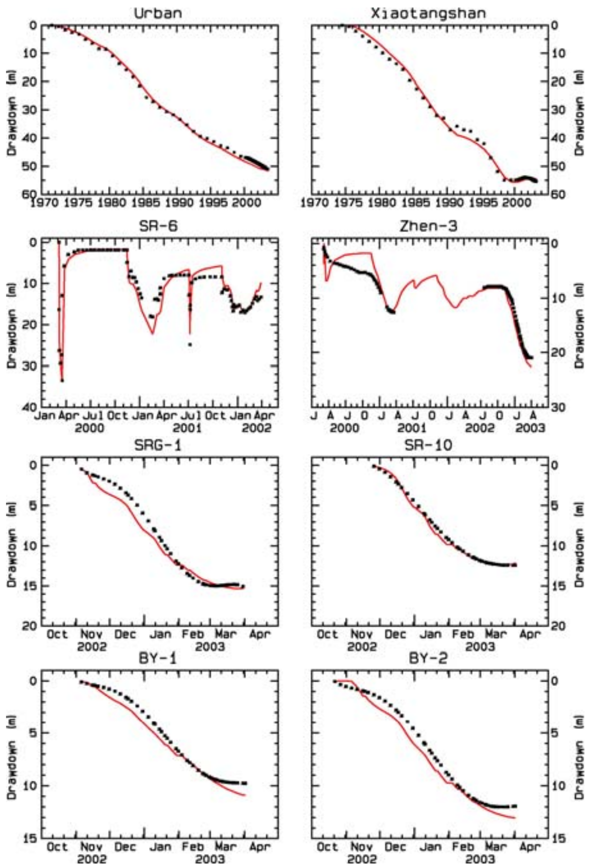

Figure 14. Simulation results of the numerical modeling. Observed water level draw-down is presented with black dots while calculated draw-down is shown with red lines.

According to the model is there about 2 bar pressure difference between the Lishuiqiao area and the Xiaotangshan geothermal field in the year 1999, prior to the start of hot water production in Lishuiqiao, as can be seen on Figure 15. The recharge area of the Xiaotangshan field is in the highlands N of the field. The Figure also shows high-pressure gradient over the Nanko-Shunhe fault SW of Xiaotangshan. This fault is a barrier according to the model but not a path of recharge water. The recharge area of the Urban system is, according to the model, in the highlands in SW and the rock formations SE of the Beijing Graben. The permeability in the Huangzhuang-Gaoliying fault is not any higher than of the rocks around it, according to the simulation results. It is therefore not path of recharge water to the Lishuiqiao area. As can be seen is the pressure disturbed all over the Beijing Basin. This means that there are some effects of the lateral model boundaries. This is not considered to affect the production potential of the Lishuiqiao area, but it might affect long term forecasts of the Urban and Xiaotangshan geothermal systems. If this model is to be updated to simulate in more detail the Beijing Basin, the lateral boundaries of the model need to be pushed further out to get rid of this effect.

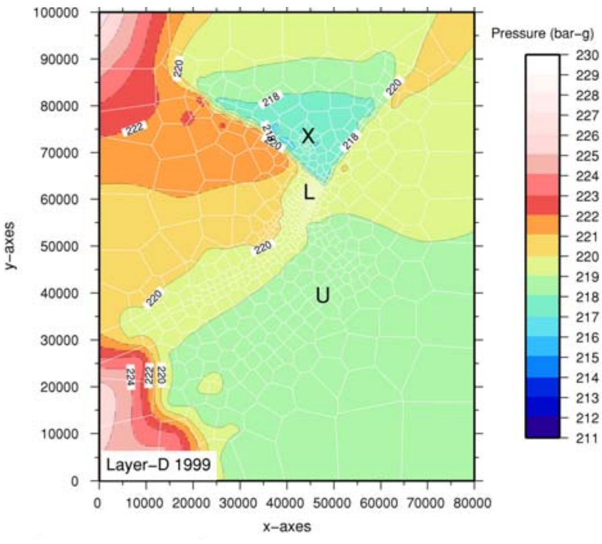

Figure 15. Calculated pressure distribution in the whole layer D at 2250 m depth in the year 1999, prior to the start of hot water production in Lishuiqiao. The letters X, L and U present the Xiaotangshan, Lishuiqiao and Urban geothermal fields, respectively. The figure is in model coordinates.

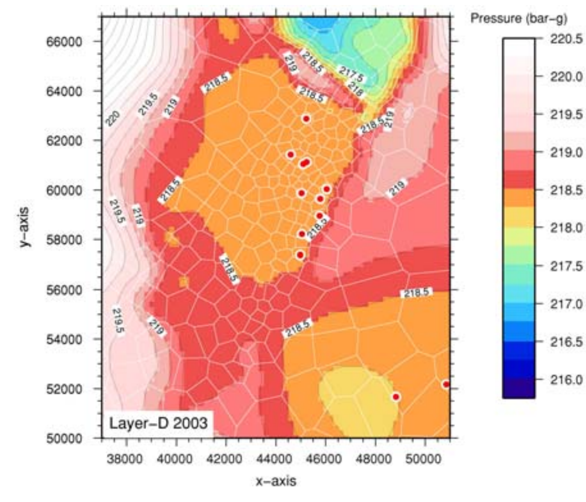

Figure 16. Calculated pressure distribution in layer D around the Lishuiqiao area after the 2002/2003 heating season. Wells in the field are marked with red dots. The figure is in model coordinates.

Figure 16 shows the pressure distribution in the Lishuiqiao area after the 2002/2003 heating season, according to the model. This figure shows clearly the barrier between the Lishuiqiao and Xiaotangshan geothermal fields. The Huangzhuang-Gaoliying fault has low permeability below 3000 m depth, according to the simulation results, but higher permeability is in the shallower part. This indicates that the fault is not the recharge zone of the geothermal system. The recharge is therefore from the rock matrix in the formations around the field, probably from westerly direction. The pressure low 10 km SE of the Lishuiqiao area is result of the production in the Urban geothermal field.

6. PREDICTIONS

6.1 Production Scenarios

This chapter presents the results of predictions calculated by the numerical model of the geothermal system under the Lishuiqiao area. These are mainly water level and/or well-head pressure predictions for the main wells in the area. It must again be emphasized that these predictions can't be considered very accurate, because of the limited data available to the study. They should only be considered to be indicative of the likely evaluation of water levels if production and reinjection is comparable to the scenarios presented here. Predictions are presented here for two main future production scenarios A) and B):

A) Wells SR-6, BY-1 and BY-4 (yet to be drilled) are assumed to be the production wells in the area (see Figure 2 for locations), all with comparable production histories. The average production varies from 7 l/s during the non-heating season to a maximum of 33 l/s during the peak of the heating season. The assumed variations in production per well for a typical year are presented in Figure 17 below. Thus the average yearly production per well amounts to about 14 l/s. Well BY-1 is assumed to come on-line in November 2003 and well BY-4 in November 2004. After that the maximum production from all wells is almost 100 l/s but the average yearly production about 40 l/s

B) In this scenario, production is assumed to be exactly the same as in scenario A, except that reinjection into wells SRG-1, BY-2 and BY-3 (yet to be drilled) is assumed. The assumed variations in reinjection per well for a typical year are presented in Figure 17 below. The assumed average reinjection varies from 0 l/s during the non-heating season to a maximum of 26 l/s during the peak of the heating season, corresponding to a yearly average of 7 l/s per well (21 l/s total), or about 50%. Reinjection into wells SRG-1 and BY-2 is assumed to start in November 2004 while reinjection into well BY-3 is assumed to start in November 2005.

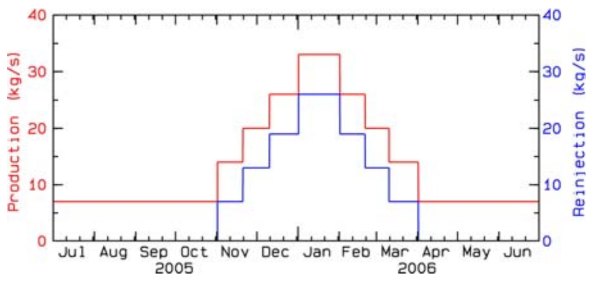

Figure 17. Annual production and reinjection pattern (per well) used in the prediction scenarios. The figure shows pattern for July 2005 until June 2006, as an example.

6.2 Prediction Results

The results of the predictions are presented in figures 18 to 23, which show predictions for production wells SR-6 and BY-1, reinjection wells BY-2 and SRG-1 as well as for wells SR-10 and Zhen-3. It should be mentioned that the predictions for each well are based on the calculations of the iTOUGH2 model and the production characteristics of the wells presented in Figure 3. The production characteristics of well BY-4 are assumed to be similar to the characteristics of well BY-1 and the characteristics of well BY-3 are assumed to be similar to the characteristics of wells BY-2 and SRG-1. It should also be mentioned that for the reinjection wells negative draw-down indicates well-head pressure. Thus, -100 m draw-down indicates a well-head pressure of close to 10 bar.

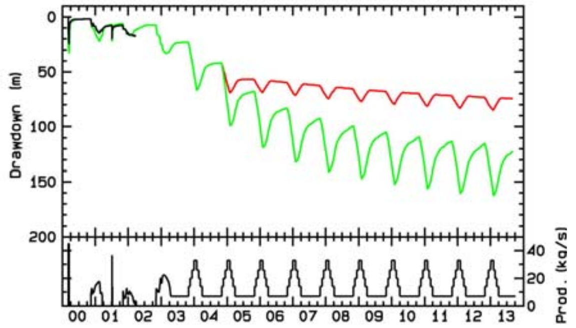

Figure 18. Water level predictions for production well SR-6 for production scenarios A (green) and B (red).

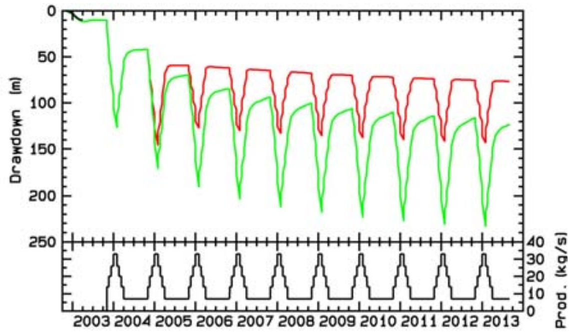

Figure 19. Water level predictions for production well BY-1 for production scenarios A (green) and B (red).

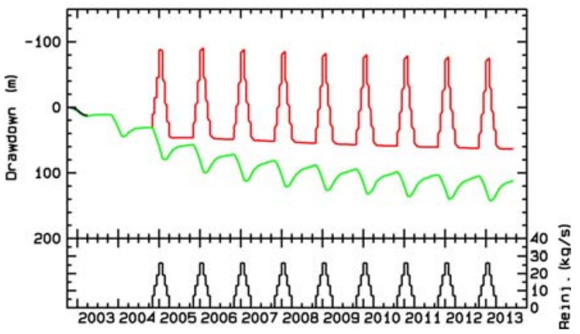

Figure 20. Water level/well-head pressure predictions for reinjection well BY-2 for production scenarios A (green) and B (red). Negative values indicate well-head pressure.

It should be noted that the predictions are only calculated for a period of ten years, because of the short data-series available. As more data become available, and the model has been updated, longer prediction periods may be considered. It should also be pointed out that predictions are only calculated for two future scenarios. A multitude of other possible scenarios may also come to mind, but it was decided to limit this work to these two predictions. The model, which has now been developed, can now very easily be used to calculate predictions for whichever scenarios the operators of the geothermal resources in the Lishuiqiao area are interested in.

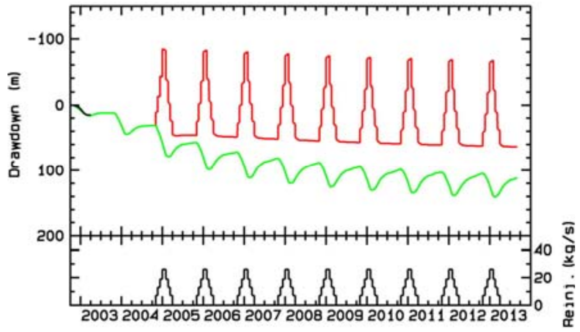

Figure 21. Water level/well-head pressure predictions for reinjection well SRG-1 for production scenarios A (green) and B (red). Negative values indicate well-head pressure.

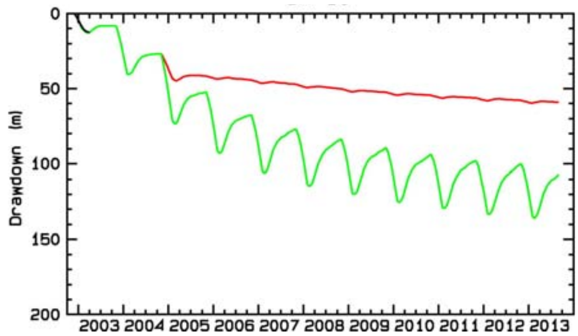

Figure 22. Water level predictions for observation well SR-10 (not in use yet) for production scenarios A (green) and B (red).

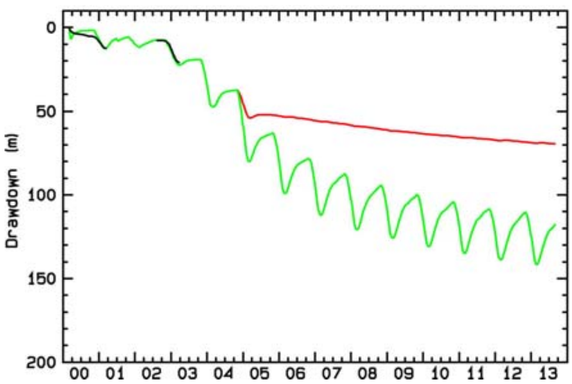

Figure 23. Water level predictions for earthquake observation well Zhen-3 for production scenarios A (green) and B (red).

6.3 Production Potential in Lishuiqiao

A few key points are evident when the results in figures 18 to 23 are contemplated:

Firstly, that the predictions indicate a drastic water-level draw-down in all the production wells, for a rather limited production of 40 l/s (annual average), when reinjection is not applied. This approaches 250 m in wells BY-1 and BY-4, but is somewhat less in well SR-6 (about 160 m), because of more favorable production characteristics (see Figure 3). This may be considered to be the maximum allowable draw-down in view of down-hole pump operation. The reason for the great draw-down is the limited recharge to the geothermal system as well as considerable interference between wells (see later).

Secondly, that the predictions show that reinjection will be extremely beneficial. Only about 50% reinjection causes a greatly reduced draw-down, which is about 100 m less in the case of BY-1, to name an example.

Thirdly, that reinjection will have to be conducted at a well-head pressure of up to 10 bar-g, in the middle of the winter. The reason for this is the fact that the wells chosen here as reinjection wells are the less productive wells, such as SRG-1 and BY-2.

Fourthly, it is noteworthy that the rate of water-level draw-down reduced as time progresses (after about 5 years). This is most likely because the pressure drop in the model causes increased inflow from low-permeability surroundings. It is not guarantied that this will occur in reality, the water-level draw-down may increase at an approximately constant rate, as has been the case in the Xiaotangshan and Urban geothermal fields.

Finally, it should be reiterated that the predictions are not as accurate as they appear in the figures. Considerable uncertainty, perhaps of the order of tens of meters, is inherent in the predictions. It is hard to quantify, however, but it also increases as the prediction time increases. This modeling uncertainty will decrease as the numerical model will be updated with more data, in particular production response data collected in the coming years.

Therefore, the production potential of the Lishuiqiao part of the Beijing geothermal region is not likely to be much greater than 40 l/s on the average, with a maximum production of the order of 100 l/s, which can easily be supplied by three wells or so. With reinjection, the production potential is much greater, perhaps of the order of 60-70 l/s on the average with 50% reinjection. With more extensive reinjection (70 – 90%) the production potential will be much greater. Detailed modeling for different reinjection scenarios is not warranted, however, because no reinjection testing has been conducted in the Lishuiqiao Area so far. Therefore, Tianyin Co. is urged to carry out some reinjection testing as soon as possible (Liu *et al.*, 2002; Wang and Li, 2002). It should also be emphasized that the benefit of reinjection will be greatly diminished if it isn't started until considerable draw-down has occurred. Therefore, reinjection should be initiated as soon as possible.

The main draw-back, or danger, associated with reinjection into low-temperature geothermal systems, such as in this case, is the cooling of nearby production wells. No predictions concerning this aspect are presented here simply because no reinjection testing has been conducted in the area. In particular, no tracer testing has been conducted, but tracer testing is the most powerful tool available to quantify the danger of cooling due to reinjection (Axelsson *et al.*, 1995). When such testing has been conducted the results may be incorporated into the model, and cooling predictions calculated. It should be pointed out that well SRG-1 is very close to SR-6 (~200 m) and the danger of rapid cooling of the latter well, because of reinjection into the former, is considerable.

6.2 Large Scale Interference

In addition to the specific predictions presented above, the model calculations reveal some interesting results concerning the interference between different wells and different fields in the Beijing region. These results are, of course, only indicative because of the limited data available for the model development. These results include:

There is clear interference between well SR-6 on one hand, and the BY-wells on the other hand. According to the model calculations this corresponds to about 50 m draw-down in well BY-1 because of production from well SR-6 (no reinjection) at the end of the ten-year prediction period. Similarly, the model calculations also show a 50 m draw-down in well SR-6 because of production from wells BY-1 (no reinjection) at the end of the ten-year prediction period. This is considerable interference, which seriously reduces the production potential of the different wells. The only way to reduce the effect of this interference is to employ massive reinjection.

Even though the Lishuiqiao Area is considered to be isolated from the Xiaotangshan and Urban geothermal fields some long-term interference between these areas should not be unexpected. Such interference is beyond the scope of this study, however. Yet, it should be mentioned that the model calculations indicate that if production in the Xiaotangshan and Urban areas continues at the present rates (See figures 7 and 8) it may cause an interference in the Lishuiqiao Area corresponding to about 7 m water-level draw-down, during the 10-year prediction period.

The model calculations also indicate that production in the Lishuiqiao Area will cause an interference in the Olympic Area, 7 km SSW of Lishuiqiao, corresponding to about 100 and 50 m water-level draw-down at the end of the ten-year prediction period, for prediction scenarios A and B, respectively. This interference also includes some interference from the Xiaotangshan and Urban areas. This result is also presented here, even though geothermal production in the Olympic Area is beyond the scope of the present study. It, however, demonstrates the power of the numerical geothermal model, which has now been set up for the whole Beijing Basin. But, it must be emphasized that this result is highly uncertain, because no real data are available on this interference. It indicates, however, that interference between these two areas may seriously reduce the production potential of both, unless extensive reinjection is conducted.

7. SUMMARY AND CONCLUSIONS

This paper has described the development of a detailed numerical reservoir model of the geothermal system underlying the Lishuiqiao area in Beijing. The model was developed according to contract between Tianyin Co. and Enex-China Ltd., which also included a conceptual design for a geothermal district heating system in Beiyuan Garden in Lishuiqiao. The purpose of the model development was, firstly, to simulate the nature and response of the geothermal system and, secondly, calculate predictions on its response to future production for different production scenarios in order to estimate its production potential, which is mainly controlled by water-level decline resulting from hot water extraction. The main points and results of the study presented here are collected below:

- The model was developed using the TOUGH2 simulator and the inverse modeling capabilities of the iTOUGH2 code was applied for parameter estimation during the work. Computations were done on cluster computer made of 52 processors.

- The model consists of about 4500 elements in 8 layers, reaching down to 4500 m depth. It covers about 80.000 km^2, which is the major part of the Beijing Basin. This was deemed necessary since the long-term hydrological response of the geothermal system below the Lishuiqiao area is certainly influenced by the whole Basin.

- The model does not simulate the natural state of the geothermal system due to lack of data. It simulates the production history in Lishuiqiao and interference tests as well as the 30-year production histories of the Urban and Xiaotangshan geothermal fields.

- The production potential assessment of the Lishuiqiao part of the Shahe geothermal system in Beijing is based on two future production scenarios. One with and one without reinjection.

- Based on the results the production potential in Lishuiqiao is not likely to be much grater then 40 l/s on the average, with maximum production of the order of 100 l/s during the heating period, which can easily be supplied by three wells or so.

- The production potential is restricted by a drastic water-level draw-down in the production wells, limited to 250 m. The reason for this is the limited recharge to the geothermal system as well as considerable interference between wells.

- With reinjection, the production potential is much greater, perhaps of the order of 60-70 l/s on the average with 50% reinjection. With more extensive reinjection (70 – 90%) the production potential will be much greater.

- The predictions show that reinjection will be extremely beneficial, through causing a greatly reduced draw-down, since the reservoir suffers from lack of water, but more than sufficient thermal energy is in-place in the geothermal reservoir, however.

- The main drawback, or danger, associated with reinjection is the cooling of nearby production wells. No such cooling predictions are presented here simply because of the lack of reinjection testing data and no tracer tests have been conducted.

The model calculations reveal some interesting results concerning the interference between different wells and different fields in the Beijing region, which are only indicative:

- Interference between well SR-6 on one hand, and the BY-wells on the other hand amounts to about 50 m additional draw-down when reinjection is not applied.

- Production in the Xiaotangshan and Urban areas may cause interference in the Lishuiqiao area corresponding to about 7 m water-level draw-down, during the next 10 years.

- Production in the Lishuiqiao area might cause an interference in the Olympic Area, 7 km SSW of Lishuiqiao where hot water production is planned, corresponding to up to 100 m water-level draw-down at the end of the ten-year prediction period, without reinjection.

Unfortunately, not as much data turned out to be available during the work presented here, as had been anticipated in the early stages. In particular, no specific testing of new wells was conducted. In addition limited and unreliable data on the temperature conditions of these wells were available, which is poor since temperature logging provides some of the most important information on conditions in geothermal systems and on characteristics of geothermal wells. The modeling results presented here are, therefore only indicative and not accurate. This modeling study should, therefore, only be looked upon as the first step in numerical model development for the area. As more data become available through drilling and testing of new wells, and in particular monitoring of the production response during actual long-term hot water production, the model developed can be easily revised and updated. Thus the model will hopefully become more and more reliable.

The model presented here has the potential of aiding sustainable management of the geothermal resources in Beijing to avoid over-exploitation and over-investment in deep wells and surface equipment. The key to successful further development of the model is comprehensive monitoring of the geothermal system in the Lishuiqiao area.

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