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Production potential of the Lishuiqiao geothermal reservoir

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PRODUCTION POTENTIAL OF THE LISHUIQIAO GEOTHERMAL RESERVOIR

1 INTRODUCTION

In this chapter the information which is available at present for a preliminary assessment of the Shahe geothermal reservoir in Lishuiqiao 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. Limited data is available on the geothermal system 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 this part of Beijing-City 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.

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 in March/April 2001 (Axelsson, Johannesson and Gunnlaugsson, 2001). These includes test data from the end of drilling of well ShaRe-6, the production history of the well during last winter, as well as some indirect data such as geological information. Some very important additional data were collected, however, during a short well test of well ShaRe-6 in July 2001 and sent to Iceland for analysis.

Some information on item (A) above is available, assuming that future wells will have characteristics comparable to ShaRe-6, but information on item (B) is very limited. Data collected during the one-year production history of ShaRe-6 may be used to approximately estimate the interference. Information on item (C) is also very limited, principally because of the limited utilisation of the geothermal reservoir to date. The long-term decline will here be estimated on basis of the one-year production history of ShaRe-6. It may to some extend also be estimated on the basis of the volume and geological nature of the reservoir, volumetric potential estimates and comparisons 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 geothermal reservoir. This is because of the limited information available. Therefore, a step-wise development of the reservoir is essential, as already discussed. Essential information on item (C) will become available, already during the first years of such development. 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 geothermal reservoir under Lishuiqiao. 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 all 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 become available.

2 THE SHAHE GEOTHERMAL RESERVOIR IN LISHUIQIAO

Beijing City is situated on top of a large and deep sedimentary basin where geothermal resources have been found at depth. These resources owe their existence to sufficient permeability at great depth (1-4 km) where the rocks are hot enough to heat water to exploitable temperatures. 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 basin has 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.

The Shahe geothermal field is located in the NW-part of Beijing, south of the Xiaotangshan field, with an area of about 100 km^2 elongated NW-SE. Two major NE-SW trending faults intersect the SE-part of the Shahe field, the Babaoshan fault to the west and the Huang Zhuang-Gao Li Ying fault to the east. The locations of these faults are shown in figures 1 and 2. The Lishuiqiao area is located in-between the faults, which are believed to play a major role in the existence of the geothermal resource in the area. Wells drilled in the Shahe-field west of the Babaoshan fault (ShaRe-5 and ShaRe-7) produce from the Tieling and Wumishan formations and are poorly productive (< 10 kg/s). Well ShaRe-6, which is the focus of the present study, is drilled in-between the two faults and is a much better producer. It produces from the so-called Cambrian formation (denoted by ε, see figures 2 and 3), which is mostly composed of limestone.

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

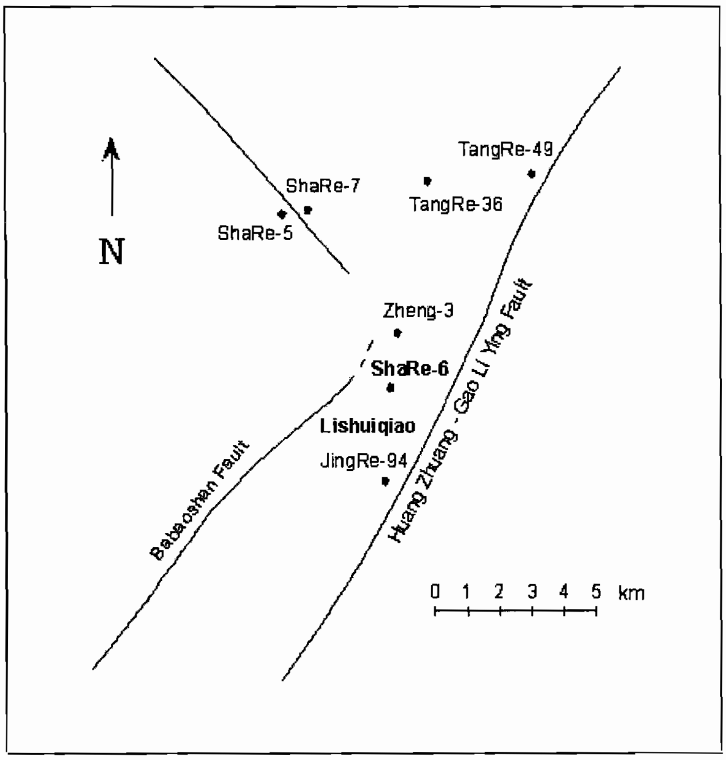

Figure 1. Geological map of the Lishuiqiao area showing main faults and deep wells.

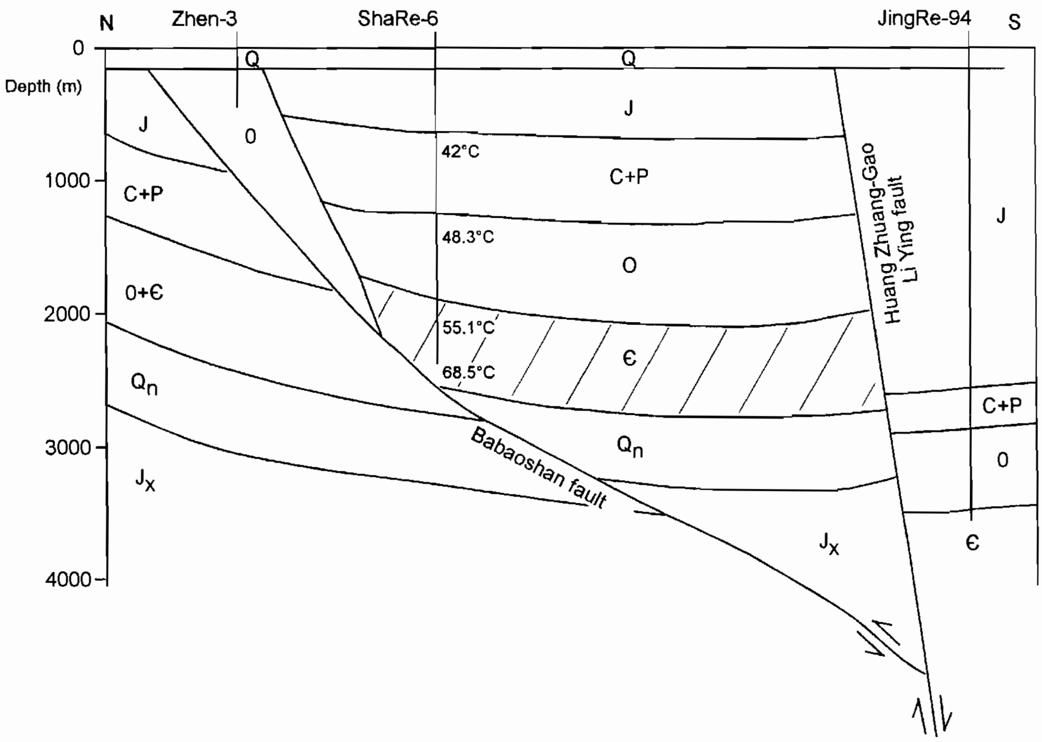

Figure 2. Geological cross-section of the Shahe geothermal area in Lishuiqiao.

Much higher permeability in this part of the Shahe geothermal system may most likely be attributed to the Huang Zhuang-Gao Li Ying fault, which is also believed to be the channel for hot up-flow to the system. The recently drilled JinRe-94 (figures 1 and 2), which was successfully drilled into the Cambrian formation on the east-side of this fault, to a depth of 3600m, supports this belief, or model.

The production potential of the Shahe-reservoir in the Lishuiqiao-area 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 19.6 km^2 area designated to the Lishuiqiao project, in the Cambrian, Tieling and Wumishan formations, are of the order of 4.5 PJ (10^{15} J). The hot water reserves in the same volume are estimated to be about $3.8 \cdot 10^9$ 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 SHARE-6

Well ShaRe-6 was drilled during the winter of 1999/2000 to a depth of 2418m. Figure 3 shows the construction of the borehole as well as the lithology intersected by the well. The well is open below 2250m depth in a lithological unit primarily composed of fractured limestone. The reservoir temperature at that depth is estimated to be about 73°C.

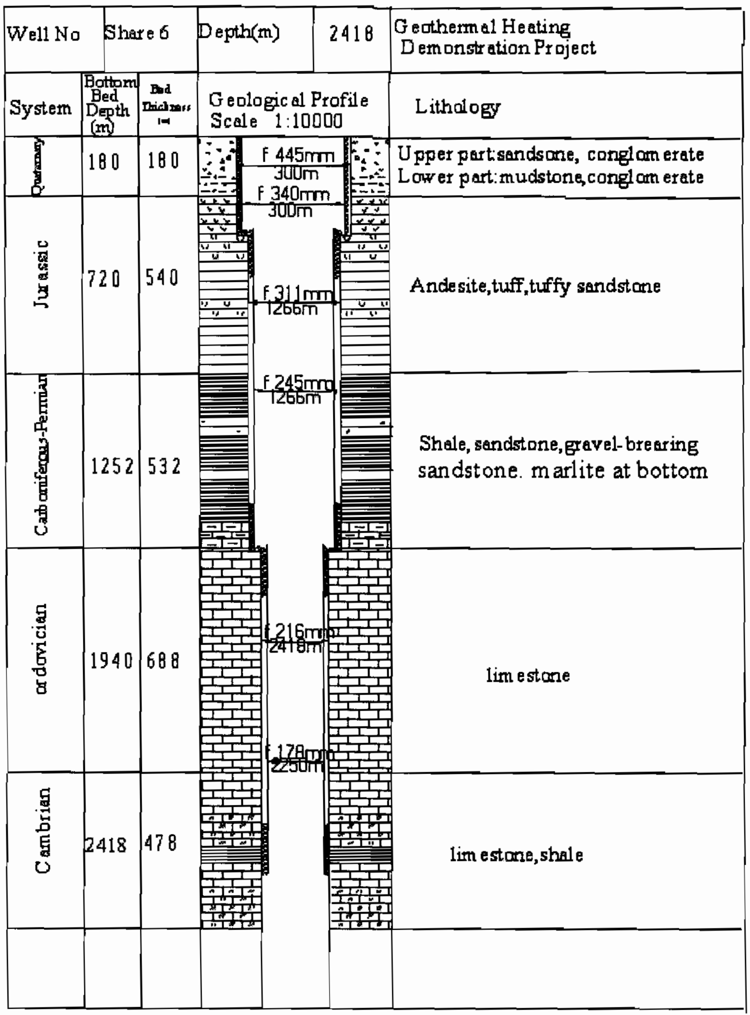

Figure 3. Design and geological cross-section of well ShaRe-6 in Lishuiqiao.

Well ShaRe-6 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 stable conditions (discharge, pressure/water-level) were attained in each step. This, however, is questionable in view of data collected later. A few days after the end of drilling the well was tested further, by a down-hole pump, actually for about a week. The principal results of these tests are presented in Figure 4 below, where an apparent discrepancy between the two tests has been corrected. The data on the production characteristics of well ShaRe-6 in Figure 4 show that the well is quite productive and able to produce up to 40 l/s, or more, in the short-term. Based on a water temperature of 65°C, and utilisation down to about 30°C, this corresponds to about 5.8 MW of thermal energy.

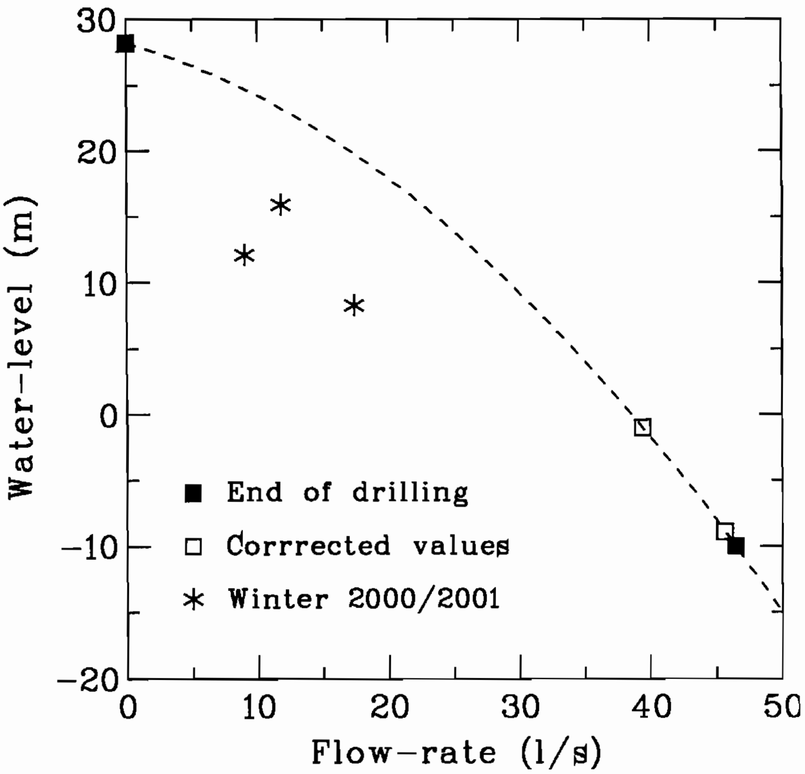

Figure 4. Results of step-rate test of well ShaRe-6 at the end of drilling with additional data from the winter of 2000/2001. Data are relative to well-head, i.e. positive values indicate well-head pressure while negative values indicate water level draw-down.

At the end of drilling the well-head pressure of the well was estimated as corresponding to a water-column extending 28 m above the well-head, as shown in the figure. A second order polynomial equation has been fit through the data:

$$h = 28.2 - 0.281\,q - 0.0117\,q^2 \qquad (1)$$

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 some turbulence pressure losses in the well or 5 m at 20 l/s, 11 m at 30 l/s and 19 m at 40 l/s.

In this study it will be assumed that new wells drilled in the area will have comparable characteristics, with a maximum yield of about 40 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 SHARE-6

The data available from the one-year production history of well ShaRe-6 is presented in figures 5 and 6. These are data collected during testing of the well in March 2000 as well as data collected during utilisation of the well through the winter of 2000/2001. The data in these figures indicate that a considerable long-term water level decline has taken place in the geothermal reservoir, perhaps as great as 15 m or so. This is supported by the data from 2000/2001 in Figure 4. This is quite a large decline considering the rather limited production from the reservoir. In addition this decline does not seem to recover when production is reduced or stopped. This indicates that the reservoir is either closed or with rather limited recharge. Therefore, the production potential of the reservoir appears to very limited unless full reinjection is applied to provide a kind of artificial recharge. More than sufficient thermal energy is in-place in the geothermal reservoir, however.

The data in figures 5 and 6 forms the basis for modelling of the geothermal reservoir, which is discussed in the following chapter.

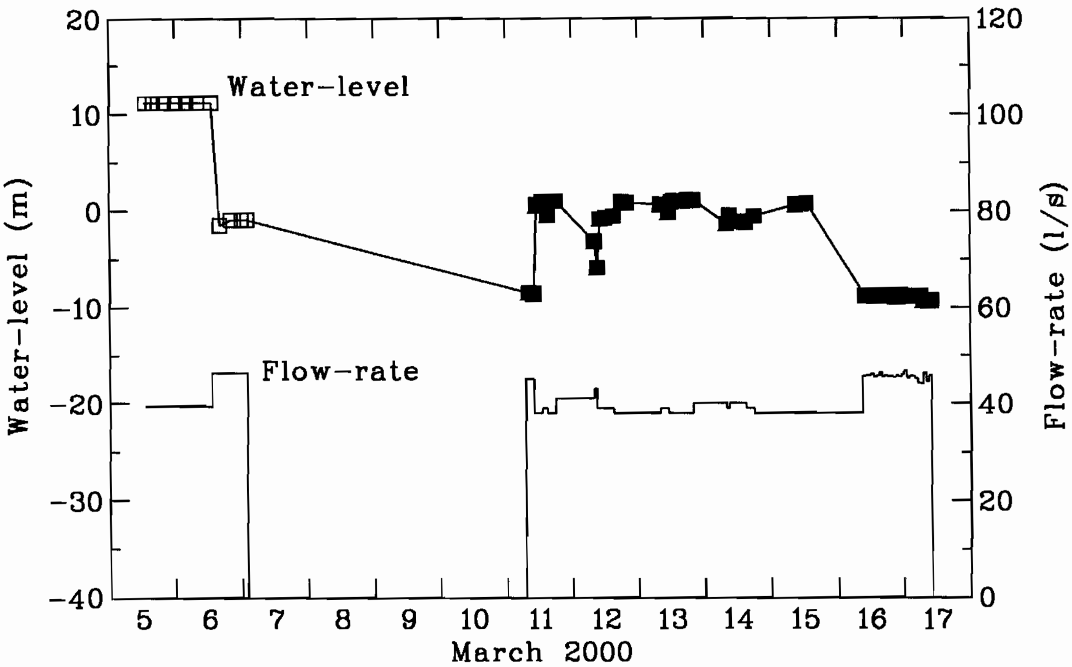

Figure 5. Production and water-level history of well ShaRe-6 after end of drilling in March 2000. Data are relative to well-head.

Figure 7, which shows the water level data from an earthquake observation well a few km north of well ShaRe-6 shows the water-level decline in the reservoir very clearly. In addition it seems to indicate that production from another well, or other wells, may be causing some of the decline. This points to an extremely important aspect of the utilisation of the Shahe reservoir, which is the influence of production by other users outside the area designated to the Lishuiqiao project, but inside the same geothermal field. This will of course put a limit to the maximum production and must be taken into account. Information on this aspect is lacking at the present point in time. Either a guarantee must be provided by the Beijing Government that this production by others, from the same reservoir, will be within acceptable limits, or a common management of the reservoir must be set up in co-operation between the different users.

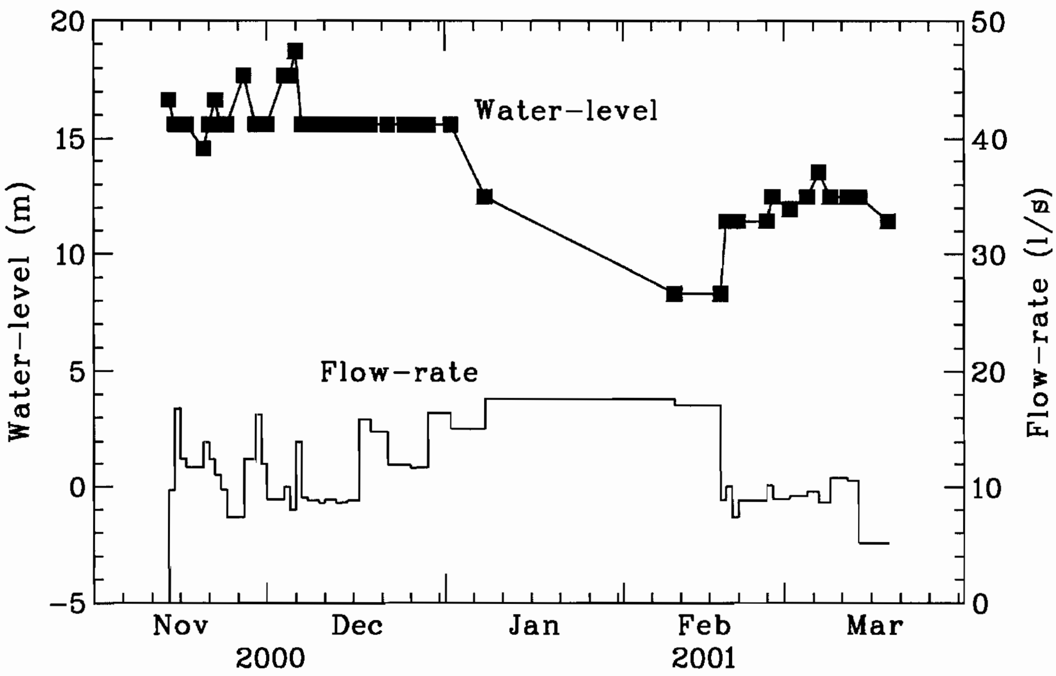

Figure 6. Production and water-level history of well ShaRe-6 during the winter of 2000/2001. Data are relative to well-head.

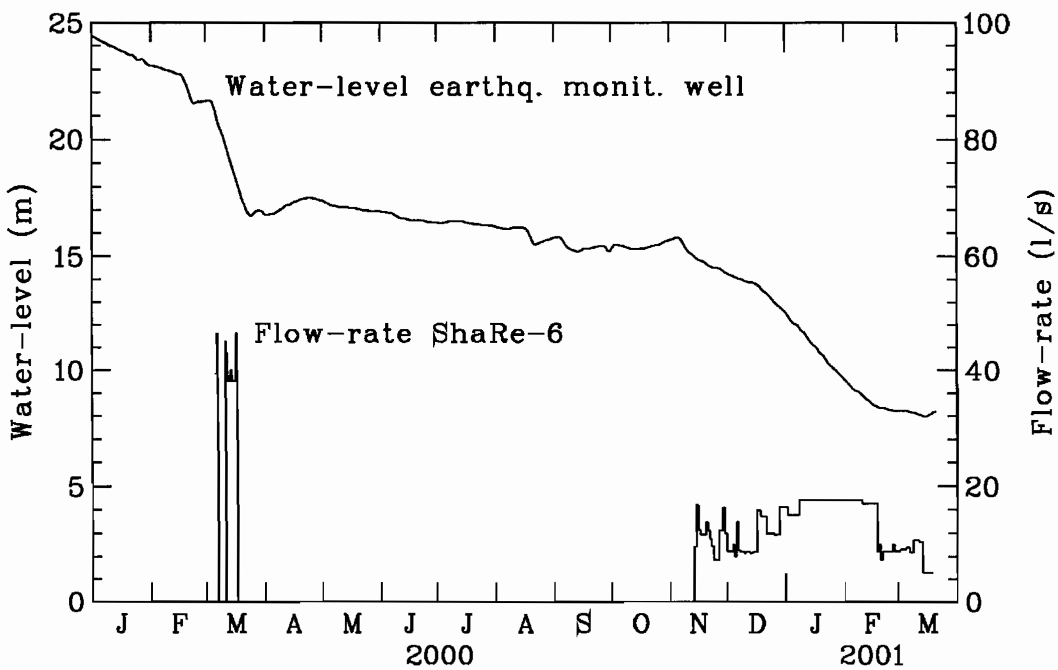

Figure 7. Production history of well ShaRe-6 along with water level data from an earthquake monitoring well north of Lishuiqiao.

5 TESTING OF WELL SHARE-6 IN JULY 2001

Well ShaRe-6 in Lishuiqiao was tested through the use of a down-hole pump, for a period of 3 days, in July 2001. The purpose of the test was to collect some additional information on the properties of the well and the associated geothermal 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 3 day test was agreed upon in order to conform with Beijing Well-Test Standards. A 1-2 month test was not approved because of what was seen as an excessive waste of hot water.

The data from the test, which was carried out in three steps, are presented in Figure 8 below. In addition the water temperature was measured frequently, being stable at about 64°C during the first step, but decreasing to about 60°C during the final step. This is simply because of more cooling of the water ascending the well during the well at lower flow-rate.

Interpretation of the test data leads to two main conclusions. Firstly, that there does not appear to be any long-term pressure decline during the test. This is positive, but the test is really too short to ascertain this. Secondly, the test data agrees with the 2000/2001 data presented in Figure 4 (denoted by *).

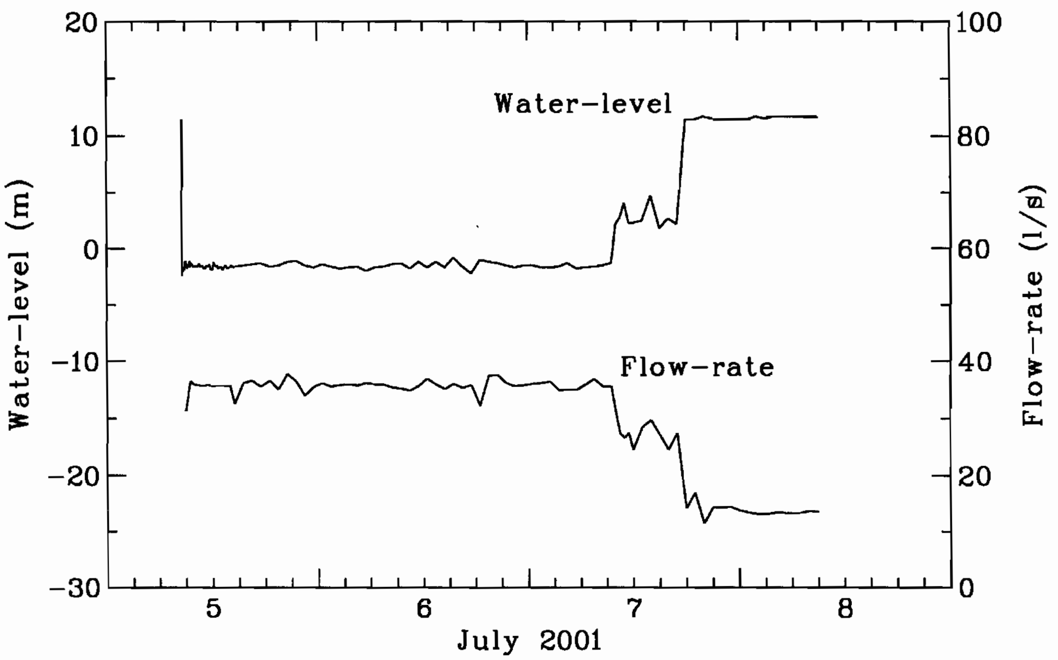

Figure 8. Flow-rate and water level data collected during testing of well ShaRe-6 in July 2001. Data is relative to well-head.

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 water-level data from well ShaRe-6 and calculate future predictions. These models will not be discussed in detail here, but they are able to simulate the data fairly well. Yet the data are limited as already mentioned and the models should not be considered very accurate. Figure 9 shows an example of the predictions calculated by the model, for a case of well ShaRe-6 being used at full capacity (40 l/s) during the winter time, but a 20 l/s average yearly production. These calculations 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 draw-down is very great, and even though reality may not be as bad as this prediction, it indicates that full reinjection will be essential for any large scale (a few wells like ShaRe-6) utilisation of the reservoir. With full reinjection the long-term draw-down should be much less than indicated in the figure. Another prediction example showing this is presented later (Figure 11).

It may be mentioned that according to the model the surface area of the reservoir is of the order of 120 km^2, which appears to be quite reasonable. Furthermore, the average reservoir permeability is about 0.09 Darcy, and the permeability-thickness about 45 Darcy-m, according to the model. These values indicate fairly good permeability, which may for example be compared with the permeability estimate for the Urban geothermal area inside the City of Beijing, which equals 0.2 Darcy (Qilong et al., 1986).

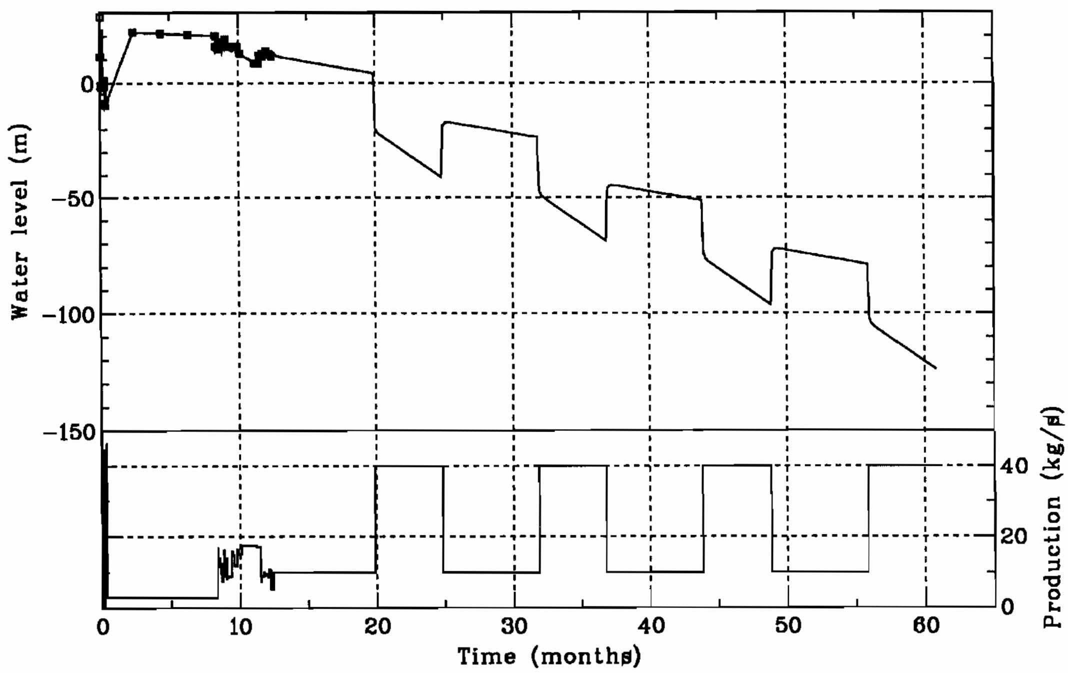

Figure 9. Predicted water-level changes in well ShaRe-6 for 4 years of full utilisation, closed (pessimistic) model and no reinjection.

The model development discussed here should only be considered the first step in developing a model for the Shahe geothermal system in Lishuiqiao. 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 will play a two-fold role in Lishuiqiao. First, as part of any modern environmentally friendly geothermal utilisation. Second, as an essential tool for maintaining the reservoir pressure, i.e. to counteract pressure draw-down (Axelsson and Gunnlaugsson, 2000). Therefore, it is recommended that full reinjection be part of the proposed Lishuiqiao project right from the beginning. Without reinjection the production potential of the reservoir appears to be quite limited. It should be pointed out that it may be more economical to assume that one reinjection well be drilled for each two production wells and high pressure (10-20 bar) utilised for the injection. It is difficult to estimate how much pressure will be needed for the reinjection. An attempt has been made to estimate this and the result is presented in Figure 10. The figure is based on the present pressure conditions in the reservoir. The well-head pressure needed will go down as the reservoir pressure declines with time. This will, however, balance against possible increases in the well-head pressure needed for reinjection, because of clogging and other effects.

It should also be pointed out that cooling is normally the greatest danger associated with reinjection. This should be fully avoidable if a distance between production and reinjection wells of 1-1.5 km is maintained. However, careful testing, such as through tracer tests, is essential for accurately assessing this danger (Axelsson et al., 1995). Another danger is clogging of feed-zones in reinjection wells due to chemical precipitation (Axelsson and Gunnlaugsson, 2000). This danger is believed to be small, but if such precipitation occurs it may in most cases be avoided through acidizing reinjection wells.

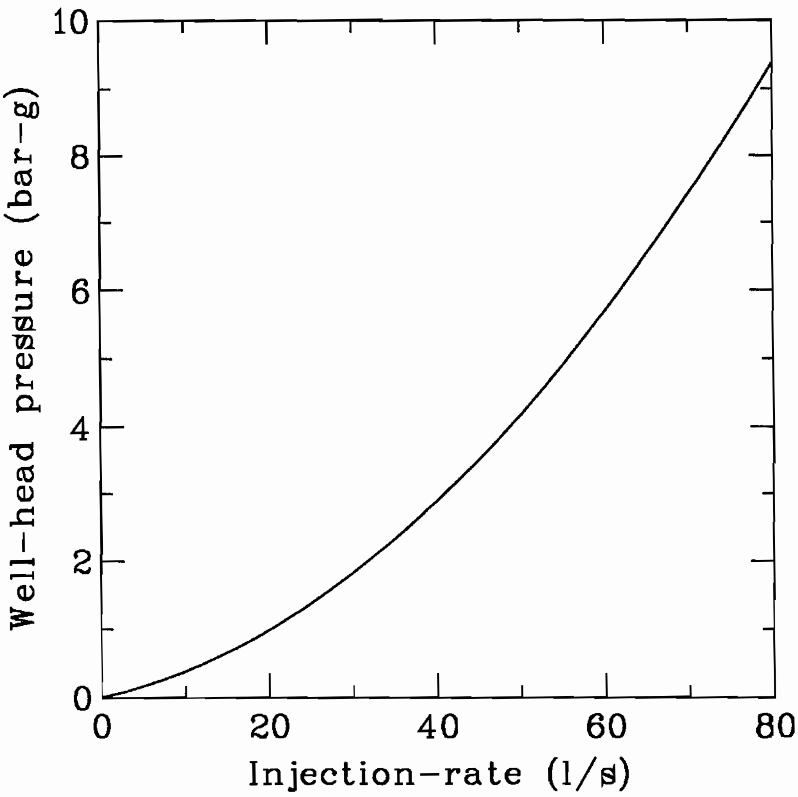

Figure 10. Estimated well-head pressure of reinjection wells with characteristics comparable to those of well ShaRe-6. Well-head pressure will most likely decrease with time as reservoir pressure declines.

8 Preliminary potential estimate of the Shahe geothermal reservoir in Lishuiqiao

Because of the uncertainty in estimating the production potential of the geothermal reservoir a step-wise increase in utilisation is essential. Such a step will already be taken during the winter of 2001/2002 since two more wells are being drilled in the area according to the latest information. The plan is to utilise these wells and ShaRe-6 for production and reinjection during next winter. If these wells are monitored carefully during this period invaluable data will be collected, which will enable a much more accurate estimate of the reservoir potential. It is important in this respect to set up a comprehensive monitoring program involving other wells in the area also.

During the first utilisation step discussed above production from two production wells (2 x 40 l/s winter production, 2 x 20 l/s average production) is assumed, as well as full reinjection. Model calculation indicate that the reservoir should be able to sustain such a level of production (see Figure 11). Following this first step utilisation should be increased in further steps, each followed be a re-assessment of the potential of the reservoir, before its ultimate potential is determined. The ultimate potential does at this moment not appear to be greater than about 100 l/s average production, with full reinjection, according to a pessimistic appraisal. The drilling of too many wells should be avoided in order to avoid over investment and over-exploitation.

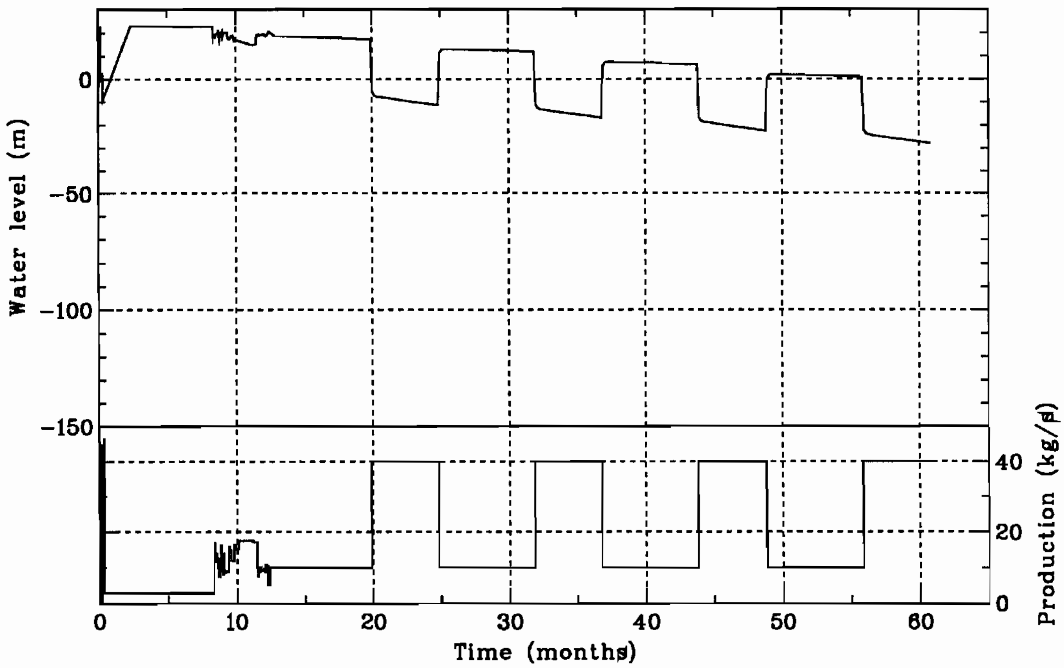

Figure 11. Predicted water-level changes (calculated for well ShaRe-6) for 4 years of full utilisation of two production wells (2 x 40 l/s winter production, 2 x 20 l/s average production) and 90% reinjection into one injection well. Based on a closed (pessimistic) model.

9 Summarised results

The main results of the preliminary assessment of the Shahe geothermal reservoir in Lishuiqiao may be summarised as follows:

1. Well ShaRe-6 is quite productive and able to produce 40 l/s, or more, in the short term.

2. Limited production appears to cause considerable long-term water-level draw-down, 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 very limited. Reinjection should also be considered as part of any modern environmentally friendly geothermal utilisation.

4. Geothermal production outside the area designated to the Lishuiqiao project, but from the Shahe reservoir, will limit the production possible. Any such outside production must be within acceptable limits. A comprehensive management program for the Shahe reservoir, involving all parties utilising the resource, must be set up.

5. A step-wise increase in utilisation of the Shahe reservoir is essential. Such a step is already being taken since two additional wells are being drilled and will be utilised, in addition to ShaRe-6, for production and reinjection during next winter. Careful monitoring will yield invaluable data, which will enable a re-assessment of the potential of the reservoir. Other wells in the area must also be monitored. Production from two production wells (2 x 40 l/s winter production, 2 x 20 l/s average production) is assumed during this first step, as well as full reinjection, which model calculation indicate the reservoir should is able to sustain. Following this first step utilisation should be increased in further steps, before its ultimate potential is determined. The ultimate potential does at this moment not appear to be greater than about 100 l/s average production, with full reinjection, according to a pessimistic appraisal. The drilling of too many wells should be avoided in order to prevent over-investment and over-exploitation.

6. Data on the Shahe geothermal reservoir in Lishuiqiao is limited at the present stage. Therefore, careful monitoring of all wells, including ShaRe-6, all new wells drilled in the Lishuiqiao-area as well as other wells outside the area designated to the Lishuiqiao project. Further data collection and detailed testing, such as tracer tests, is also emphasised in the coming months. Finally, training of Chinese counterparts is emphasised, to facilitate successful co-operation in the future.