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Production potential of the Yanqing geothermal reservoir

Guðni Axelsson

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PRODUCTION POTENTIAL OF THE YANQING GEOTHERMAL RESERVOIR

In this chapter the information which is available at present for a preliminary assessment of the Yanqing geothermal reservoir will be reviewed. The results of model calculations for the reservoir, used for predictions for different future production scenarios, will also be presented, along with a preliminary assessment of the potential of the reservoir. Very limited data is available yet on the Yanqing reservoir and its' production potential. Therefore, an utilisation scheme involving a step-wise increase in production, allowing more reliable re-assessment of the reservoirs' potential, as more data become available, is essential. In that way over-exploitation of the resource, and over-investment in deep wells and surface equipment, can be avoided. An essential part of such an utilisation scheme is careful monitoring and detailed testing. Common, total management of the geothermal resources in the Yanqing basin will be of paramount importance, so that over-exploitation can be avoided. Reinjection is suggested as an essential tool in this management, principally for pressure maintenance but also for environmental reasons.

1 INTRODUCTION

The production potential of the geothermal reservoir is controlled by water level changes, or in more detail by:

(A) capacity of each well,

(B) interference between wells and

(C) long-term pressure (water-level) decline in the reservoir.

Item (A) is controlled by turbulence pressure losses in a well and near-well permeability, item (B) by reservoir permeability and storage properties (porosity) and item (C) by the size of reservoir, storage mechanism and boundary conditions. The boundary conditions control the inflow, or recharge, to the reservoir, which may either be constant (as small as zero) or variable. Even though the first two items may be favourable for utilisation, item (C) is what ultimately determines the long-term potential of a geothermal reservoir. But it should be emphasised that if item (C) is determined to be unfavourable re-injection can be used to reduce, or counteract, its limitations.

Most of the information reviewed in this chapter was provided by Chinese counterparts during a fact-finding mission to Beijing and Yanqing in March/April 2001 (Axelsson, Johannesson and Gunnlaugsson, 2001). This includes test data from the end of drilling, the production history of well NY-01 since 1998, as well as some indirect data such as geological information. Some of the most important data were collected, however, during a 2-week detailed production test of well NY-01 in May 2001 and sent to Iceland for analysis.

Some information on item (A) above is available, assuming that future wells will have comparable characteristics, but information on item (B) is very limited. The data from the well test provides information, which may be used to approximately estimate the interference. Information on item (C) is also very limited, principally because of the limited utilisation of the Yanqing reservoir to date. The long-term decline will here be estimated on basis of data from the well test in May 2001, constrained by the production history of well NY-01. It may to some extent also be estimated on the basis of the volume and geological nature of the reservoir, volumetric potential estimates and a comparison with other similar geothermal systems in China.

It should be emphasised that there is great uncertainty in forecasting for item (C), the long-term decline in the reservoir, which in fact is the item most responsible for the ultimate potential of the Yanqing reservoir. This is because of the limited information available. Therefore it is suggested that the development of the Yanqing reservoir be carried out in steps and the potential reassessed during each step. Essential information on item (c) will become available, already during the first 1-3 years. Reinjection will most likely become essential in future utilisation of the reservoir to counteract the decline. More than sufficient thermal energy should be in-place in reservoir, however, because of its great volume.

In this chapter a model is set up to simulate the long-term behaviour and potential of the Yanqing geothermal reservoir. This model is, of course, no more accurate than the available data allows. Two models are in fact set up, one pessimistic and the other optimistic, showing the uncertainty involved in the forecasts. In this respect the importance of highly careful monitoring of well NY-01 and other wells drilled in the area must be emphasised because the accuracy of the model(s) will greatly increase in the coming months and years, as more data becomes available.

2 THE YANQING GEOTHERMAL RESERVOIR

Beijing City is situated on top of a large and deep sedimentary basin where geothermal resources have been found at depth. The Yanqing basin is a comparable, but much smaller sedimentary basin located in the mountains NW of Beijing City, also containing geothermal resources. These resources owe their existence to sufficient permeability at great depth (a few km) where the rocks are hot enough to heat water to exploitable temperatures. Major faults and fractures also play a 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/fractures.

The Beijing and Yanqing basins have been divided into several (about ten) geothermal areas on the basis of geological and geothermal conditions. The best known areas are the Urban and Xiaotangshan areas, which have been utilised since the 70's and 80's, respectively. Some information on these areas is summarised in Table 1 below. The yearly production from the Urban and Xiaotangshan fields corresponds to an average production of about 110 and 120 kg/s, respectively. This has resulted in a water level draw-down of the order of 1.5 m/year in the two fields. The reservoir rocks in the Urban and Xiaotangshan systems are mostly limestone and dolomite of the so-called Wumishan and Tieling formations.

Table 1. Information on the Urban and Xiaotangshan geothermal fields in Beijing, based on 1999 data.

Name of area	Area (km^2)	Reservoir Temp. (°C)	No. of wells	Well depths (m)	Yearly production (Mm^3/yr)
Urban	390	40-88	68	1000-3600	3.6
Xiaotangshan	150	40-72	46	800-2100	3.9
Other areas	~1800		86		2.5

Figures 1 and 2 show a simplified map of the Yanqing basin and an E-W geological cross-section through the Yanqing reservoir, respectively. The surface area of the Yanqing reservoir is estimated to be about 95 km^2. The figures show the locations of the three geothermal wells drilled in the area. Well CH, which yields 45°C water, drilled near the historical Fuyukon warm spring, well Q-2, which was drilled as an earthquake observation well to a depth of 533m yielding 33°C water and well NY-1, the focus of this study. Well NY-1 is located by Salihe-village a little bit north of the town of Yanqing. The reservoir rocks in the Yanqing basin are believed to be mostly composed of Wumishan dolomite intersected be several faults/fractures, some of which are shown in the figures. Some of these faults are believed to play a major role in the existence of the geothermal resource in the area, acting as the principal permeable flow-channels. Well NY-1 is located close to the Liangshan-Gucheng fault, which is certainly responsible for the good permeability encounterd by the well.

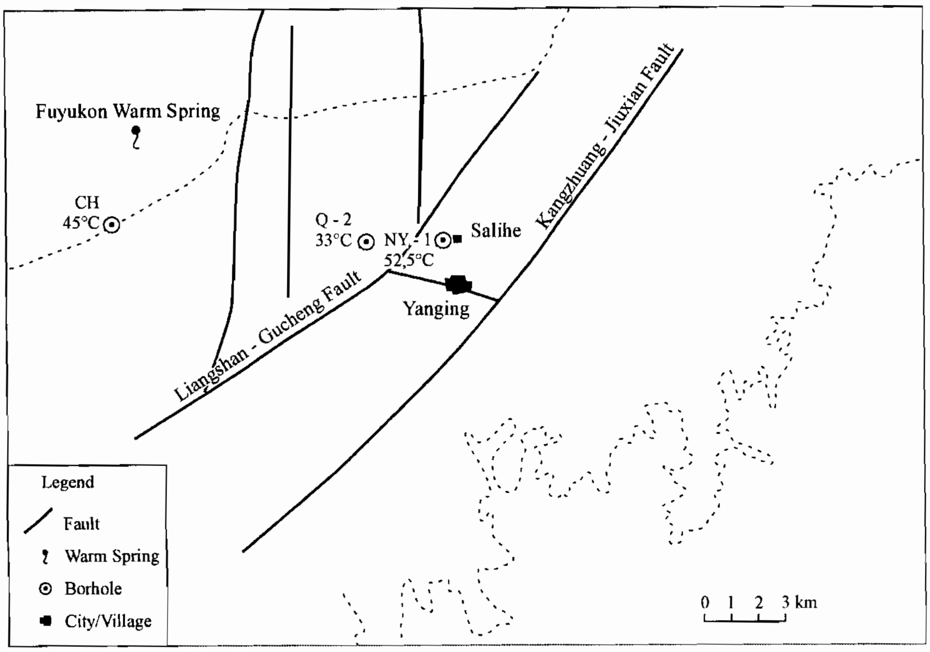

Figure 1. A simplified map of the Yanqing area showing the main faults and wells in the area.

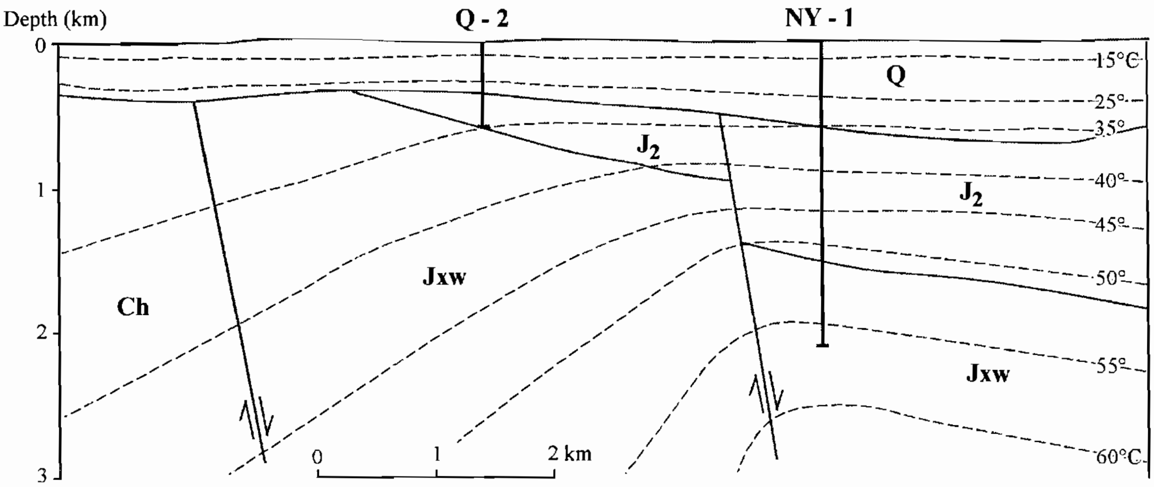

Figure 2. An E-W geological cross-section of the Yanqing geothermal reservoir.

The production potential of the Yanqing reservoir has only been estimated on the basis of volumetric methods so far. Such estimates are only first order estimates and not very reliable. The results show that heat reserves under the 95 km^2 area of the Yanqing reservoir, in the Wumishan formation, are of the order of 10 PJ (10^{16} J). The hot water reserves in the same volume are estimated to be about $6.3 \cdot 10^8$ m^3. Chinese scientists assume that an annual safe yield of water is about 0.5 – 1% of the water reserves, partly based on long-term experience from other geothermal fields.

3 Geothermal well NY-1

Well NY-1 was drilled during the winter of 1993/1994 to a depth of 2006m. Figure 3 shows the construction of the borehole, the lithology intersected by the well and other relevant information. Well NY-1 entered the geothermal reservoir (Wumishan formation) at a depth of 1397 m. It is cased to a depth of 1429 m, but open below that depth. It is cased with a 331 – 340 mm casing above 290 m depth. A bottom-hole temperature between 57 and 60°C has been reported.

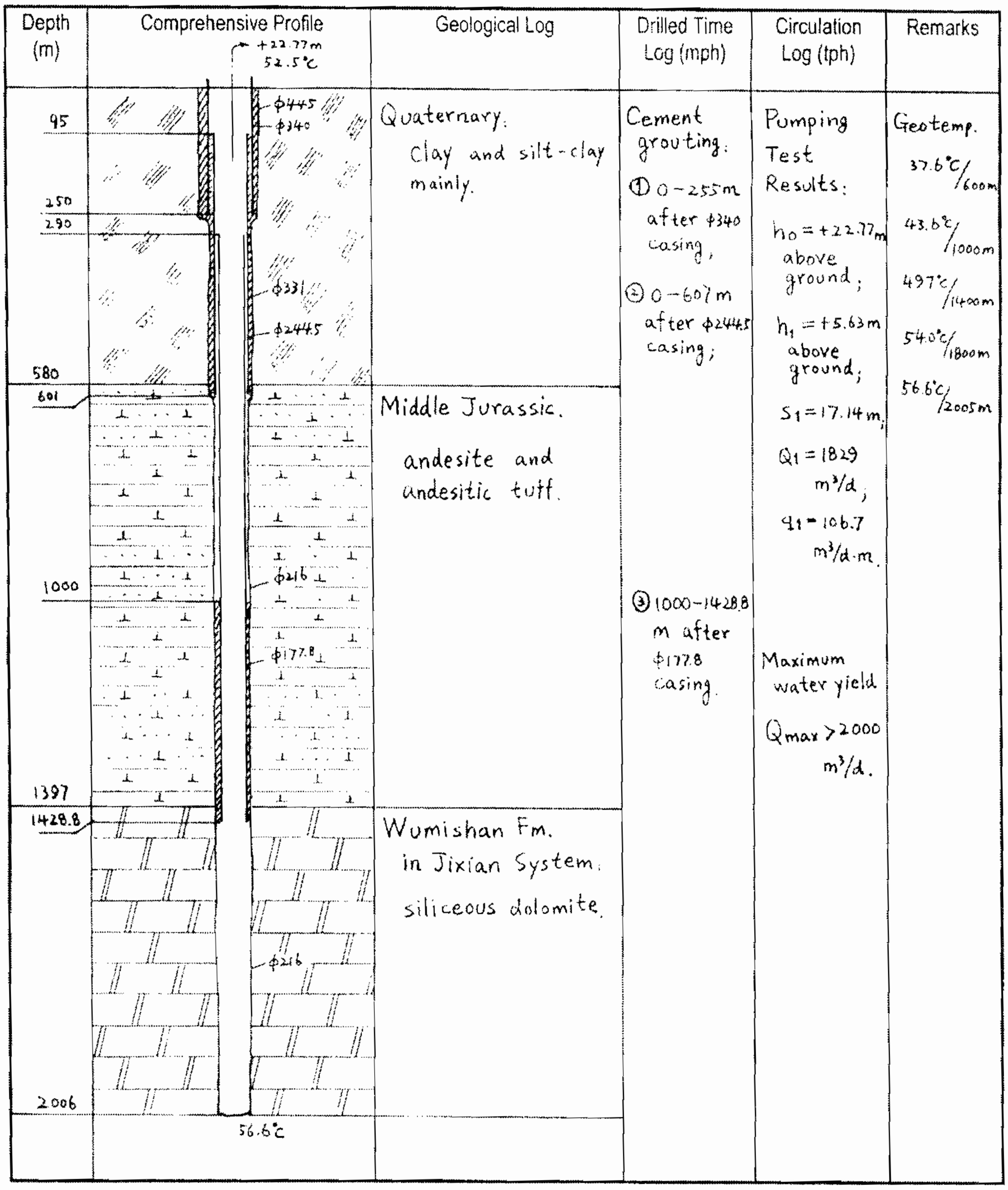

Figure 3. Design and geological cross-section of well NY-1 in Yanqing.

The well was tested at the end of drilling according to Chinese (Beijing) Standards. This involves production, either by free-flow or through pumping, in a few steps. Such testing is usually carried out for a few days at the maximum. According to the drilling report well NY-01 was tested by free-flow in three steps, lasting from 9 – 15 hours each. The available information indicates that stable conditions (discharge, pressure/water-level) were attained in each step. This, however, is questionable in view of the more accurate data collected last May (see later). The principal results of the completion test are presented in Figure 4 below.

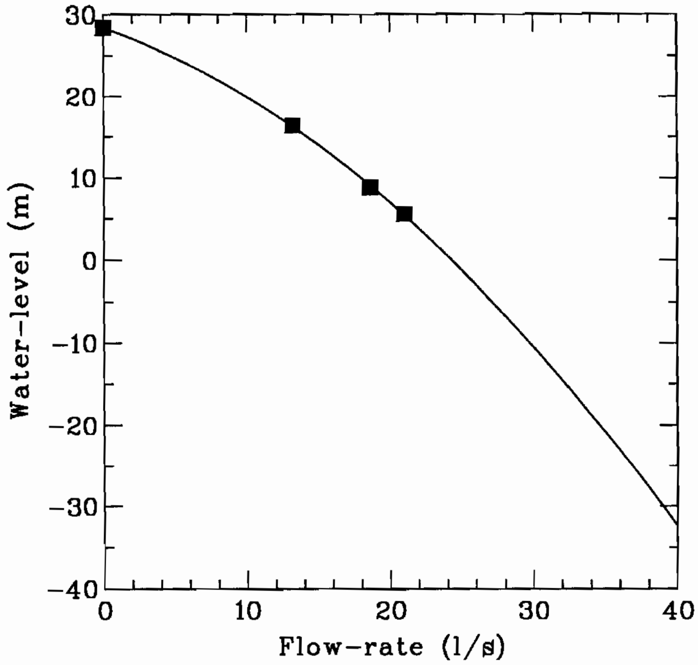

Figure 4. Results of step-rate test of well NY-01 at the end of drilling. Boxes indicate measured data, while the solid line shows the calculated characteristics of the well. Water level is relative to well-head (positive above ground, negative below ground).

At the end of drilling the well-head pressure of the well was estimated as corresponding to a water-column extending 28.4 m above the well-head, as shown in the figure. A second order polynomial equation has been fit through the data:

$$h = 28.4 - 0.622\,q - 0.0225\,q^2 \qquad (1)$$

Here h denotes the water-level in the well relative to the well-head (positive above ground, negative below ground) and q the flow-rate from the well in l/s. The second term describes the pressure-drop in the reservoir around the well, which is expected to change (increase) with time. The third term describes the pressure losses resulting from turbulent flow in the flow-paths (fractures) the well intersects. This term is not expected to change with time. The results in Figure 4 imply considerable turbulence pressure losses in the well or 9 m at 20 l/s, 20 m at 30 l/s and 36 m at 40 l/s. The maximum capacity of the well appears to be about 40 l/s, but production from the well should be limited to about 30 l/s. Based on a water temperature of 55°C, and utilisation down to about 30°C, this corresponds to about 2.5 MW of thermal energy.

In this study it will be assumed that new wells drilled in the area will have comparable characteristics, with a maximum yield of about 30 l/s. A success rate of drilling of about 80% will be assumed, keeping in mind that the success rate for other geothermal fields in the Beijing area is of the order of 90%.

4 Production history of well NY-1

Utilisation of well NY-01 started soon after completion, and in recent years it has been utilised for tap-water in the Salihe village and the Hot Spring Resort Hotel. Since 1998 accurate information is available on the monthly mass-extraction from the well, while only information on the average production from 1994-1998 is available. These data, i.e. the production history of the well, up to April 2001 are presented in Figure 5.

Unfortunately no data are available on the well-head pressure of the well during this time-span. Such data would have been invaluable in estimating the potential of the Yanqing reservoir.

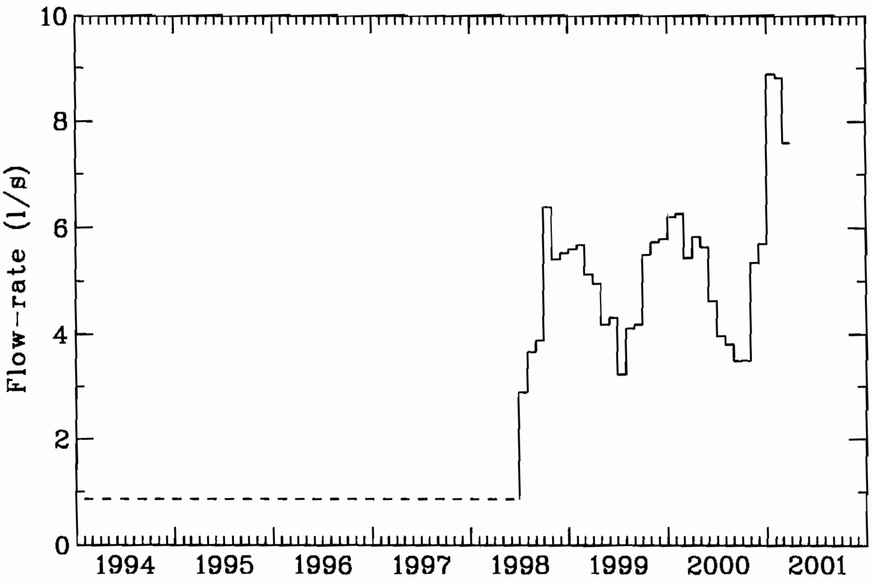

Figure 5. Production history of well NY-01 until April 2001.

The total amount of water produced from well NY-01 until the end of March 2001 is about 450,000 m3, which corresponds to slightly less than 2 l/s on the average. The average production in the year 2000 was 5 l/s, however.

5 TESTING OF WELL NY-1, AND THE YANQING RESERVOIR, IN MAY 2001

Well NY-01 in Yanqing was tested through the use of a down-hole pump, for a period of 15 days, in May 2001. The purpose of the test was to collect some additional information on the properties and nature of the Yanqing geothermal reservoir. This information, along with other data reviewed above, forms the basis for the assessment of the potential of the Yanqing reservoir. The test was carried out in accordance with a plan set up during the visit of Icelandic specialists in March/April 2001. Initial plans anticipated a 1-2 month well-test, in order for it to provide as much additional information as possible. After negotiations with the Beijing authorities a two-week test was agreed upon. Such a long test is in fact not according to Beijing Well-Test Standards, but was approved because of the importance of collecting as much information as possible. A 1-2 month test was not approved because of what was seen as an excessive waste of hot water.

The test started at 16:30 on May 12th. A constant rate of pumping of 26.6 l/s was maintained throughout the test, except for two short breaks in pumping on May 16th. The flow-rate was measured through the use of a V-notch. The water-level was measured manually every hour, and in fact more frequently during the first hours of the test. These water-level data are presented in Figure 6. In addition the water temperature was measured frequently, being stable at about 54°C.

The data from this test are quite good and are considered to be fully reliable. It is interesting to note that stable conditions are not reached during the 15-day test. This is in contrast with the data from the well-test at the end of drilling, which claims that stable conditions were reached within a few hours of pumping. It is also interesting to note that the water-level appears to decline almost linearly with time indicating a “closed” reservoir.

The well-test data, along with the production history of well NY-01, will in the following provide the basis for a lumped parameter model of the Yanqing reservoir. This model will, consequently, be used to calculate water-level predictions for different future production scenarios. These will, in turn, be used to assess the production potential of the Yanqing geothermal reservoir.

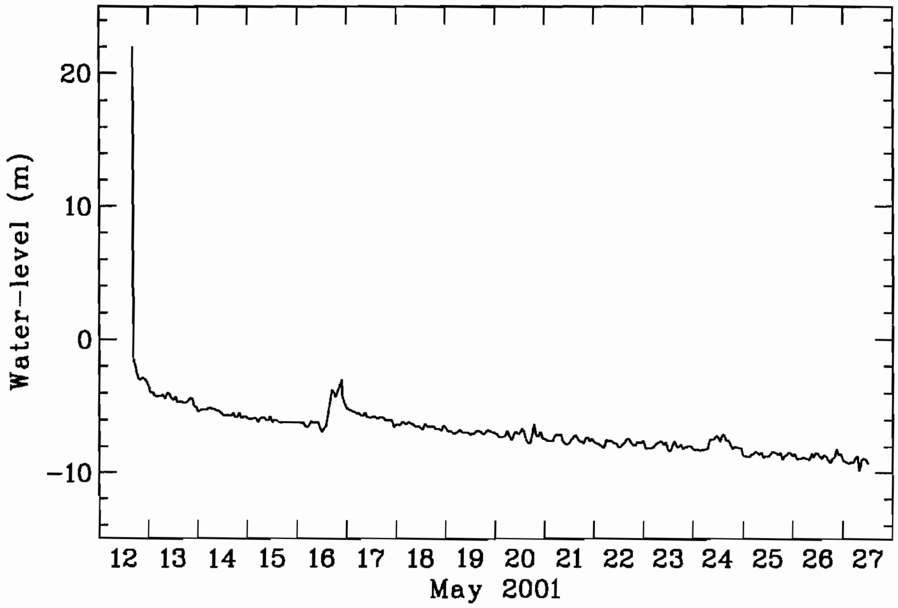

Figure 6. Water level data collected during well-test of well NY-01 May 2001. Data is relative to well-head, i.e. positive values indicate well-head pressure while negative values indicate water level draw-down.

6 SIMPLE LUMPED PARAMETER MODELLING

Lumped models have been used extensively to simulate data on water level and pressure changes in geothermal systems in Iceland and elsewhere. Lumped models can simulate such data very accurately, even very long data sets (several decades). Axelsson (1989) has described a method that tackles the simulation as an inverse problem. It automatically fits the analytical response functions of the lumped models to observed data by using a non-linear iterative least-squares technique for estimating the model parameters. Being automatic it requires very little time compared to other forward modelling approaches, in particular detailed numerical modelling.

Today, lumped models have been developed by this method for almost about 20 geothermal systems in Iceland, as well as geothermal systems in China, The Philippines, Turkey, Eastern Europe and El Salvador, as examples. Some examples of this are presented by Axelsson (1989 and 1991), Bjornsson et al. (1994) and Axelsson and Dong (1998). It may also be mentioned that a lumped parameter model was developed for the "Urban" geothermal system in Beijing by Qilong et al. (1986). The theoretical basis of this automatic method of lumped parameter modelling is presented by Axelsson (1989). The computer code LUMPFIT has been used since 1986 in the lumped modelling studies carried out in Iceland (Axelsson and Arason, 1992).

Lumped parameter models have been set up to simulate the available data and calculate future predictions. These models will not be discussed in detail here, but quite a good match was obtained with closed and open three-tank models. The comparison between observed and simulated data is presented in Figure 7. The responses of the lumped models show that the geothermal reservoir behaves in fact like a closed system. Whether this is truly because the system is closed or because of some confining boundaries or lower permeability towards the outskirts of the system, can not be ascertained at the present time. This will become clearer when more information on the response of the system becomes available (longer production history) and once more effort has been put into exploring the Yanqing geothermal system.

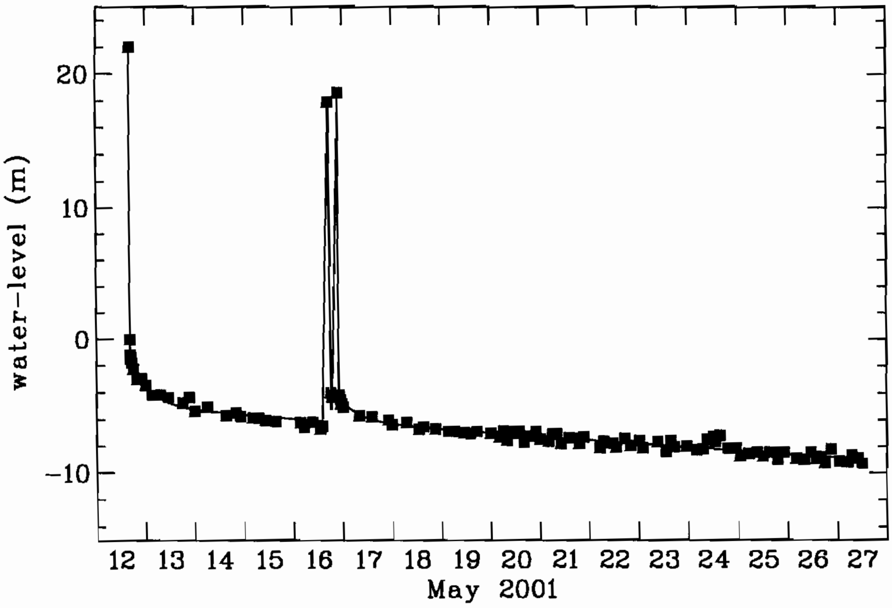

Figure 7. Observed (filled boxes) and simulated (solid line) water level changes during the well test of NY-01, values relative to well-head.

It should be mentioned that unfortunately no data are available on well-head pressure changes during the production history of well NY-01, but it appears that the well-head pressure of the well has declined from about 0.28 MPa in 1994 to 0.22 MPa in 2001. This puts a much-needed constraint on the long-term water level decline in the geothermal system. The two lumped models were used to calculate water level predictions for different future production scenarios. It should be pointed that the closed and open models will provide pessimistic and optimistic predictions, respectively. Therefore, the closed model will provide a lower bound to the production capacity of the reservoir, while the open model will give an upper bound. Reality may be expected to lie somewhere in-between these two extremes. This also applies to the nature of the geothermal system, which are also expected to be in the range determined by the two models.

The properties of the models provide information on the size and permeability of the Yanqing geothermal reservoir. The surface areas are about 30-400 km^2 for the open and closed models, respectively. At this stage it is impossible to ascertain which model is closer to reality. The most important parameter of any hydrological reservoir is its permeability. The model permeability values, for the inside the reservoir, are of the order of 0.2 Darcy. These values indicate relatively good permeability, which may for example be compared with the permeability estimate for the Urban geothermal area inside the City of Beijing, which also equals 0.2 Darcy (Qilong et al., 1986). What is noteworthy is that according to the open model the permeability of the outskirts of the reservoir is much lower, or of the order of 0.01 Darcy. Thus the open model behaves, in fact, as semi-closed.

The principal results of modelling the Yanqing geothermal reservoir is that it appears to be either closed or semi-closed (low permeability outskirts) with relatively high permeability. Therefore, recharge to the reservoir will be limited and reinjection will be essential in its utilisation. It should also be mentioned that the model development discussed here should only be considered the first step in developing a model for the Yanqing geothermal system. Once more data, in particular production response data, become available in the coming months and years the models should be updated and refined. Modelling the reservoir temperature conditions, in addition, is of particular interest since it will provide constraints on the natural hot-water inflow into the geothermal system.

7 REINJECTION

Reinjection is carried out in many geothermal fields world-wide (Stefansson, 1997). Reinjection first started out as a method of waste-water disposal for environmental reasons, but has now become a method of pressure maintenance and thermal energy extraction in geothermal reservoirs (Axelsson and Gunnlaugsson, 2000). It is foreseeable that reinjection will become an essential element in the sustainable utilisation of all geothermal resources. In addition, it appears that reinjection will be essential for pressure maintenance in the Yanqing reservoir in the future. Otherwise, pressure draw-down will limit the possible production greatly. Reinjection can be looked upon as a method of artificial recharge replacing the apparent lack of recharge to the Yanqing reservoir. It is therefore recommended that full reinjection be assumed in all plans for geothermal utilisation in Yanqing.

Reinjection into low-temperature sedimentary geothermal reservoirs has been attempted in a number of locations. Problems of clogging are often associated with reinjection in the case of sandstone reservoirs (Axelsson and Gunnlaugsson, 2000). Reinjection into carbonate-rocks, such as limestone and dolomite has usually been possible without any problems. A good example of this is the carbonate Dogger reservoir in the Paris-basin in France, where geothermal energy has been utilised through a double-scheme for decades (Axelsson and Gunnlaugsson, 2000). Reinjection has not been employed on a large scale in the sedimentary geothermal systems utilised in China, except for Tianjin where reinjection into carbonate rocks is now successfully reinjected into several wells (Wang, 2001). Therefore, it is expected that full reinjection will be possible in the future in Yanqing. Some countermeasures, such as acid-treatment may be envisioned to counteract clogging of reinjection wells during long-term reinjection.

The main danger associated with reinjection is cooling of near-by production wells (Axelsson and Gunnlaugsson, 2000). This may normally be avoided by locating injection wells at a sufficient distance from production wells. Simple calculations for the Yanqing reservoir indicate that a distance of 1-1.5 km should be sufficient. It is highly important, however, that once a reinjection well has been drilled that its connection to near-by production wells be studied through tracer tests (Axelsson et al., 1995). The results of such test can be used to calculate more accurate cooling predictions.

It is believed to be more economical that one reinjection well be drilled for each two production wells in Yanqing and to use high-pressure pumps to inject the water. Assuming similar characteristics for future reinjection wells as those of well NY-01 (Figure 4), it may be estimated that a well-head pressure of up to 15 bar will be needed to inject a maximum flow-rate of about 60 l/s.

8 PRELIMINARY POTENTIAL ESTIMATE OF THE YANQING GEOTHERMAL RESERVOIR

The lumped parameter models have been used to calculate water-level predictions for a few future production scenarios. These are:

(I) One production well (NY-01) producing 30 l/s for 4 months and 7.5 l/s for 8 months, 15 l/s on the average.

(II) Four comparable production wells, producing 120 l/s for 4 months and 30 l/s for 8 months, 60 l/s on the average.

(III) Four comparable production wells, producing 120 l/s for 4 months and 30 l/s for 8 months, 60 l/s on the average. One reinjection well utilised for testing, injection rate 30 l/s for 4 months and 7.5 l/s for 8 months, 15 l/s injection on the average. Net production equals 90 l/s for 4 months and 22.5 l/s for 8 months, 45 l/s on the average.

(IV) Four comparable production wells, producing 120 l/s for 4 months and 30 l/s for 8 months, 60 l/s on the average. Two reinjection wells and about 90% reinjection, 108 l/s for 4 months and 27 l/s for 8 months, 54 l/s injection on the average. Net production equals 12 l/s for 4 months and 3 l/s for 8 months, 6 l/s on the average.

Examples of the results, i.e. for scenarios (I) and (III), are presented in figures 8 and 9. Examples of the results for two different cases are presented in figures 8 and 9. The predictions are only presented for 3 years since the limited data, and consequent uncertainty, do not warrant predictions for longer periods. The calculations in Figure 8 are done by the more pessimistic model, which is completely closed (no recharge), and should provide indications of the lower bounds of the water-level decline for this production case. The long-term draw-down increases rapidly, and even though reality may not be as bad as this prediction, it indicates that reinjection will be essential for any large scale (a few wells like NY-01) utilisation of the reservoir. With full reinjection the long-term draw-down should be much less than indicated in the figure.

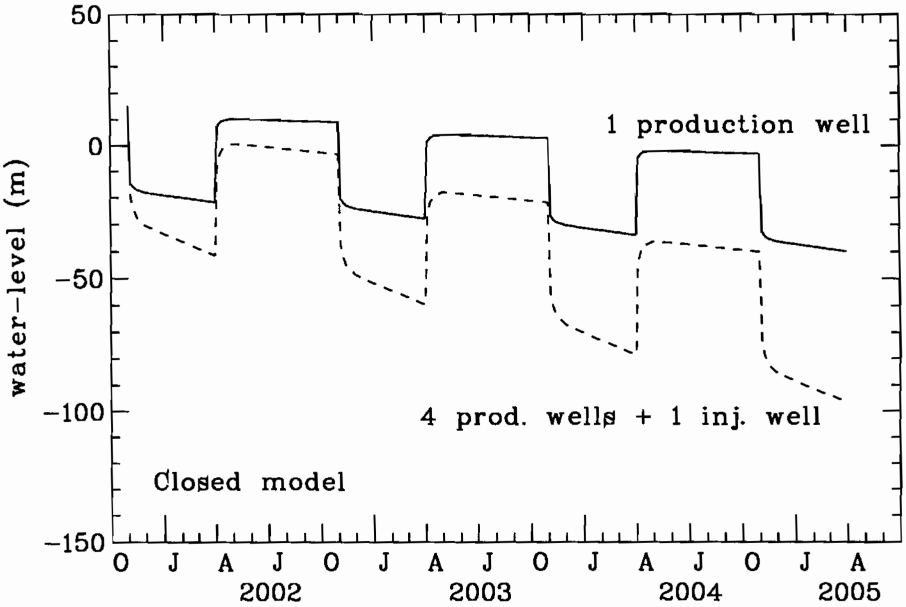

Figure 8. *Predicted water-level changes in well NY-01 for two future production scenarios; (a) one production well (30 l/s for 4 months, 15 l/s yearly average) and (b) four production wells (4x30 l/s for 4 months, 60 l/s yearly average) and one reinjection well (25% reinjection). Calculated by a closed model (pessimistic predictions), values relative to well-head.*

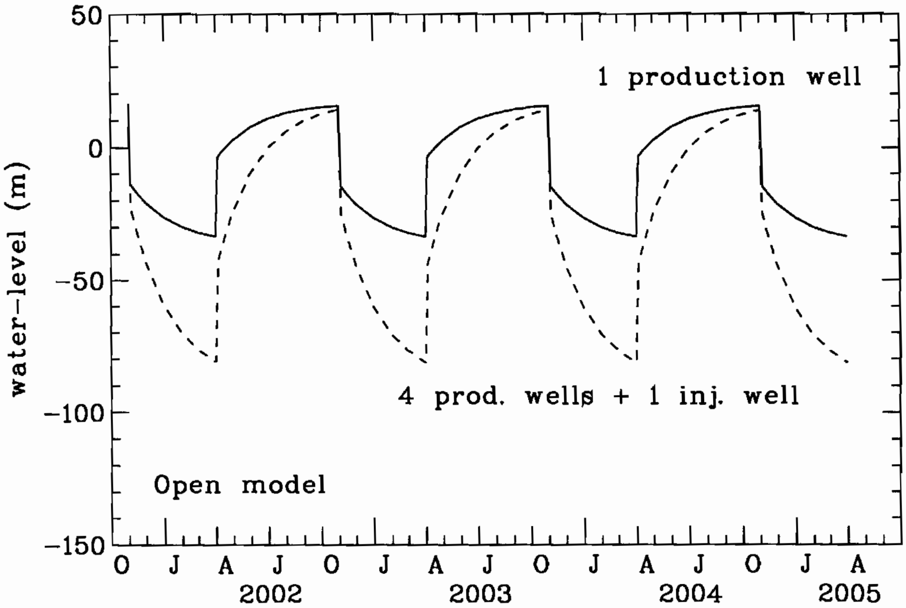

Figure 9. *Predicted water-level changes in well NY-01 for two future production scenarios; (a) one production well (30 l/s for 4 months, 15 l/s yearly average) and (b) four production wells (4x30 l/s for 4 months, 60 l/s yearly average) and on reinjection well (25% reinjection). Calculated by an open model (optimistic predictions), values relative to well-head.*

9 SUMMARISED RESULTS

The main results of the preliminary assessment of the Yanqing geothermal reservoir, and related recommendations, are as follows:

1. Well NY-01 is fairly productive and able to produce up to 30 l/s in the short term.

2. Limited production appears to cause a considerable long-term water level draw-down, however, indicating that the reservoir is either closed or with limited recharge.

3. Full reinjection must be applied to counteract water-level draw-down and provide artificial recharge. Otherwise it appears that the sustainable potential of the geothermal reservoir is rather limited. Reinjection should also be considered as part of any modern environmentally friendly geothermal utilisation.

4. An utilisation scheme is propose involving a step-wise increase in production and frequent re-assessment of the potential of the reservoir, before its ultimate potential is determined. During the first step production from four production wells (4 x 30 l/s winter production, 4 x 15 l/s average production) is proposed, as well as full reinjection (more than 90%). The ultimate potential does at this moment not appear to be greater than about 200 l/s average production, with full reinjection, according to a pessimistic appraisal.

5. It must be emphasised that only one user should be given the rights for utilisation of the geothermal resources in the Yanqing basin. Firstly, because this allows for a more efficient management of the resource. Secondly, because the potential of the resource does, at this moment, appear to be not too great. Further exploration for geothermal resources on the outskirts of the basin, where indications have been found for higher reservoir temperature, is recommended.

6. Data on the Yanqing geothermal reservoir is limited at the present stage. Therefore, careful monitoring of all wells (including NY-01), further data collection and exploration as well as detailed testing, such as tracer testing, is emphasised in the coming months. The drilling of a new production well in the area, to confirm the existence of the resource, is essential. Finally, training of Chinese counterparts is emphasised, to facilitate successful co-operation in the future.