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RESERVOIR EVALUATION FOR THE WUQING GEOTHERMAL FIELD, TIANJIN, CHINA

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ABSTRACT

The Wuqing geothermal field is a typical sedimentary basin low-temperature geothermal system, located in the middle-lower reaches of the Haihe river system on the North China Plain. It is an extensive horizontal sandstone reservoir with a temperature range of 76-86°C. Hot water production started in 1994 and reached 1.18 Mm^3 in 1997. The properties of the reservoir were estimated by analysing well test data and by simulating the available water level data by a simple distributed parameter model. The average permeability of the Wuqing reservoir is of the order 300-500 mD. For the next five years the production potential of the field is estimated to be 2.11 Mm^3/year, assuming an allowable maximum draw-down of 100 m. The water level draw-down may be reduced, or the production increased, by reinjection. A tracer test is recommended to estimate the possible cooling due to reinjection as well as comprehensive reservoir monitoring.

1. INTRODUCTION

The Wuqing geothermal field is located in the middle-lower reaches of the Haihe river system on the North China alluvial plain, about 95 km southeast of Beijing and 29 km northwest of the city of Tianjin (Figure 1). The county of Wuqing, which is situated approximately in the centre of the geothermal field, has a population of about 300,000.

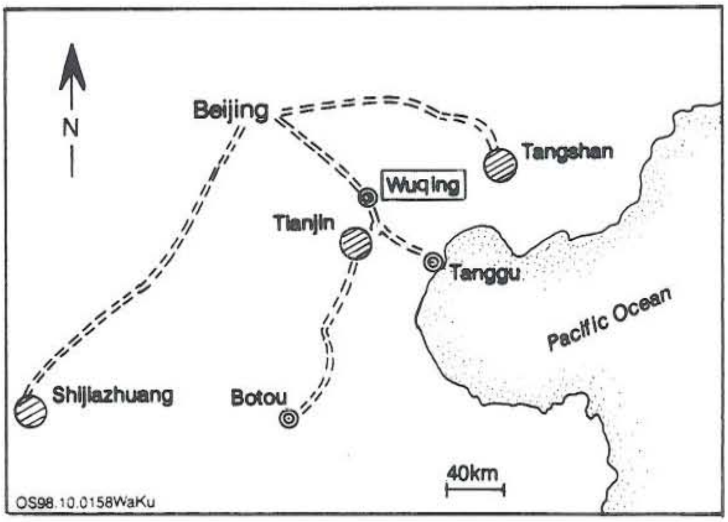

FIGURE 1: Location of the Wuqing geothermal field

The Wuqing geothermal field is a typical sedimentary basin low-temperature system, common in eastern and northeastern China (Wang et al., 1995). The geothermal resource is the result of permeable sediments at great depth (>2 km) and greater than average conductive heat flow. Eight wells have been drilled in the Wuqing field since 1993, but a detailed reservoir engineering study has not been carried out for the geothermal field, so far. During 1997 production from the field amounted to 1.18 Mm^3 which was mainly used for space heating. As a result of this, the water level in the system declined to about -54 m in early 1998.

This report describes a reservoir evaluation carried out for the Wuquing geothermal system. The most important question that needs to be answered is how the reservoir will respond to future exploitation, i.e. what is the production potential of the reservoir. A reservoir model for the Wuqing geothermal field is presented and an attempt is made to answer these questions. Available water level, temperature and production data are limited due to the short production history at Wuqing, as well as insufficient monitoring. A simple distributed-parameter model, in agreement with geological conditions in this area was, therefore, selected for the estimation of the reservoir parameters and prediction of the future response of the reservoir to different production and reinjection rates. Some suggestions for the future development and reservoir management of the Wuqing field are also presented, as well as a review of the presently available information on the system.

Even though a reservoir evaluation has not been carried out previously for the Wuqing geothermal system, some reservoir engineering work has been carried out for other sedimentary basin geothermal systems in the region. Among these are the Wanglanzhuang geothermal field (Tianjin Geothermal Exploration and Development Institute, 1985), Shanlingzi geothermal field (Tianjin Geothermal Exploration and Development Institute,1992), the Tanggu geothermal system (Axelsson and Dong,1998) and other such systems in the Tianjin area.

2. THE WUQING GEOTHERMAL FIELD

2.1 Geological outline

The Wuqing geothermal field is located on the southeastern flank of the Wuqing sedimentary basin, one of the sub-basins of the Jizhong regional sedimentary depression. The northwestern margin of the Wuqing basin is fault bounded, but the fault zones (Bao-di and He-xi-wu fault zones) are thought to be permeable. These faults are presented in Figure 2 along with a geothermal gradient map of the Wuqing area.

Based on stratigraphic data from boreholes, resistivity logs and correlations with the regional stratigraphy using marker beds, Cenozoic sedimentary strata are found to be widespread in the Wuqing basin (Lin et al., 1997). Their thickness ranges from 1800 m in the southeast to 9000 m in the northwest. The upper Tertiary (Neogene) strata are divided into the Minhuazhen and Guantao groups (Figure 3).

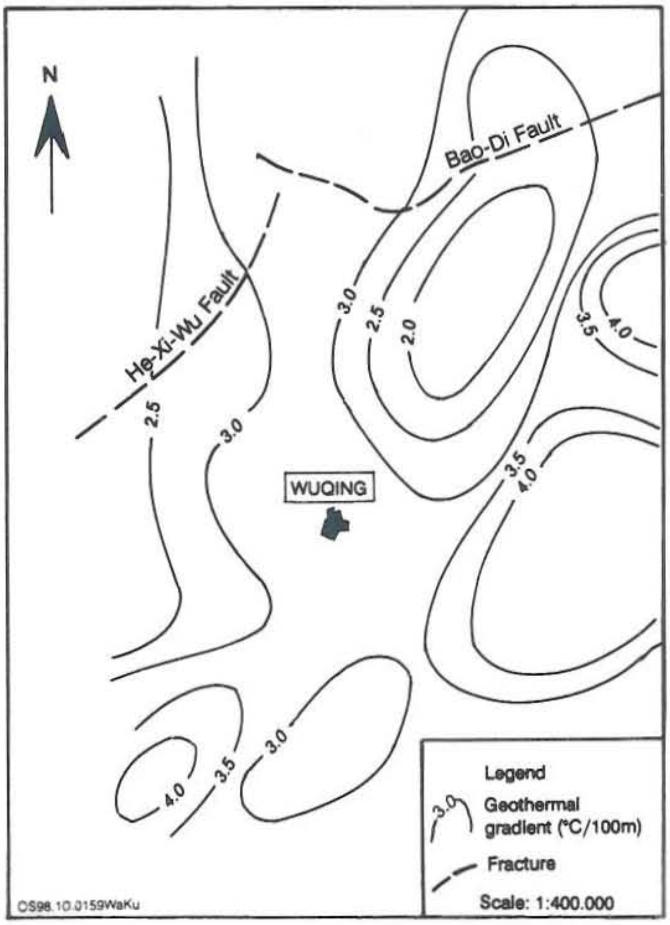

FIGURE 2: Contour map of the geothermal gradient in the area around Wuqing

The Guantao group has a coarse-fine-coarse cyclic sedimentation from top to bottom and can be divided into three lithological formations: an upper sandstone formation with argillite interbeds, a middle formation of argillite with sandstone interbeds, and a lower sandstone formation with argillite interbeds and a basal conglomerate bed.

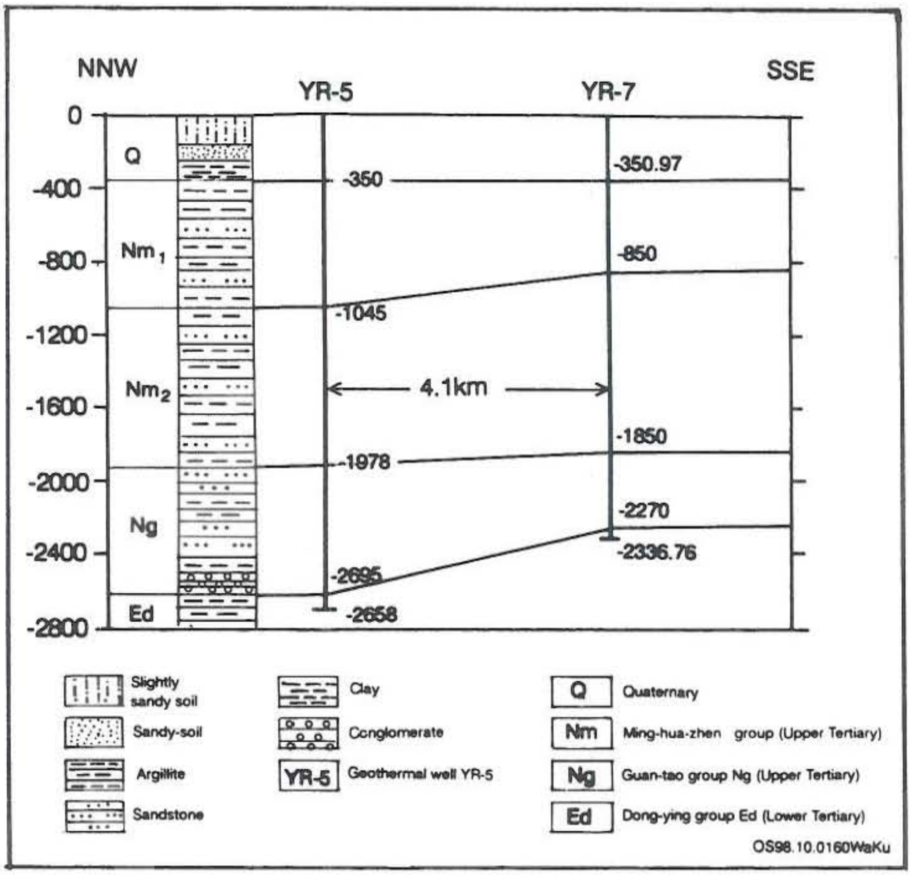

FIGURE 3: Geological cross-section of the Wuqing field

The Wuqing geothermal reservoir is located within the Guantao group and has an areal extent of approximately 67 km^2 (Lin, et al., 1997). It thickens and deepens in a northwesterly direction into the basin (Figure 4). In the southeastern part, it is approximately 520 m thick and its base lies at a depth of 2100 m, whereas in the northwestern part the corresponding values are 700 m and 2700 m. The conglomerate bed at the base of the Guantao group defines the base of the reservoir and acts as the main feed zone. Temperature in the feed zones increases with depth from 76 °C in the southeast to 86 °C in the northwest.

2.2 Hydrological and chemical conditions

Although the reservoir at Wuqing involves the whole Guantao group, hot water production is mainly from the lower coarse and sandy part of the group. In this part of the reservoir, most of the aquifers are composed of permeable sandstone or conglomerate beds of constant thickness. The permeable beds are typically about 5-40 m thick, have a porosity of 16-25% and a permeability of 0.04-1.4 Darcy.

The water produced from this reservoir has a homogeneous composition. It is slightly mineralized alkaline soft water of the Na-HCO_3 type and has a total amount of dissolved solids of 1050-1250 mg/l (Table 1). The high iodine concentration of 0.7-0.8 mg/l should be noticed (Lin et al., 1997).

TABLE 1: Chemical composition of water from the Guantao group in Wuqing (mg/l)

K^+	Na^+	Ca^{2+}	Mg^{2+}	Fe	Cl^-	SO_4^{2-}	HCO_3^-	F^-	I	Soluble SiO_2	TDS	Hard-ness	Alkali-nity	pH
5.0	320	3.0	1.2	0	70	31	700	4.0-5.6	0.7-0.8	63.0	1050-1250	10-15	500-610	8.0-8.4

2.3 Exploitation and development history

Since 1993, eight successful production wells have been drilled at Wuqing. The location of the wells is shown in Figure 4. The initial water level in well YR-1 was at a depth of 22 m. With the addition of more geothermal wells and increased production, the hydrostatic water level has been falling at a rate of approximately 6 m/year, coming down to a depth of 40-50 m in early 1998. Each of the wells yields 70-100 m^3/h of water with a temperature of 70-84°C. According to a temperature log in well YR-5 and other available data, the geothermal gradient is estimated to be about 2.7-3.1°C/100 m down to the top of the reservoir.

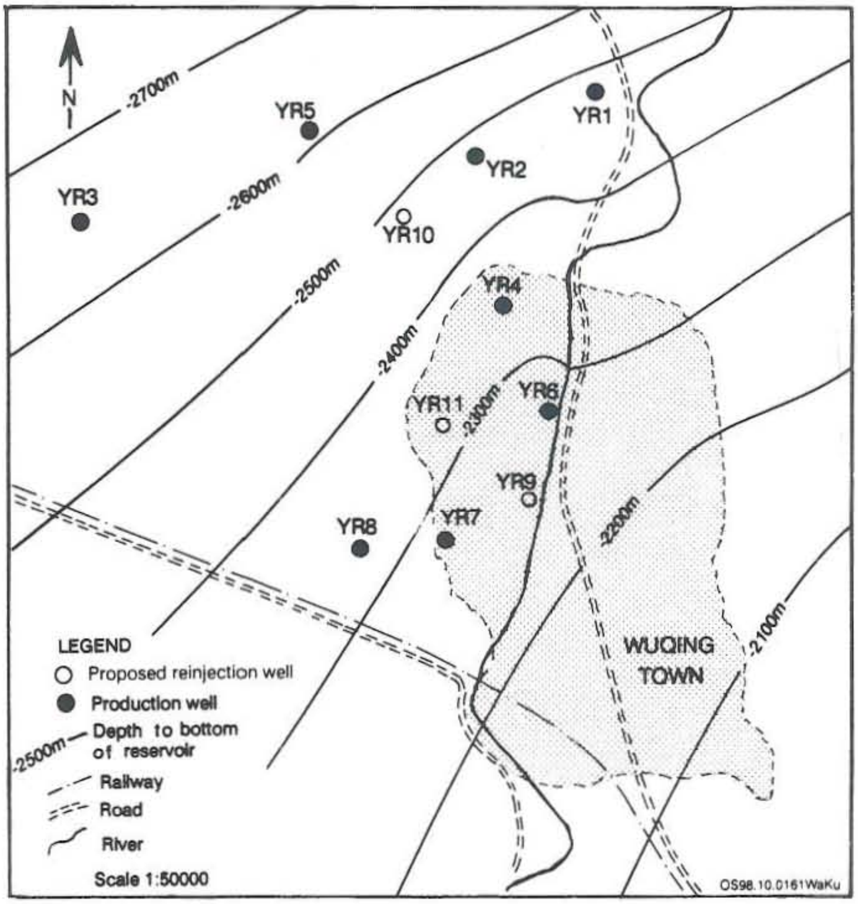

FIGURE 4: Location of geothermal wells in the Wuqing geothermal field and depth to the base of the Guantao group

Most of the wells are used for space heating in winter, the official winter season being 135 days from the middle of November till late March. But a few of the wells are used for other purposes such as heating swimming pools. General information on the utilization of the geothermal wells in Wuqing is given in Table 2.

TABLE 2: Information on utilization of wells in Wuqing

Geothermal well	YR-1	YR-2	YR-3	YR-4	YR-5	YR-6	YR-7
Time of well completion	93.01	94	94.08	95.05	96.09	98.02	97.12
Initial water level (m)	22.2	8.9	0	19.6	19	33.8	35.3
Reservoir temperature (°C)	74		85		86	76	80
Beginning of utilization	93.11	97.11	95.11	95.11	96.11	not yet	97.11
Maximum production capacity (m^3/hr)	80	80	80	80	90	100	100
Pumping time during winter(hrs/day)	24	24	10	24	24	24	24
Pumping time during summer (hrs/day)	0	0	8	8	0	8	0

All of these wells completely penetrate the Guantao group. They were cased to the bottom and the casing was perforated at the main feed zones. In addition, the upper 200-300 m were cut off to make room for submersible pumps. Detailed information on each of the wells is presented in Table 3.

TABLE 3: Geothermal wells in the Wuqing geothermal field

Well No.	Depth (m)	Perforated casing		Guantao group depth range (m)	Casing		Diameter of well (mm)
		Depth (m)	Thickness (m)		Diameter (mm)	Depth (m)	
YR-1	2488	2330-2484	83.5	1878-2469	339.7 177.8	252 2486	445 245
YR-2	2480	2055-2078 2166-2177 2186-2197 2236-2258 2268-2279 2288-2309 2321-2365	143.3				
YR-3	2700	2497-2553 2564-2662	154.3	1996-2660	339.7 177.8	256 2696	445 245
YR-4	2470	2126-2137 2160-2325	176.3				
YR-5	2628	2385-2405 2414-2424 2497-2508 2518-2538 2558-2579 2588-2598	92.4	1928-2620	339.7 177.8	348 2628	445 245
YR-6	2306	1978-1999 2126-2136 2156-2166 2186-2195 2206-2234 2245-2265	99.1				
YR-7	2336	2028-2057 2124-2134 2163-2172 2200-2230 2240-2259	97.5	1850-2258	500 340 177.8	20 400 2279	660 445 245

Monitoring of the production response of the Wuqing geothermal reservoir has been limited. But automatic monitoring of well YR-4 started in the fall of 1997 with the recording of the production rate, water level and water temperature. Some limited monitoring data is also available for wells YR-5, YR-6 and YR-7. Figure 5 shows the data collected for well YR-4 until the middle of this year.

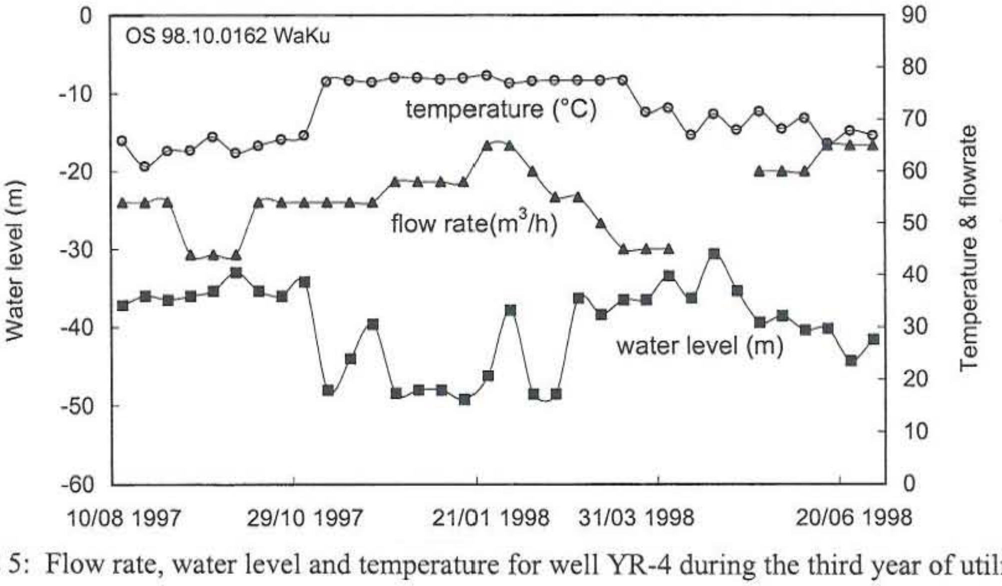

FIGURE 5: Flow rate, water level and temperature for well YR-4 during the third year of utilization

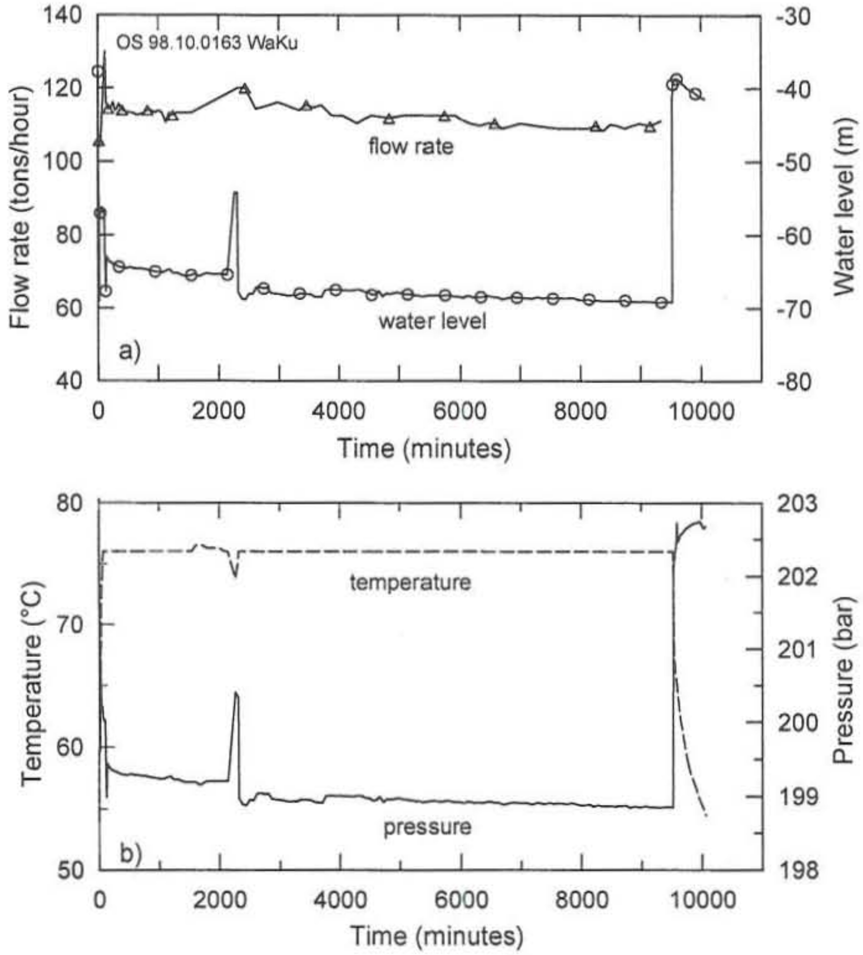

FIGURE 6: Data from the well test of well YR-7 in December 1997; a) Flowrate and water level; b) Wellhead temperature and calculated reservoir pressure

3. ANALYSIS OF WELL TEST DATA

In December 1997, a well test of YR-7 was carried out, lasting about one week. The data collected are presented in Figure 6. The initial water level was at a depth of 38 m. Production and buildup data from this test have been used to estimate the hydrological properties of the Wuqing geothermal reservoir. Due to electrical failure resulting in a pump stop, the test was disturbed after 15 and later after 2100 minutes.

The water level changes do not directly reflect pressure changes in the reservoir since they are also influenced by water temperature changes. After correcting for this effect, two methods were used to analyse the well test data. Firstly, graphical methods, i.e. semi-log and Horner plot methods were used to interpret the draw-down and build-up separately. Secondly, computerised analysis was used to simulate the whole data set.

3.1 Correction of the water level for temperature effects

During the initial well bore storage period of the well test, production is derived from the well bore only. The wellhead temperature rises, and continues to rise until an equilibrium is approached. The water level, therefore, does not reflect the pressure changes in the well, due to the water density decrease caused by the temperature increase. Thus, the water level may stay constant even though the reservoir

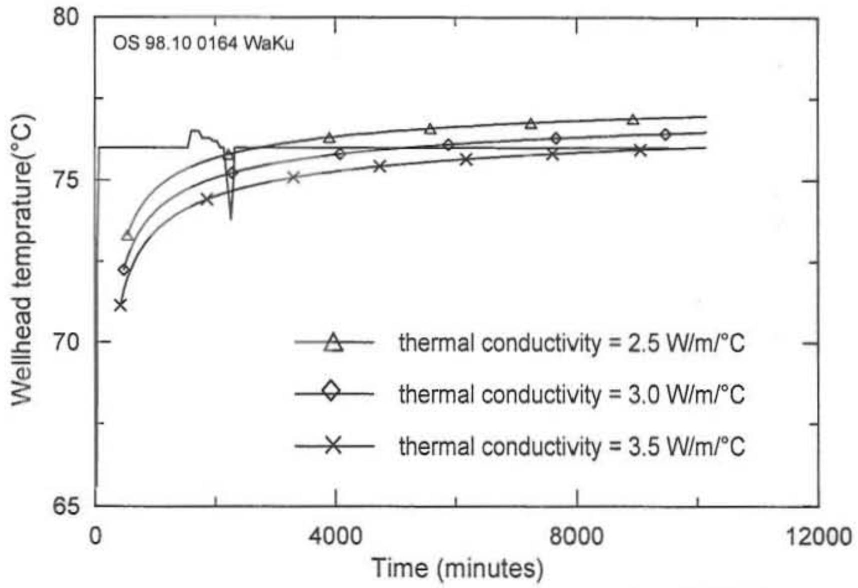

FIGURE 7: Simulated wellhead temperature of well YR-7 during well test

pressure is increasing, and temperature is decreasing such as during pressure build-up. Therefore it is necessary to correct the water level for temperature effects. In fact, working with reservoir pressure rather than water level, is more appropriate.

From the map of the regional thermal gradient (Figure 2) and a temperature log in well YR-5 in the same reservoir, it is inferred that the reservoir temperature in well YR-7 is 80°C. The computer program FLOWTEMP (Arason and Björnsson, 1994) in the ICEBOX software package, was used to further verify the reservoir temperature. Figure 7 shows the result of a wellhead temperature simulation by FLOWTEMP, carried out for different values of thermal conductivity and a reservoir temperature of 80°C. The calculated results are in good agreement with observed values. This confirms that the average feed zone temperature for well YR-7 is of the order of 80°C. This temperature value is, therefore, used to correct the water level.

A linear relationship between temperature and depth is assumed. The relationship between measured water level and reservoir pressure is given by:

$$p(z) = (z - s)\cdot\langle\rho\rangle\cdot g \qquad (1)$$

where $p(z)$ = Reservoir pressure (Pa);
z = Depth to the center of the feed zone (m);
s = Measured water level (m);
$\langle\rho\rangle$ = Average water column density, the average value of the density at the wellhead temperature and reservoir temperature.

The result of the correction, i.e. the reservoir pressure during the well test, is shown in Figure 6 b.

3.2 Pressure transient analysis

Pressure transient tests provide information on the hydrological conditions of the well/reservoir system and form a basis for the future prediction on well yield and pressure draw-down in the reservoir. During a well test, the flow rate from a well is changed. This will cause a time-dependent pressure change in the reservoir, which is either monitored in the production well itself (single well test) or in an observation well (interference test). Well known methods of analysing test data are based on the Theis solution to the pressure diffusion equation. The semi-log method and Horner method will be introduced in the following (Grant et al., 1982).

Several simplifying assumptions are made in the Theis model:

1. Prior to the well test, the reservoir pressure is uniform;
2. The reservoir is homogeneous, isothermal and isotropic and the wells fully penetrate the

reservoir;

3. The reservoir is horizontal, of uniform thickness and infinite in radial extent, and has impermeable boundaries at the top and bottom;
4. The reservoir fluid flow follows Darcy's law.

It should be noted that these assumptions agree fairly well with the geological conditions in the Wuqing reservoir.

3.2.1 Constant flow rate solution - semi-log and Horner methods

The pressure diffusion equation describing horizontal single-phase flow, of a slightly compressible fluid, through a homogenous and isotropic porous media can be written as;

$$\frac{\partial p}{\partial t} = D[\frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r}] \tag{2}$$

where
- p = Pressure (Pa);
- t = Time (s),
- r = Radial distance from the well (m);
- D = $k/c_t\mu$, reservoir hydraulic diffusivity (m^2/s);
- k = Permeability (Darcy, 10^{-12} m^2);
- μ = Dynamic viscosity of geothermal water (kg/m/s);
- c_t = $\phi c_w + (1-\phi)c_r$, compressibility of the reservoir (1/Pa);
- ϕ = Reservoir porosity;
- c_w = Compressibility of water (1/Pa);
- c_r = Compressibility of rock (1/Pa).

The Theis solution to the diffusion equation is given by

$$p(r,t) - p_o = \frac{q\mu}{4\pi kh}\int_u^\infty \frac{e^{-u}}{u}du = \frac{q}{4\pi T}\int_u^\infty \frac{e^{-u}}{u}du \tag{3}$$

where
- p_o = Initial reservoir pressure (Pa);
- u = $Sr^2/4Tt$;
- h = Aquifer thickness (m);
- q = Production flow rate (m^3/s);
- S = $c_t h$, storage coefficient of the reservoir (m/Pa);
- T = kh/μ, transmissivity (m^3/Pa/s).

If r is small and t is large, Equation 3 with $r = r_w$, can be approximated by

$$p(r_w,t) = p_o - 0.1832\frac{q\mu}{kh}\left[\log(t) + \log(\frac{k}{\mu c_t r_w^2}) + 0.3514 + 0.8686s\right] \tag{4}$$

In Equation 4 a so-called skin factor s is also introduced, representing an additional pressure drop because of near well effects. Equation 4 shows that a plot of p versus time t on a semi-logarithmic graph should yield a straight-line portion with a slope m = 0.1832 qu/kh, from which the permeability or transmissivity can be calculated.

The skin factor is estimated from a rearranged form of the above equation

$$s = 1.1513[\frac{\Delta p}{m} - \log(\frac{k}{\mu c_t r_w^2}) - 0.3514] \tag{5}$$

The effects of pressure build-up can be looked upon as if an imaginary well located at the same point started injecting with the same flow rate as the prior production rate. Therefore, this can be treated with the principle of superposition in time, and we obtain:

$$p(t_p + \Delta t) = p_o - 0.1832\frac{q\mu}{kh}\log(\frac{t_p + \Delta t}{\Delta t}) \tag{6}$$

where t_p = Time at the beginning of the build-up (s);
Δt = Time since the beginning of the build-up (s).

The Horner method is based on the above equation and applies during the infinite acting time period after wellbore storage effects have diminished. From the above equation it can be seen that a semi-log plot of p versus $[(t_p+\Delta t)/\Delta t]$ should yield a straight line portion with slope $m = 0.1832\, q\mu/kh$ and the intercept with the pressure axis $p_{INT} = p_o$. The skin factor is again determined by Equation 5.

3.2.2 Variable flow rate - computerized analysis

In cases where production is variable, the pressure changes in the Theis model may be calculated by the following equation:

$$p(r,t) - p_o = \frac{\mu}{4\pi kh}\int_0^t \frac{q(\tau)}{t-\tau}\exp[\frac{-\mu c_t r^2}{4k(t-\tau)}]d\tau \tag{7}$$

The VARFLOW computer code, which is based on this equation, can be used to analyse pressure transient data by varying the parameters until a satisfactory fit is obtained (EG&G Idaho Inc. and Lawrence Berkeley Laboratory, 1982). In addition VARFLOW can be used to calculate pressure changes caused by several production/injection wells, all with variable flow rates. VARFLOW can also incorporate a no-flow or constant pressure boundary as well as permeability anisotropy.

3.3 Results of well test analysis

Analysis of the pressure transients in the YR-7 well test was carried out using the above-mentioned method. The parameters used in the calculations are given in Table 4. The semi-log plot and Horner plot of well test data are presented in Figure 8, along with the best fitting straight lines. The parameters

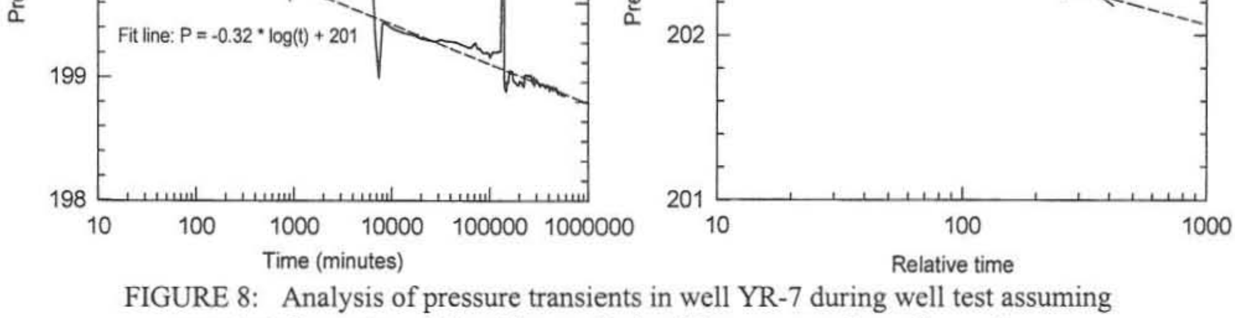

FIGURE 8: Analysis of pressure transients in well YR-7 during well test assuming constant flow rate, a) Semi-log analysis of the pressure draw-down phase, and b) Horner plot analysis of the pressure build-up phase

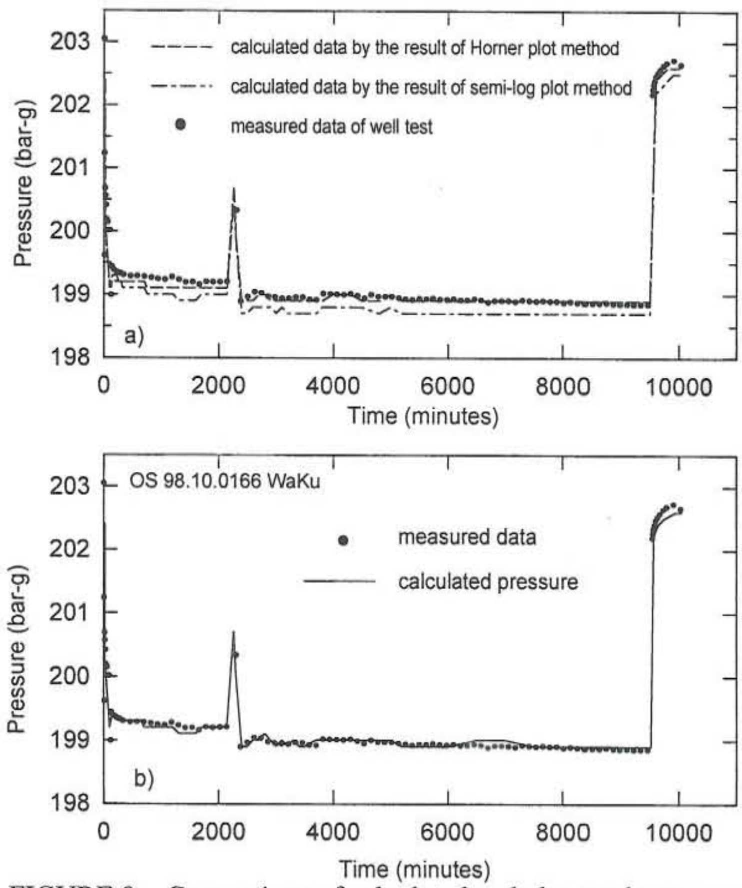

FIGURE 9: Comparison of calculated and observed pressure transients in well YR-7; a) Based on the results of semi-log and Horner plot analysis, b) Results of computerized analysis (program VARFLOW)

determined are presented in Table 5. Consequently, the results of both methods were used to simulate the measured pressure data by VARFLOW. Figure 9a shows the results, i.e. the comparison between observed and calculated pressures. The difference between the results for the two methods is also evident. The result of the Horner plot analysis appears to simulate the data more accurately.

Figure 9b shows the results of the simulation of the well test data by VARFLOW. The resulting parameters are presented in Table 5. It is noteworthy that the three different methods give quite comparable results, especially for permeability. The storativity and skin factor values are more variable. These cannot, in fact, be independently estimated. It should be pointed out that the permibility estimates are almost the same as for the Dagang and Tanggu geothermal reservoirs (Ouyang et al., 1990, Axelsson and Dong,1998). This is not surprising since the same formation is involved in all cases.

TABLE 4: Reservoir parameters used in the well test analysis

Average flow rate (m^3/s)	0.0306
Total thickness of feed zones (m)	108
Water compressibility (Pa^{-1})	5.0×10^{-10}
Sandstone compressibility (Pa^{-1})	0.51×10^{-10}
Weighted average porosity (%)	27
Reservoir compressibility (Pa^{-1})	1.7×10^{-10}

TABLE 5: Parameters estimated from analysis of the YR-7 well test

Parameter	**Semi-log plot**	**Horner plot**	**VARFLOW**
Transmissivity (10^{-6} $m^3/Pa/s$)	0.172	0.133	0.15
Storage coefficient (10^{-8} m/Pa)	0.51		0.22
Skin factor	4.56	1.9	2.2
Permeability (mD)*	560	430	490

* Using a thickness of 108 m

4. THE WUQING RESERVOIR MODEL

4.1 Conceptual model

The main features of the current conceptual model of the Wuqing geothermal reservoir are as follows. The system may be assumed to be an extensive horizontal sandstone reservoir. The depth of the reservoir varies from 2100 to 2700 m. Its thickness is between 80 and 170 m and the reservoir temperature ranges from 74 to 86°C, depending on the depth. The reservoir is believed to be independent of the faults nearby and is fully isolated from the deeper strata, but may be connected with the upper parts of the Guantao formation. As to the initial state prior to production, it is assumed that the reservoir pressure was constant.

4.2 Simulation of the production history

Among the available geothermal wells, six wells have been put into production since 1993. The total production rate from the whole field increased rapidly in 1995 and reached 1.18 Mm^3 in 1997. Because of a short production history with few available water-level, temperature, and production data, a simple distributed parameter model was set up. This was a Theis-model as discussed in the previous chapter. The programme VARFLOW was again used for calibration of the reservoir parameters and the simulation of the production history of the reservoir.

In this model, the average depth to the central part of the reservoir is assumed to be 2360 m, the average thickness of the reservoir is 120 m, and the average reservoir temperature is 80°C. Anisotropic permeability is adopted. A satisfactory calibration was assumed when a good match between the measured and the computed data had been achieved. The parameters giving the best fit are:

X-axis transmissivity, $T_x = 0.293 \times 10^{-6}$ $m^3/Pa/s$,
Y-axis transmissivity, $T_y = 0.06 \times 10^{-6}$ $m^3/Pa/s$,
Storage coefficient, $S = 0.278 \times 10^{-3}$ m/Pa.

The SW-NE and SE-NW directions were selected as the X and Y axes, respectively. Thus, the transmissivity of the model in the SW-NE direction is 4.8 times that in the SE-NW direction. This direction coincides with the direction of the Hexiwu fault (Figure 2) and the general flow direction of the geothermal water in the Tianjin area. The average permeability of the reservoir is 390 mD, which is in very good agreement with the results of the well test analysis.

The simulated water levels of YR-4 and YR-6 as well as the total production from the reservoir, are presented in Figure 10. The calculated water levels showed a marked drop in October,1995, caused by the rapid growth in the total production from the reservoir.

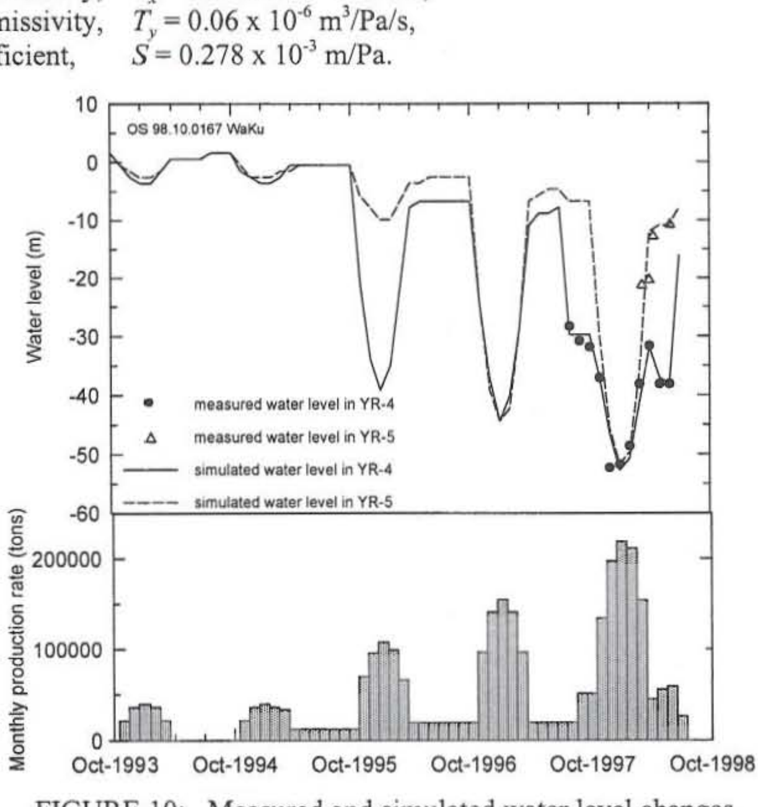

FIGURE 10: Measured and simulated water level changes in wells YR-4 and YR-6

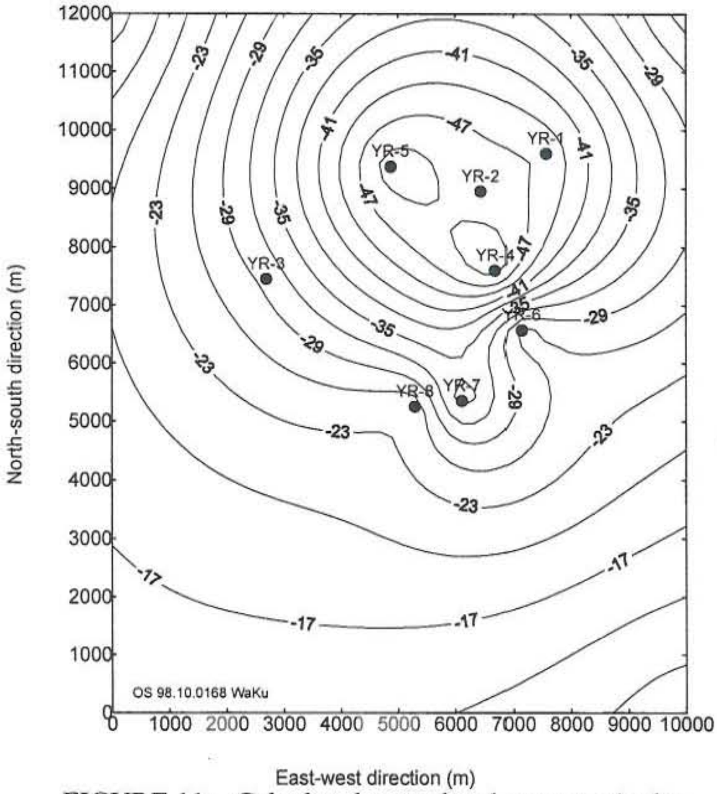

FIGURE 11: Calculated water level contours in the Wuqing reservoir at the end of March 1997

During the following summer, the pumps stopped for most of the wells and the water level promptly recovered. Figure 11 shows the dynamic water level contours at the end of March 1997 as calculated by the model. The centre of the water level depression is around wells YR-4 and YR-5 with a maximum water level depth of 45-50 m.

5. FUTURE PREDICTIONS FOR THE WUQING RESERVOIR

5.1 Predicted water level changes for the next five years

Comprehensive monitoring of the exploitation history of the Wuqing geothermal field would provide the most reliable data for prediction of future development. But the few available data limit the accuracy of performance predictions for the Wuqing geothermal field. The simulation model presented here will predict the response of the Wuqing geothermal field for two cases of future production for the next five years, i.e. till the end of July, 2003. These predictions (Figures 12 and 13) are believed to be rather accurate, because the reservoir parameter estimates based on the well test data and the production history simulation are in good agreement. These cases are:

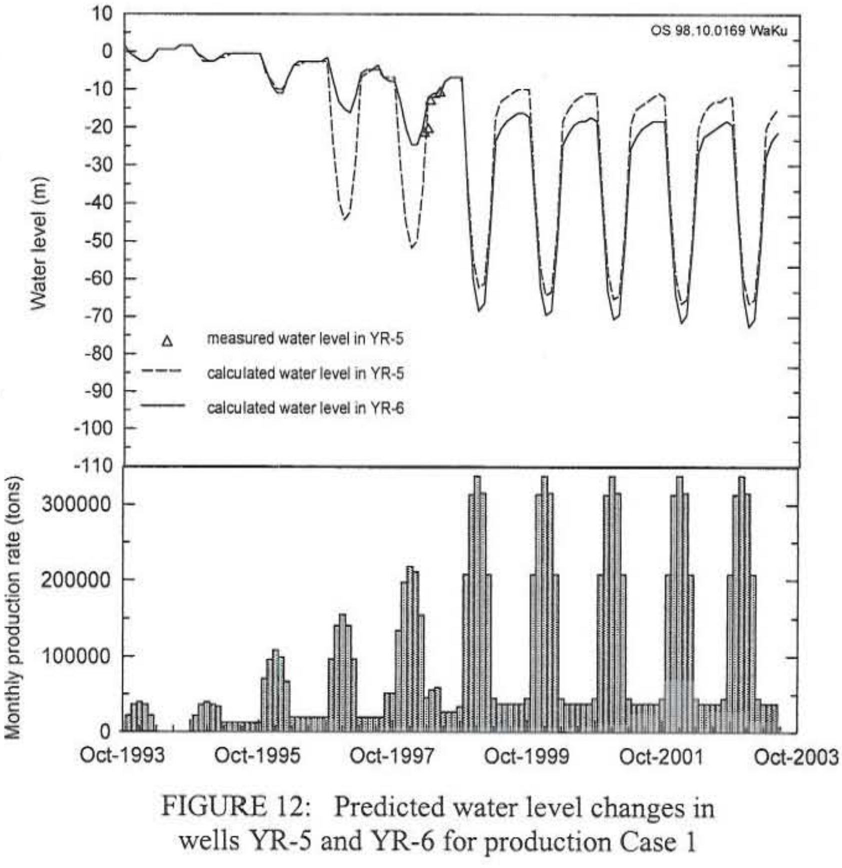

FIGURE 12: Predicted water level changes in wells YR-5 and YR-6 for production Case 1

Case 1: All the available wells are put into utilization in 1998 at the 1997 production rate, which is then maintained for the next five years. The total production rate for the field would be 1.65 Mm^3/year and the peak production would reach 131 kg/s. Wells YR-6 and YR-8 would start to produce at the end of 1998, with production rates equalling that of YR-7 (Figure 12).

Case 2: All the available wells are put into production at full capacity with the total production rate reaching 2.17 Mm^3/year for the whole field. The peak production would reach 183 kg/s (Figure 13).

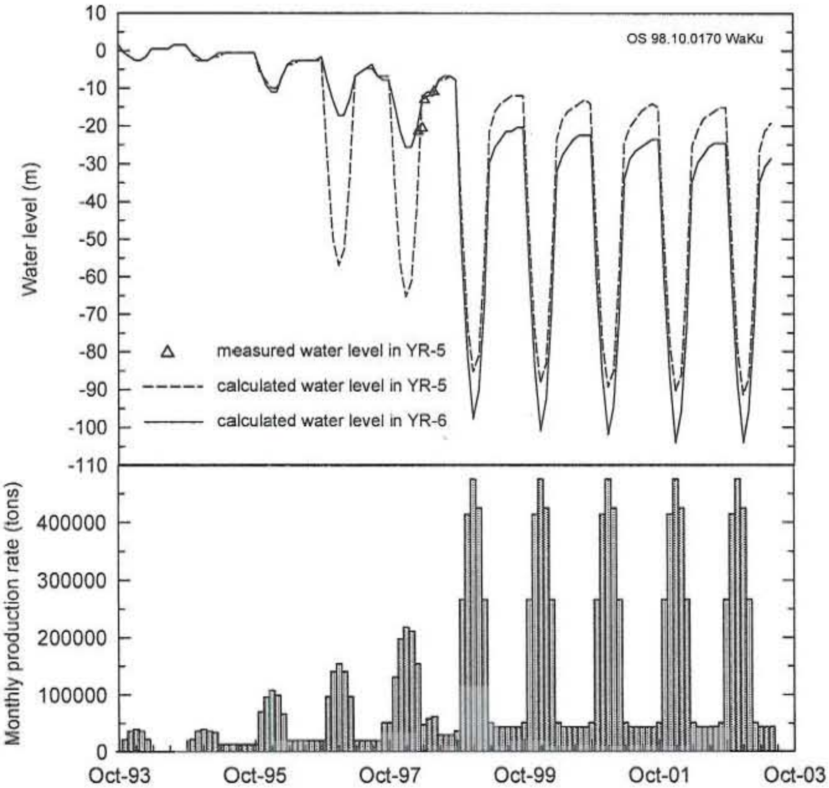

FIGURE 13: Predicted water level changes in wells YR-5 and YR-6 for production Case 2

According to the model, the draw-down will for both cases increase greatly during the first year of the prediction period . Consequently, the water level will decline slowly or with an average annual increase in draw-down of about 1 m. For Case 1 the lowest dynamic water level will be at 74 m depth in well YR-6 by the end of the prediction period. It should be pointed out that no boundaries are incorporated in the model, since the limited data do not indicate any boundaries. Such boundaries would cause a greater long-term draw-down than predicted here.

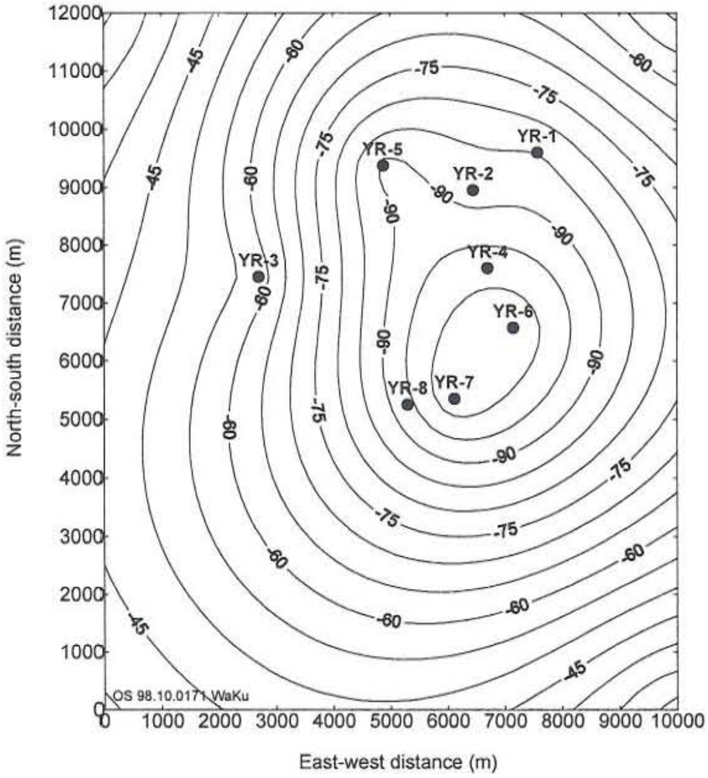

FIGURE 14: Predicted water level contours at the end of January 2003

In Case 2, the greatest draw-down is predicted around wells YR-6 and YR-7 during the winter of 2002 to 2003, with the lowest water level at -104 m. This is because the production capacity of wells YR-6 and YR-7 is greater than that of the other wells. In Case 2, the water level in YR-6 will swiftly drop by 70 m during the first two years. Compared with Figure 11, the draw-down will be much greater for Case 2 than Case 1. Figure 14 shows the predicted water level contours for Case 2, at the end of January 2003.

5.2 Reinjection

According to the predictions of the Wuqing model, the draw-down of the water level will be greatest during the winter in the future, when the wells are used at maximum yield (Case 2). During the official heating season, submersible pumps are installed at a depth of 80-100 m in all of the wells. The water level will, therefore, exceed the current depth of the installed pumps. Reinjection will provide pressure support to counteract this, and should be considered as a part of the management of the Wuqing field in the future. Reinjection is practised in numerous geothermal systems worldwide, in most cases for waste-water disposal, while in a few areas it is done to maintain reservoir pressure as suggested here (Stefánsson, 1997). Reinjection has not been practised in the porous media geothermal systems as in China, but some injection experiments have been carried out (Ouyang and Wang, 1992 and Axelsson and Dong, 1998).

5.2.1 Thermal breakthrough time

The main side effect anticipated from reinjection is a cooling of the reservoir and production wells. Therefore, several methods are used here to estimate the thermal break through time for different injection-production well spacings, i.e. the time from initial injection until a significant cooling is observed in a production well.

At first, the condition of only one reinjection well without production nearby is considered. Porous media heat transport by intergranular fluid flow is assumed. In this case the rock grains are so small that rock and fluid will have the same temperature at any point. A liquid reservoir system is assumed and the gravity affect of the variable water temperature is neglected. The differential equation which approximately describes this process is

$$\frac{\partial T}{\partial t}+\frac{\beta_w}{<\rho\beta>}\bar{q}\cdot\nabla T=0 \tag{8}$$

where T = Temperature (°C);
β_w = Heat capacity of water (J/kg/°C);
$<\rho\beta>$ = $\phi\rho_w\beta_w+(1-\phi)\rho_r\beta_r$, volumetric heat capacity of the reservoir (J/m^3/°C);
$\bar{q}$ = Mass flux vector (kg/m^2/s);
∇T = (dT/dx, dT/dy, dT/dz).

An infinite horizontal reservoir of constant thickness H, is again considered. It is assumed that Q kg/s of cold water ($T = 0$) are injected since time $t = 0$. The cold front consequently moves away from the well, with the radial distance from the well to the temperature front given by:

$$r_T=\left[\frac{\beta_w Qt}{\pi H<\rho\beta>}\right]^{\frac{1}{2}} \tag{9}$$

If we assume that the reinjected water diffuses fairly evenly through the reservoir, an average thickness of 120 m is adopted. Using $Q = 14$ kg/s, it takes 380 years for the temperature front to move 800 m from the reinjection well. However, most of the reinjected water may travel through specific flow channels in the feed-zones. Assuming the thickness to be 12 m (10% of the total effective thickness), it takes the temperature front only 39 years to travel the same distance.

Another case considered is a reservoir of temperature T_0 surrounded by fluid of temperature $T = 0$, initially at a radial distance r_0. Fluid is withdrawn from a line-sink at rate Q kg/s. In this case, the cold-front reaches the well when

$$t = \frac{r_0^2 \pi H <\rho\beta>}{\beta_w Q} \tag{10}$$

Assuming again Q = 28 kg/s and r_0 = 800 m, the cold-front reaches the production well in 170 and 17 years when the thickness is 120 and 12 m, respectively.

The final case considered involves production and reinjection wells with a spacing of 800 m. The average reinjection rates are assumed as 7 kg/s and 14 kg/s, and the average production rate is 28 kg/s. The thermal breakthrough is calculated by a one dimensional flow-channel model. The program TRCOOL in the ICEBOX program package is utilized for this purpose (Arason and Björnsson, 1994)

This model assumes one-dimensional flow in a flow-channel of cross-sectional area A. Given the flow channel inlet temperature T_i, the channel height h, length L and width b as well as the undisturbed rock temperature T_0, the temperature of the injected water can be estimated at any distance x along the flow channel by the equation:

$$T(x,t) = \begin{cases} T_i + (T_o - T_i) erf\left[\dfrac{Kxh}{\beta_w q \sqrt{D(t - x/\alpha)}}\right] & t > x/\alpha \\ T_o & t \le x/\alpha \end{cases} \tag{11}$$

with α defined by $\alpha = q\rho_w / <\rho\beta> hb$.

Here, K = Thermal conductivity of the reservoir rock (J/°C/m/s);
D = Thermal diffusivity of the reservoir rock (m^2/s);
q = Reinjection flow rate (kg/s);
and other parameters as defined before.

As the production well produces at rate $Q > q$, the following equation is used to calculate the production temperature T_p:

$$T_p = T_o - \frac{q}{Q}\left[T_o - T(L,t)\right] \tag{12}$$

with $T(L,t)$ given by Equation 11.

The results of using this model to predict the thermal breakthrough and temperature decline for a few different cases are presented in Figure 15, for L = 800 m and b = 400 m.

It appears from these results that locating reinjection wells at a distance of about 800 m from production wells should not cause a thermal breakthrough in less than 20-30 years. However, these results are highly uncertain because the flow channel dimensions are unknown. A tracer test would provide

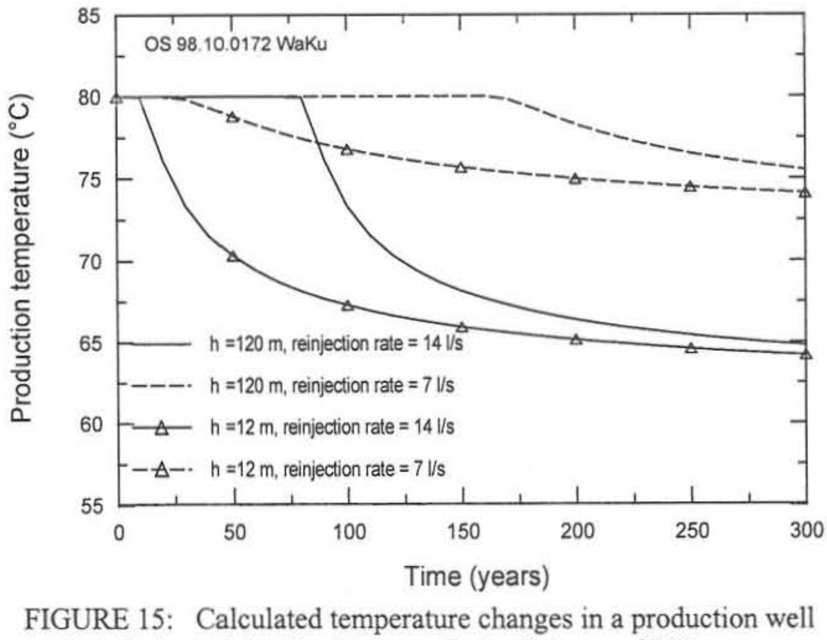

FIGURE 15: Calculated temperature changes in a production well during reinjection into a well at a distance of 800 m

very important information on these, and will be discussed later. It should also be pointed out that reinjection would only be carried out in winter time. The reinjected water will extract more thermal energy from the rock matrix when the geothermal wells are shut down in summer, resulting in slower cooling rates than predicted.

Based on the above, it is recommended that the reinjection wells should be located at about 800 m from production wells in the Wuqing geothermal field. If they are too close, reinjection may cause rapid cooling of the production wells. If they are much further away, the pressure support from reinjection will diminish.

5.2.2 Future predictions including reinjection

As a first case, one reinjection well (YR-9) between wells YR-6 and YR-7 is adapted. An average injection rate of 14 kg/s is assumed during the heating season. Production Case 2 is furthermore assumed. Figure 16 shows the result and indicates that water level recovery in YR-6, as calculated by the VARFLOW model, will be about 7 m in five years. The effect of only one reinjection well is, therefore, not very significant.

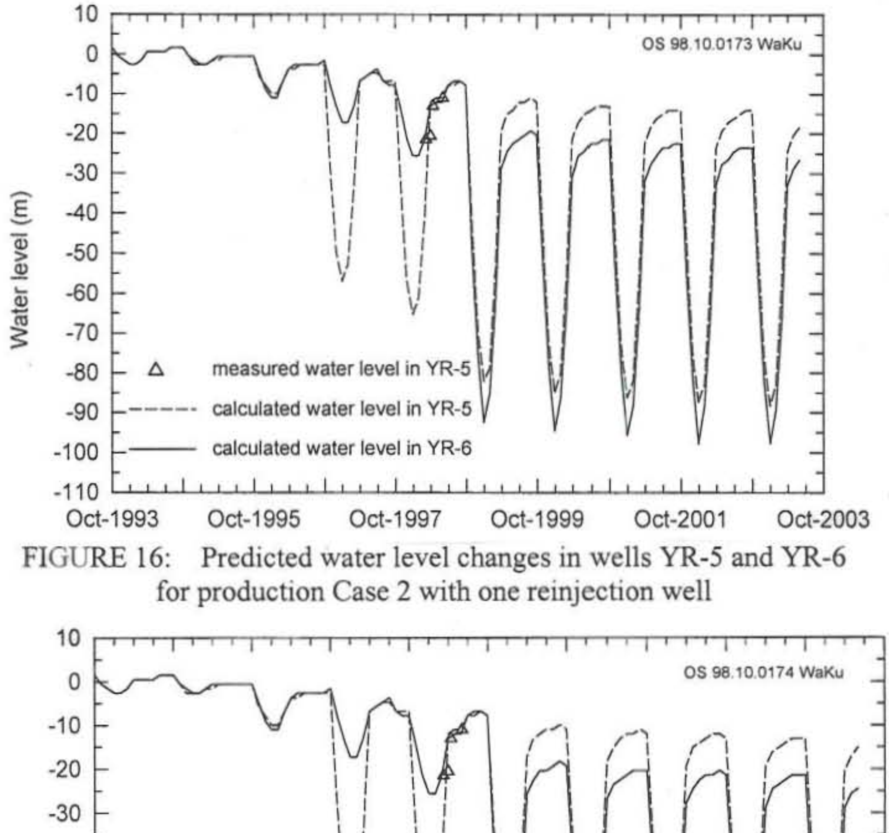

FIGURE 16: Predicted water level changes in wells YR-5 and YR-6 for production Case 2 with one reinjection well

In the second case, three reinjection wells YR-9, YR-10, YR-11 are included. The response of the reservoir is again predicted for five years, and the results are presented in Figures 17 and 18. Since the fall of 1998, 14 kg/s of cold water at the temperature 40°C are assumed to be reinjected in these three wells, respectively. The injection rate is thus about 23% of the total production. By the end of January 2003 the water level in well YR-6 is calculated to be at a depth of 87 m. Comparing this with the results without reinjection, the water level recovers by 17 m. Thus, it is obvious that reinjection will be instrumental in maintaining water levels above the depth of the pumps used.

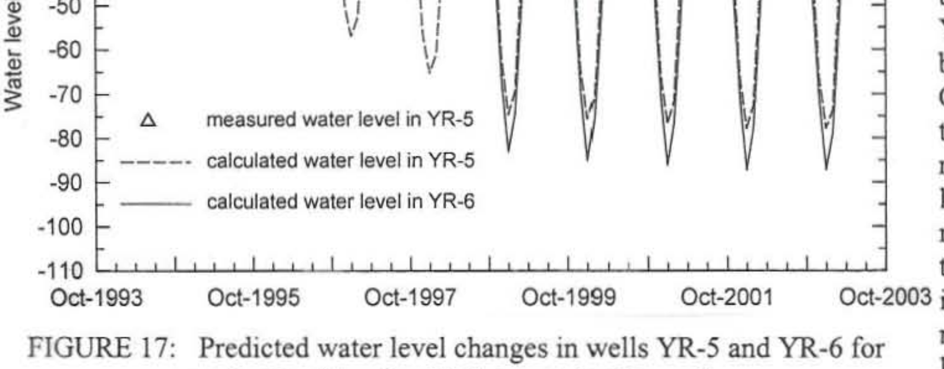

FIGURE 17: Predicted water level changes in wells YR-5 and YR-6 for production Case 2 with three reinjection wells

5.3 Wuqing reservoir potential

The reservoir model described in this report simulates and predicts the response of the Wuqing geothermal field to production and reinjection. The average production rate in 1997 was 37.5 kg/s, with a maximum production rate of 97.2 kg/s during the heating season. During the 1997/98 heating season, the lowest water level was at 52 m depth.

All of the geothermal wells in Wuqing are cased with a 13 3/8" pump pipe down to 200-300 m. At present, the pumps used in Wuqing are set at a depth of 80-100 m, depending on the production rate of each well. Therefore, allowable draw-down is here set at 100 m depth. In the more distant future the maximum allowable draw-down may be increased to 200 m depth.

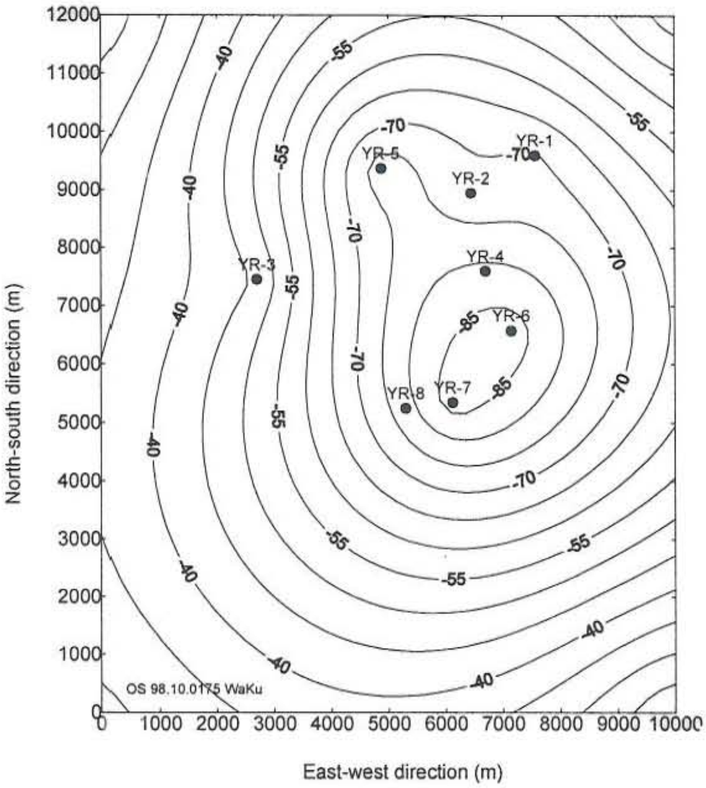

FIGURE 18: Predicted water level contours for production Case 2 with three reinjection wells at end of January, 2003

For future production Case 1, the average production rate is 52 kg/s, and the dynamic water level will stay above 73 m depth when the peak production rate is 130.6 kg/s. For case 2, the average production rate is 69 kg/s with a maximum production rate of 183.3 kg/s during the heating period. According to the model, the dynamic water level will drop to 104 m depth in well YR-6 in this case.

The Wuqing reservoir is clearly not over-exploited at the moment. The production potential of the geothermal reservoir is estimated to be about 2.1 Mm^3/year, which equals an average production rate of 67 kg/s, based on the above results and an allowable draw-down of 100 m the next five years. This is an increase of about 80% from the 1997 production rates.

6. RECOMMENDED DESIGN OF A TRACER TEST

The thermal breakthrough time estimated earlier depends on the channel geometry of the channels connecting the production and reinjection wells. Some assumptions have been made on this geometry. A method of detecting the flow paths and estimating the channel volume involves injecting a chemical tracer into the water, and monitoring its recovery in nearby production wells (Axelsson et al., 1995). This is a so-called tracer test. The design of such a test in Wuqing is discussed below.

One-dimensional flow, with a pore water velocity of u, is assumed in a column or channel of porous media connecting the reinjection and production wells. Concentration is initially zero everywhere in the channel. At time $t = 0$, a mass M of the tracer is injected instantaneously into the reinjection well, and consequently transported along the flow channel to the production well. The governing equation for the concentration distribution $C(x, t)$ becomes

$$D\frac{\partial^2 C}{\partial x^2} = u\frac{\partial C}{\partial x} + \frac{\partial C}{\partial t} \qquad (13)$$

The initial and boundary conditions are $C(x, 0) = 0$, and $C(x, t) = 0$ when $x \to \infty$. In addition, the total mass of the injected solute is given by

$$M = \int_{-\infty}^{\infty} \phi C(x,t)dx \qquad (14)$$

The solution for the tracer concentration $c(t)$, in the produced fluid for an injection-production well-pair is (Axelssson et al., 1995)

$$c(t) = \frac{\mu M}{Q} \frac{1}{2\sqrt{Dt\pi}} e^{-\frac{(x-\mu t)^2}{4Dt}}, \qquad u = \frac{q}{\rho A \phi} \qquad (15)$$

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

Thus, the tracer recovery in the production well mainly depends on the geometric and hydrological properties of the formation, i.e. the cross-sectional area of the flow channel $A\phi$ and its dispersivity α_L.

A suitable tracer for the Wuqing geothermal reservoir has not been selected. Sodium-fluorescein, which can be measured at very low concentrations, has been used successfully in many geothermal fields. Whether it can be used successfully in the sandstone reservoir at Wuqing is not clear at this time. Other tracers are available. Therefore, using two tracers would be advisable.

Assume that a tracer test is conducted between wells YR-9 and YR-6, with a constant production of 15 kg/s from well YR-6 and a stable reinjection rate into the injection well YR-9. During the experiments, 10 kg of fluorescein are injected into well YR-9 as a tracer. Equation 16 was used to calculate tracer recovery in well YR-9 for a range of parameters. Figure 19 shows the results and can be used to estimate the amount of tracer needed in an actual tracer test and the sampling frequency. Since the detection limit for fluorescein is on the order of 0.1-1 ppb, 10 kg appears to be a suitable amount. If a different tracer is used, its detection limit will determine the amount needed. A sampling frequency of once per week

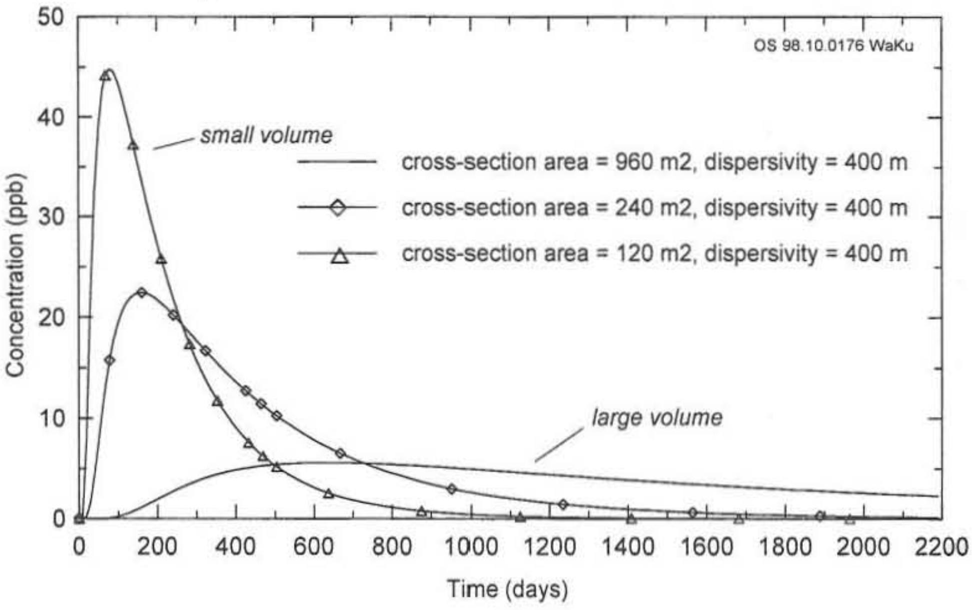

FIGURE 19: Calculated tracer recovery curves for different properties of the flow channel connecting production and reinjection wells, separated by 800 m

appears to be suitable according to Figure 19, except for the first two weeks were sampling once per day is recommended.

A tracer test lasting several months seems to be required. However, if the tracer concentration reaches the maximum value in a very short time, it means a small volume of the reservoir interacts with the injected fluid, the tracer test may be terminated sooner than planned. On the other hand, if the injected water diffuses into a large volume, only a small part of the tracer will be recovered during the test. In that case, thermal breakthrough will not be a problem for the well-pair in question.

7. SUMMARY AND RECOMMENDATIONS

The main conclusions and recommendations of this report may be summarized as follows:

1. The results of well test analysis and reservoir modelling indicate that the average permeability of the Wuqing reservoir is rather high, or about 300-500 mD.

2. Model predictions indicate that the water level will reach a depth of 73 m in 2003, when all available geothermal wells produce with a production rate of 1.65 Mm^3/year (Case 1). A 33% increase in production to 2.17 Mm^3/year (Case 2) will cause the water level to reach 104 m depth in 2003. According to the model, in both cases the water level declines very slowly, 2-3 years after production is increased.

3. During the five year prediction period, the production potential of the reservoir is estimated to be 2.11 Mm^3/year, if the allowable draw-down is assumed as 100 m. The peak production rate must be less than 175 kg/s during the yearly heating period.

4. During long term utilization of the field, reinjection will allow an increase in production without causing too much draw-down. If 23% of the water produced in Case 2 would be reinjected into the reservoir, the calculated water level recovery reaches 17 m in five years.

5. The reservoir is not over-exploited at the moment. The maximum allowable draw-down may be increased to 200 m such that production potential will increase to 3.9 Mm^3/year in the future. This should not be done before more data is collected and more research carried out.

6. A tracer test must be conducted in Wuqing to detect the flow paths between injection and production wells and estimate possible cooling resulting from the injection.

7. In sandstone reservoirs the injectivity decreases due to particle deposition in the slotted liners or formation plugging. Injectivity and scaling problems are minimized if the fluids are injected directly from a heat exchanger in a closed system. Meanwhile, intermitent pumping from injection wells appears to be an effective way to clean injection wells and restore their injectivity (Ouyang and Wang,1992).

8. Long-term monitoring of the Wuqing geothermal field must be further improved and equipped. The production rate, water level and water temperature for each production well need to be recorded on a regular basis, preferably continuously. In addition to being an integral part of geothermal management, it will enable more accurate modelling and more reliable predictions. Collection of water samples for chemical analysis is also recommended to provide information on changes in the reservoir, such as cold water infiltration due to lowered reservoir pressure.

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