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ASSESSMENT OF SEDIMENTARY GEOTHERMAL RESERVOIRS IN DEZHOU, CHINA AND GALANTA, SLOVAKIA

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ABSTRACT

Sedimentary geothermal reservoirs are characterized by large areas, homogeneous aquifers, quite productive wells and great energy potential. Effective methods for sedimentary geothermal reservoir assessment are reviewed along with operational options for geothermal reservoir management with respect to sustainable production of geothermal water. The Dezhou reservoir in China and Galanta reservoir in Slovakia are presented as examples. The Dezhou geothermal system is a typical sedimentary sandstone reservoir, located in an alluvial plain dominated by the Yellow River in China, which is part of the North China Sedimentary Basin. It is an extensive, almost horizontal, highly permeable, low-temperature reservoir. Two successful production wells (DR1 and DR2), with temperatures between 46 and 58°C at depths from 1490 to 1530 m, have been drilled into the reservoir. The properties and parameters of the reservoir are estimated from interpretation of well test data. On the basis of these data, the production potential of the Dezhou reservoir has been estimated to be 6.9 million tons per year, for the next 10 years, by using a simple analytical distributed parameter model and a lumped parameter model, with the constraint of maximum allowable drawdown of 100 m. The Galanta geothermal system is also a sedimentary low-temperature reservoir. It is located on the periphery of the central depression of the Danube Basin. Three geothermal wells have been drilled there to depths between 1990 and 2102 m, with temperatures varying between 62 and 80°C. Based on long-term observation data of two wells (FGG2 and FGG3), the production potential of the Galanta reservoir has been assessed to be 1.3 million tons per year, for the next 10 years, by using a simple analytical distributed parameter model and a lumped parameter model, with the constraint of maximum allowable drawdown of 200 m. For the objective of sustainable reservoir development, comprehensive management strategies are recommended including reinjection in terms of mitigating land subsidence, counteracting water level drawdown, and extracting more thermal energy.

1. INTRODUCTION

Sedimentary geothermal reservoirs, which are widely distributed in the world, are characterized by large areal extent, rather homogeneous aquifers, quite productive wells and great energy potential. They are quite different in nature from typical fractured reservoirs. By taking the Dezhou reservoir in China and the Galanta reservoir in Slovakia as examples, this report discusses suitable methods for sedimentary geothermal reservoir assessment. Dezhou is located in the North China Sedimentary Basin while Galanta is in the Danube Basin.

On the basis of the conceptual model and analyses of pumping test data from the Dezhou geothermal reservoir, a distributed parameter model, approximately in agreement with reservoir conditions, and a lumped parameter model, are established to estimate the production potential and to predict the reservoir response to long-term production and reinjection. Comparable models are also developed for the Galanta geothermal reservoir on the basis of interpretation of long-term observation data. Finally, comprehensive management strategies are suggested for sustainable development of the reservoirs in questions.

FIGURE 1: Location of the Dezhou geothermal field in China

1.1 Dezhou geothermal reservoir

The Dezhou geothermal reservoir is located in the alluvial plain dominated by the Yellow River, which is within the North China Sedimentary Basin (Figure 1). Dezhou, a city situated in the northwest part of Shandong Province, has a population of 300,000 and lies approximately in the centre of the geothermal area.

The Dezhou geothermal reservoir is a low-temperature sedimentary reservoir yielding water with temperatures between 46 and 58˚C. Two successful production wells have been drilled into the reservoir since 1997. The emphasis on geothermal development has been in the area of direct-utilization, such as for space heating, swimming pools and balneology.

Owing to its very low actual production, 2.9 l/s in 1999, the Dezhou geothermal reservoir, on the whole, is still in its natural state. However, cold winters coupled with growing concerns over greenhouse gas emissions suggest that the geothermal waters will be developed intensively in the future. For the purpose of rational exploitation of the geothermal resource, it is essential to carry out a reservoir evaluation and estimate the long-term production potential, by predicting the water level response of the reservoir. However, available studies appear to have focused on geological conditions.

1.2 Galanta geothermal reservoir

The Galanta geothermal system is also a sedimentary low-temperature reservoir. It is located on the periphery of the central depression of the Danube Basin in southwest Slovakia (Figure 2). Three geothermal wells (FGG1, FGG2 and FGG3) have been drilled there to depths between 1990 and 2102 m, with temperatures varying between 62 and 80˚C.

FIGURE 2: Location of the Galanta geothermal system in the central depression of the Danube Basin, Slovakia

2. THE DEZHOU AND GALANTA GEOTHERMAL RESERVOIRS

2.1 The Dezhou geothermal reservoir

2.1.1 Geological background

The Dezhou geo-thermal reservoir is situated within the Dezhou depression. It is bounded by the Bianlinzhen fault to the east, the Cangdong fault to the west, the Xiaoyuzhuang fault to the south, and the Xisongmen fault to the north. All of these faults appear to act as permeable boundaries, which are presented in Figure 3. Some other faults, such as the Jianhe fault, intersect the Dezhou reservoir, and are believed to cause the anisotropic permeabilities of the reservoir.

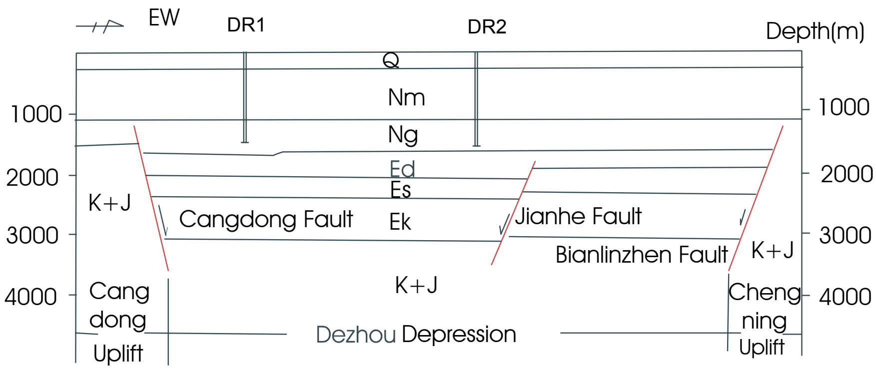

FIGURE 3: Tectonic cross-section of the Dezhou depression

According to stratigraphic data from boreholes (Figure 4) and interpretation of geophysical exploration, the Cenozoic sedimentary strata appear to be more than 3100 m thick.

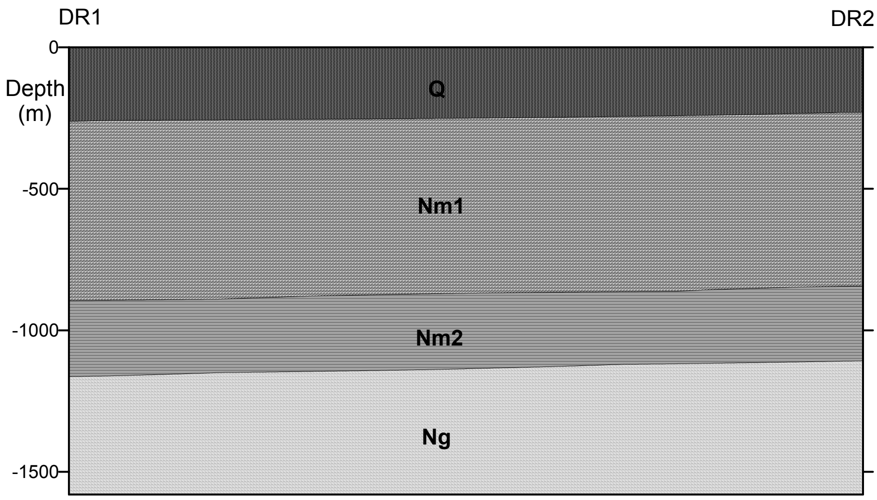

FIGURE 4: Borehole cross-section in the Dezhou geothermal field

2.1.2 Reservoir features

The Dezhou geothermal reservoir is a sedimentary reservoir with heat-flow dominated by conduction. It is believed that the reservoir exists because of the occurrence of highly permeable sedimentary layers at great depth, an above average geothermal gradient (Figure 5), as well as because of the faults and fractures. The cap rock is upper Minghuazhen formation of Neogene age. The upper Minghuazhen formation, with a thickness of 900 m, is composed of argillite and sandy argillite with interbedded sandstone.

The Dezhou geothermal reservoir is located within the Guantao formation of Neogene age, with a depth ranging from 1350 to 1650 m and a thickness of 300-480 m (Figure 6). The main production aquifer of the reservoir is composed of sandstone and conglomerate, covers an area of 169 km^2 and has a thickness of 160-180 m.

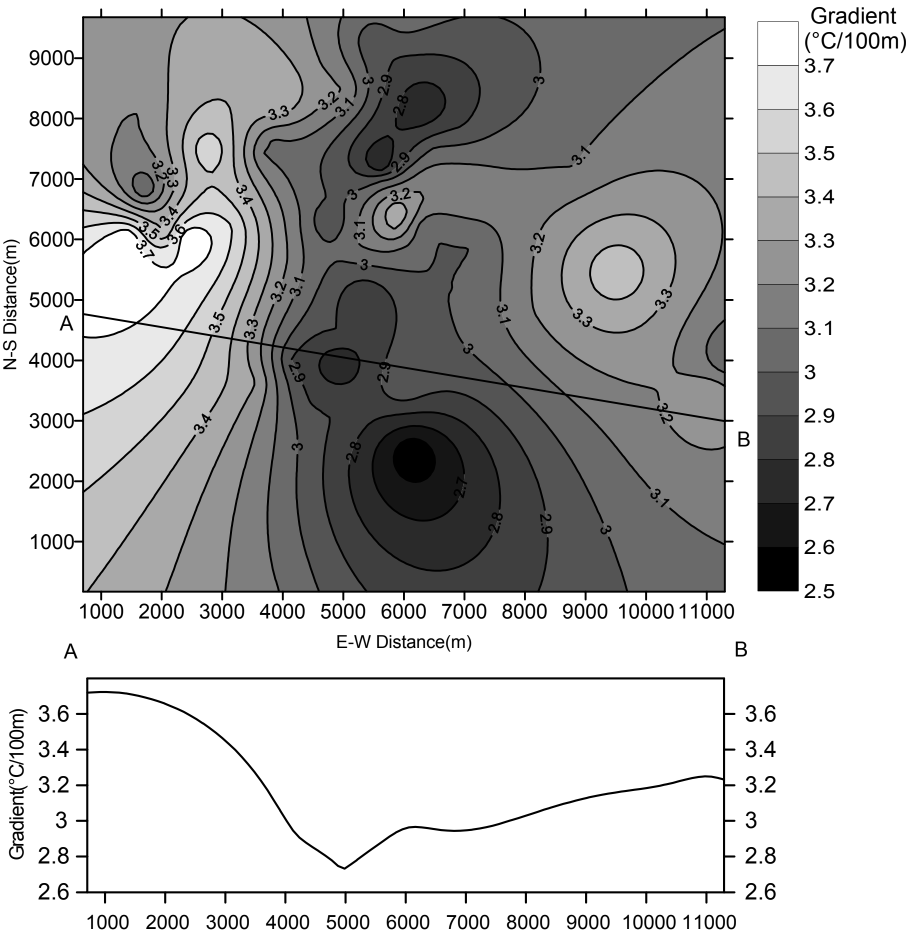

FIGURE 5: Geothermal gradient contours (top) along with a cross-section (AB, bottom)

The production aquifer has high porosity (24-30%) according to cores. In the natural state, the wells are artesian, with an artesian pressure of 7-8 m and a free-flow rate of 8.3-11.1 l/s. Production rates of single wells are 27.8-33.4 l/s at pump depths of about 50 m, and temperatures 46-58˚C at depths between 1350 and 1600 m (Figure 7). It should be pointed out that the temperature logs in wells 1 and 2 were carried out before well completion; there was colder drilling fluid still in the well, so the measured temperatures were lower than production temperatures in the pumping test (53-55.5˚C).

The water produced from the Dezhou geothermal reservoir is of chloride-sodium type, with a total dissolved solids concentration of 4000 to 5000 mg/l and total hardness of 318 to 400 mg/l. Due to the uniform geological character of the production reservoir, the chemical composition appears to be homogeneous over the entire reservoir. The main anion is chloride, with concentrations between 2053 and 2213 mg/l. The dominant cation is sodium, with concentrations from 1525 to 1628 mg/l. The pH of the water ranges from 7.8 to 8.1. Based on isotope analyses, the geothermal water in Dezhou reservoir is of meteoric origin, with a cycling time of more than 50 years (Liu et al., 1998).

2.1.3 Production history of both geothermal water and colder groundwater

The first geothermal well was drilled in 1997, and the second in 1998. Unfortunately, there are no production data available now, but it is believed that the actual current production is very small about 2.9 l/s on average. Accordingly, the Dezhou geothermal reservoir is still in its natural state.

The geothermal aquifer is overlain by a colder groundwater aquifer, at a depth of 190-250 m. It is the

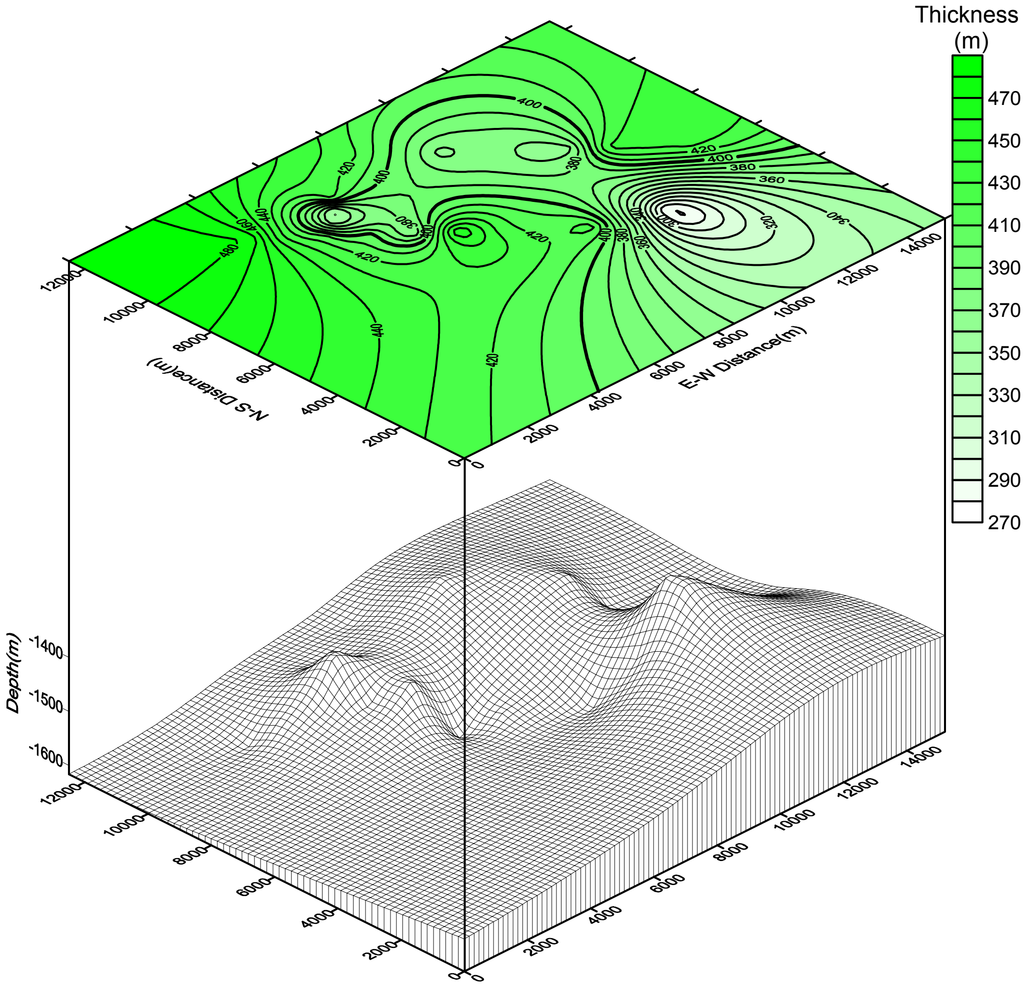

FIGURE 6: Contour diagram of the thickness of the Guantao formation in m (top) and a three-dimensional surface map of its bottom (bottom)

main water-supply source in the Dezhou City, and has been pumped since 1965. Due to an arbitrary increase of groundwater exploitation up to 69,900 m^3/day now, the groundwater level is continuously falling. In response to extended heavy pumping, the deepest depth to the groundwater level has fallen from 2 m to 95.5 m, and a depression cone with an area of about 3,200 km^2 has formed. At present, the groundwater level is still decreasing at a rate of 2-3 m/year. Accompanying this significant lowering of the groundwater level, land subsidence at a rate of 25-50 mm/year (Figure 8) has occurred. The affected area basically coincides with the depression cone. The cause of the subsidence is considered to be compaction of high-porosity, low-permeability mudstone at 90-150 m depth.

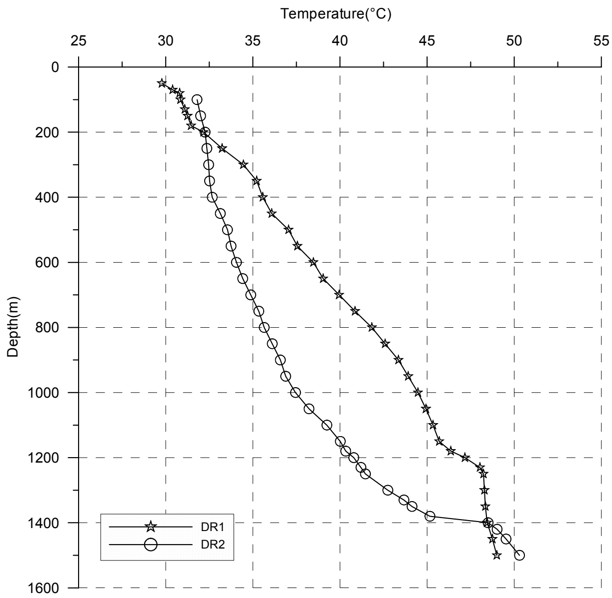

FIGURE 7: Temperature logs in wells DR1 and DR2

In order to reduce the problem of land subsidence caused by cold groundwater extraction, it is important to estimate the rational production

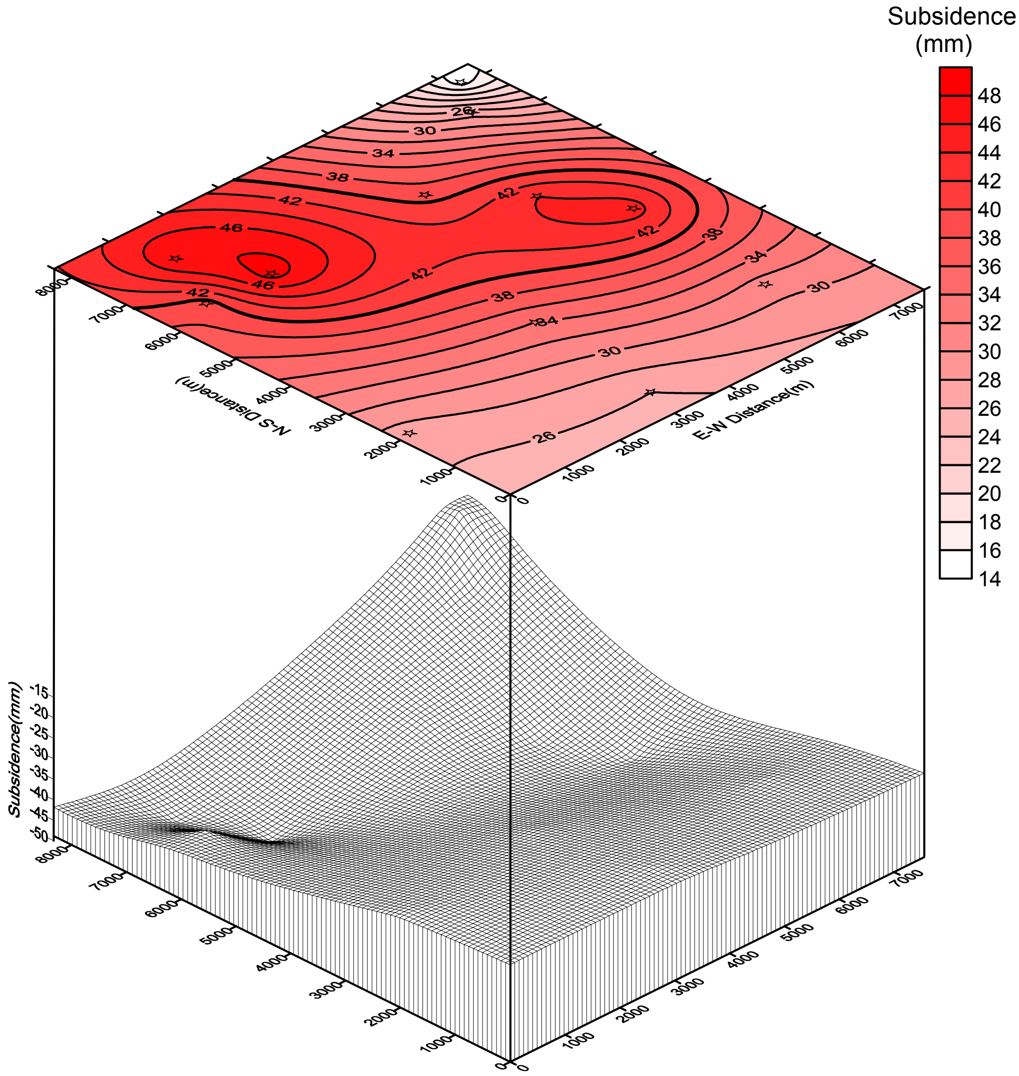

FIGURE 8: Contour (top) and 3D surface map (bottom) of land subsidence in mm over the period of May 1991 - May 1992

potential of the geothermal water and to predict the response of water levels. In other words, a reasonable assessment of production potential is a prerequisite for developing the geothermal resource perennially; and comprehensive management countermeasures should be adopted to assure sustainable development of the geothermal reservoir.

2.2 The Galanta geothermal reservoir

2.2.1 Geological background

The most intensive geothermal activity in Slovakia is concentrated in the Danube-, and the E-Slovakian basins. The central depression of the Danube Basin is located in southern Slovakia, on the border of Hungary, east of the capital city Bratislava. It occupies a surface area of 4070 km^2 (100×50 km). It is the largest geothermal field in Slovakia, believed to have originated in the Pannonian period and to have developed up to the end of the Pliocene. The depression was caused partly by bending, and partly by vertical movement along faults (Fendek, 1992).

The Galanta reservoir lies in the Galanta depression, which is on the northern periphery of the central depression of the Danube Basin. It is a brachy-syncline, with its centre in the area of Gabdikovo.

2.2.2 Reservoir features

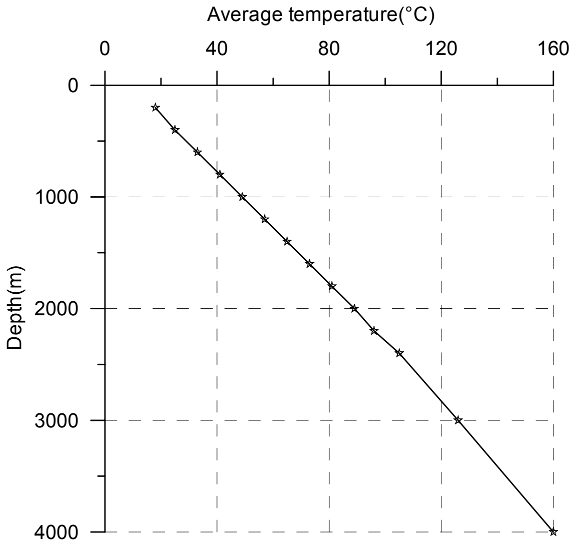

FIGURE 9: Average temperature versus depth in the central depression of the Danube Basin

The top of the geothermal reservoir is horizontal and lies at a depth of 1000 m; on the flanks and bottom is a relatively impermeable basement (clayey aquiclude). The aquiclude slopes from all sides to its centre at a depth of approximately 3400 m.

The geothermal gradient varies within the limits of 3.6-4.4˚C/100 m, with an average value of 3.9˚C/100 m in the depth interval of 2,000-2,500 m (Franko and Bodis, 1992). At a depth of 1000 m, the average temperature is 49˚C, at 2000 m it is 89˚C and at 3000 m it is 126˚C (Figure 9).

Sandstones are the main geothermal reservoir rock. In their natural state, geothermal wells discharge freely, with an artesian pressure of about 50 m and an artesian flow rate of 10.8-25 l/s. The waters are of bicarbonate-sodium type, have a temperature of about 78˚C, and contain about 5 g/l total dissolved solids.

2.2.3 Production history

Wells FGG2 and FGG3 in Galanta geothermal reservoir have been utilized for more than three years. As shown in Figure 10, flowrates, wellhead pressures or water levels, and water temperatures have been monitored carefully for both wells. From Nov. 1, 1996 to May 15, 2000, the average production rate was 9.57 l/s and 11 l/s for wells FGG2 and FGG3 respectively, while the highest production rate for well FGG2 was 17 l/s and for well FGG3 21 l/s during the heating season.

It can be seen from Figure 10 that the wellhead pressure, measured while the well was shut in, was much lower than expected. This is due to the cooling of the water column in the well. To avoid discrepancies, the pressure data observed while the wells were shut in were not used in the following modelling of the reservoir.

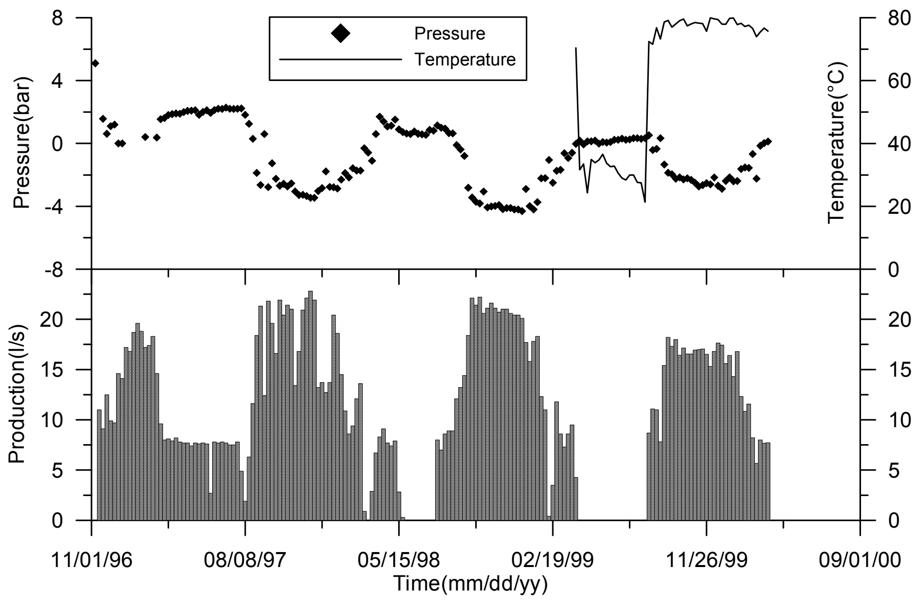

FIGURE 10: Pressure variations vs weekly average production rates along with water temperatures for well FGG3

3. PRESSURE TRANSIENT TEST DATA

It is noteworthy that the drawdown of a production well includes not only that of the usual pressure change, which is caused by laminar flow in the vicinity of a well, but also an additional pressure drop, which is associated with turbulent flow caused by flow through narrow feed-zones, flow through the well screen and flow inside the well to the pump intake. So, the water level or pressure measured in a production well does not correspond directly to the water level in an observation well. To evaluate the turbulence effect, a step rate pumping test is required. As shown in Figure 11, by plotting water levels versus flow rates, the effect of turbulence in well DR1, Dezhou geothermal reservoir, can be estimated. The curve deviates from linear behaviour to second order behaviour, implying turbulence. This situation is expressed by the polynomial regression equation:

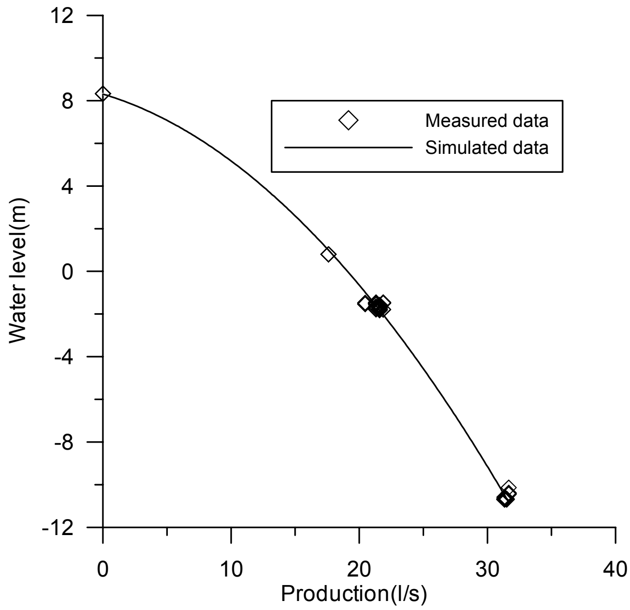

FIGURE 11: Production characteristics of well DR1 in the Dezhou geothermal reservoir

$$H = H_o + BQ + CQ^2 \tag{1}$$

where Q = Production flow rate [l/s];
H_0 = Water level in the production well at zero flow, i.e. initial water level [m];
BQ = The linear drawdown between the well and reservoir, caused by Darcy' flow [m];
CQ^2 = The pressure loss caused by turbulent flow at the location of inflow into the well and in the well itself [m].

The best fitting equation for the pumping test data presented in Figure 11 is

$H = 8.31 - 0.18\ Q - 0.0134\ Q^2$ (Coefficient of determination = 0.999)

The measured water level or pressure in production wells should be revised by using the above equation. The relationship between the water level and pressure is determined by the following equation:

$$\Delta H = \Delta P / \rho g \tag{2}$$

where ΔH = Water level change [m];
ΔP = Pressure change [bar];
ρ = Water density [kg/m^3];
g = Acceleration of gravity [m/s^2].

4. RESERVOIR MODELLING

It is important to appreciate quantitatively the physical processes that occur within a geothermal system, because this permits optimum exploitation of the reservoir. This "appreciation" can be divided into three main steps: first, the physical processes associated with the particular geothermal system under study must be identified and used to develop a conceptual model of the reservoir; second, a careful assessment of the physical and thermal properties of the rocks and fluids must be made (these data will be extremely useful for simulation study purposes); and third, a mathematical or physical model of the reservoir is developed, using the previously determined information about the reservoir. This model should include the properly identified initial and boundary conditions for the system (Samaniego, 1982).

4.1 Reservoir modelling for the Dezhou geothermal system

4.1.1 Conceptual model

A conceptual model is the fundamental element of reservoir modelling. The conceptual model of the Dezhou geothermal reservoir may be briefly delineated as follows:

Reservoir type: Low-temperature sedimentary sandstone reservoir, conduction-dominated;
Boundary: Permeable fault boundaries;
Production aquifer: Confined Neogene Guantao formation, with a thickness from 160 to 180 m at a depth between 1350 and 1650 m, and covering an area of 169 km^2;
Cap rock: Upper Minghuazhen formation of Neogene period, composed of argillite and sandy mudstone;
Underlying rock: Eogene Dongying Formation, composed of argillite, fine sandstone, and siltstone;
Recharge: Meteoric origin.

4.1.2 Analytical distributed parameter modelling

The reservoir response under production should be carefully matched with the response model. This technique of matching the observed production history data by means of a suitable model and using the model to predict future performance is fundamental to the subject of reservoir engineering.

On the basis of its conceptual model, the Dezhou geothermal reservoir can be outlined as horizontal and homogeneous, with a constant thickness and an infinite areal extent. This kind of reservoir is in good agreement with the prerequisites of a simple analytical distributed parameter model. In the distributed parameter model, locations, production, injection, and observations of each individual well are taken into account. In other words, the behaviour of individual wells and the interferences between different wells can be simulated by the distributed model.

The distributed parameter computer code VARFLOW (EG&G Idaho Inc., and Lawrence Berkeley Laboratory, 1982) is based on the Theis model as follows:

$$\Delta p(t) = \frac{\mu}{4\pi kh} \int_{\tau_n}^{\tau_{n+1}} \frac{q(\tau)}{t-\tau} \exp\left[\frac{-r^2}{4\eta(t-\tau)}\right] d\tau \tag{3}$$

where
Δp(t) = Pressure change at time t due to the flow rate $q(\tau)$, $\tau_n < t < \tau_{n+1}$ [bar];
μ = Dynamic viscosity of the fluid [Pa.s, kg/m/s];
k = Permeability [D, 10^{-12} m^2];
h = Reservoir thickness [m];
τ_n = Time at which the flow starts [s];
τ_{n+1} = Time at which the flow stops [s];
$q(\tau)$ = Volumetric flow rate at time τ [l/s];
r = Distance between the observation well and the production/injection well [m];
η = The hydraulic diffusivity ($k/\mu c_t$) [m^2/s];
c_t = $c_w\phi + c_r(1-\phi)$ = Total compressibility of water-saturated formation [1/Pa];
c_w = Compressibility of water [1/Pa];
c_r = Compressibility of rock matrix [1/Pa];
ϕ = Reservoir porosity.

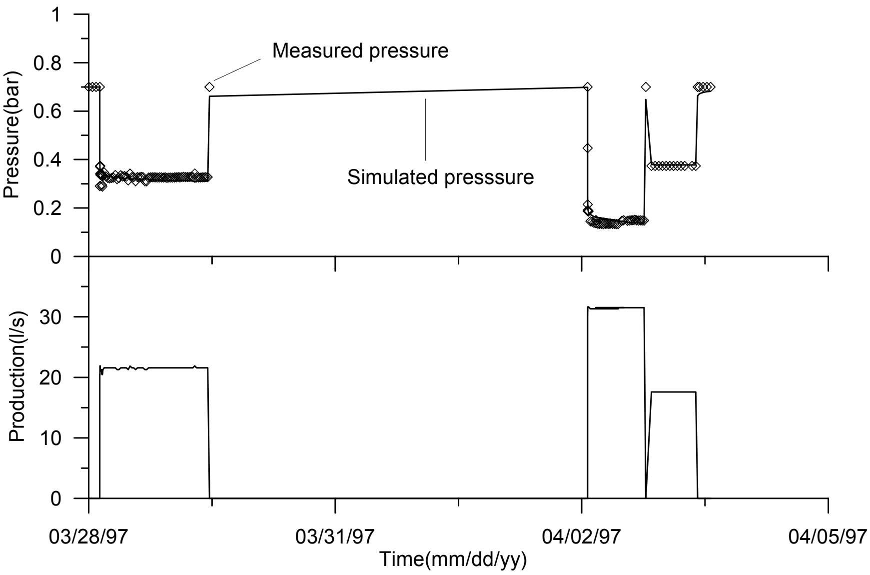

FIGURE 12: Comparison between observed and simulated (Theis-model, VARFLOW) pressure changes combined with production during testing of well DR1 in 1997

VARFLOW calculates pressure changes in response to water production/injection from/into an idealized reservoir system. Based on the actual conditions of the Dezhou reservoir, anisotropic permeabilities are chosen, and the initial state of reservoir pressures prior to production is assumed as constant. The parameters (transmissivity and storage coefficient) were varied until a satisfactory match was obtained. Figure 12 represents the match between the observed and simulated pressure in well DR1 by using the data of a short-term well test between Mar. 28 - Apr. 4, 1997. It is obvious that the match is quite good. The parameters of the reservoir are estimated as follows:

X-direction transmissivity:	$T_x = k_x h / \mu$	$= 1 \times 10^{-6}$ m^3 / Pa s;
Y-direction transmissivity:	$T_y = k_y h / \mu$	$= 5 \times 10^{-6}$ m^3 / Pa s;
Storage coefficient:	$S = c_t h$	$= 2 \times 10^{-4}$ m / Pa s;

A moderate anisotropy, $k_y / k_x = 5$, is incorporated into the model, which means that the permeability in the north-south direction is assumed 5 times that into the east-west direction. The north-south direction coincides with the concentrated runoff zone direction of the groundwater in the Dezhou geothermal reservoir. From the above results, the average permeability-thickness and permeability of the reservoir are calculated as (assuming h = 170 m):

$k_x h = 500$ Dm $\quad$ $k_y h = 2500$ Dm $\quad$ Average $kh = \sqrt{(k_x h)(k_y h)} = 1118$ Dm

$k_x = 2.94$ D $\quad$ $k_y = 14.7$ D $\quad$ Average $k = \sqrt{k_x k_y} = 6.6$ D

The pressure distribution in the reservoir can also be calculated by the distributed parameter model, and then the water level contour maps can be plotted at any time. Figure 13 shows the calculated water level contours around well DR1 during the pumping test in April 4, 1997. Due to its short production, the extent of its influence during the well test is mostly concentrated in an area around well DR1, several square kilometres in size. Figure 13 presents the influenced area only.

4.1.3 Lumped parameter modelling

Lumped parameter models have been extensively used to simulate data on water level and pressure changes in geothermal systems in Iceland (Axelsson, 2000). An automatic non-linear iterative least-squares technique for estimating model parameters, which tackles the simulation as an inverse problem, was applied during simulation (Axelsson and Arason, 1992). Being automatic it requires very little time compared to other forward modelling approaches, in particular detailed numerical modelling. Lumped

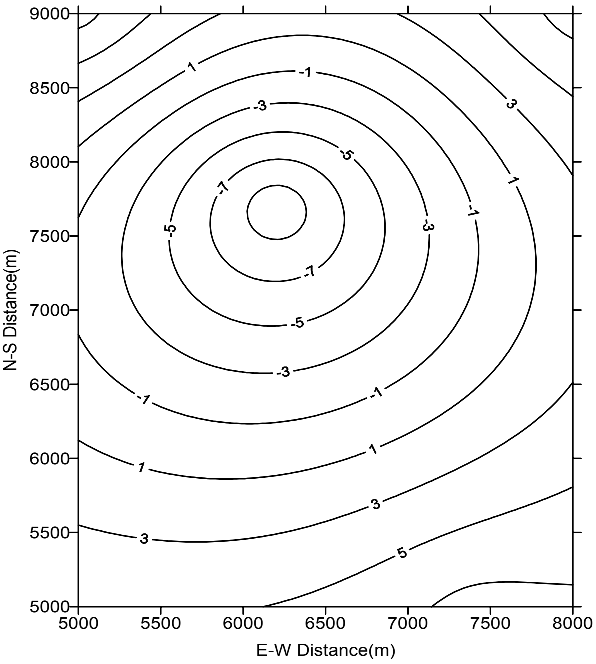

FIGURE 13: Water level contour (m) map on April 4, 1997, during pumping test of well DR1

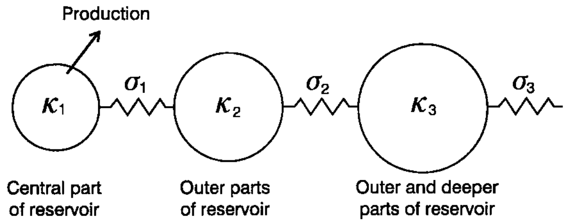

FIGURE 14: Schematic diagram of a lumped parameter model (Axelsson, 2000)

parameter models can simply be considered as numerical distributed parameter models with a very coarse spatial discretization (Bödvarsson et al., 1986). The method presented here tackles the modelling as an inverse problem that requires far less time than direct, or forward modelling, where the interactions are done manually. This makes the lumped parameter simulations highly cost effective (Axelsson, 1989). To tackle the simulation as an automatic inverse problem, a powerful and effective computer code, LUMPFIT, was developed (Axelsson, 1985; Axelsson and Arason, 1992). A general lumped model is shown in Figure 14, which consists of a few tanks and flow resistors. The water level or pressure in the tanks simulates the water level or pressure in different parts of a geothermal system. The pressure response p of a general open lumped model with N tanks, to a constant production Q since time $t = 0$, is given by the equation:

$$p(t) = -\sum_{j=1}^{N} Q\frac{A_j}{L_j}\left[1 - e^{-L_j t}\right] \tag{4}$$

The pressure response of an equivalent N tank closed model is given by the equation:

$$p(t) = -\sum_{j=1}^{N-1} Q\frac{A_j}{L_j}\left[1 - e^{-L_j t}\right] + QBt \tag{5}$$

The coefficients A_j, L_j and B are functions of the storage coefficients of the tanks (κ_j) and the conductance coefficients of resistors σ_j in the model.

The resistors, controlled by the permeability of the rocks, simulate the flow resistance in a reservoir. The first tank simulates the innermost part of a geothermal reservoir, i.e. it represents the active well field; the second and third tanks simulate outer and deeper parts of a system, i.e. they act as recharge parts from either deeper or outside parts of the main reservoir. If the third tank is connected by a resistor to a constant pressure source, which supplies recharge to a geothermal system, the model is open. Otherwise, without the connection to a constant pressure source, the model would be closed. An open model is optimistic, since equilibrium between production and recharge is eventually reached during long-term production, causing water level drawdown to stabilize. In contrast, a closed model may be considered pessimistic, since no recharge is allowed for such a model and the water level declines continuously as production proceeds. Hot water is pumped out from the first tank, which causes the pressure or water level in the model to decline. This in turn simulates the decline of pressure or water level in the real geothermal system. When using this method of lumped parameter modelling, the data fitted (simulated) are the water level data for an observation well inside the well field, while the input for the model is the production history of the geothermal field in question. A first guess of the lumped model parameters is made and then, consequently, the parameters are changed by the automatic iterative process described above until a satisfactory match (in the least squares sense) for the selected model is obtained. There are no a-priori assumptions made on the nature and geometry of the reservoir (Axelsson, 1991, 2000).

As mentioned previously, due to the extended heavy pumping of colder groundwater, land subsidence has occurred in Dezhou geothermal field. A conservative lumped model, closed three-tank model, is suggested to simulate the pumping test data.

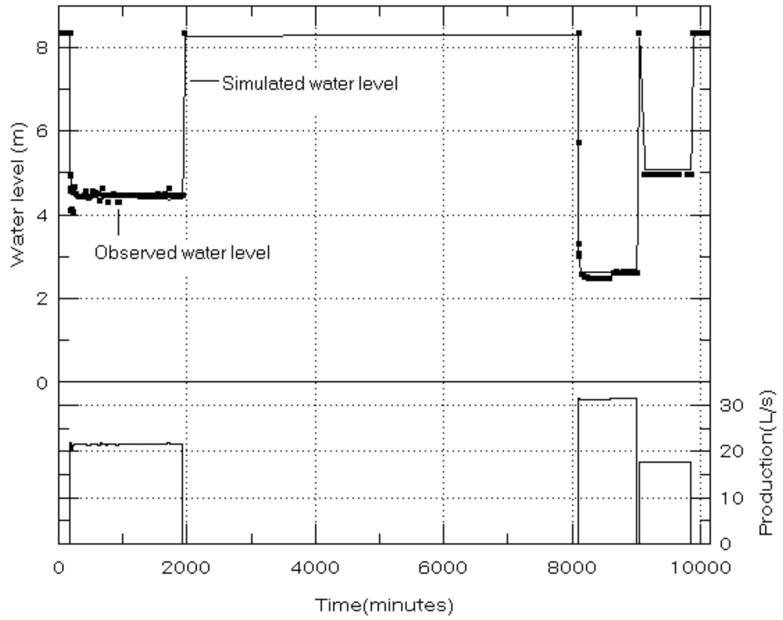

FIGURE 15: Observed water level variations during pumping test for well DR1 in the Dezhou geothermal reservoir, simulated by a lumped parameter model (LUMPFIT)

The simulated and monitored water level changes over the period from Mar. 28 to Apr. 4, 1997 combined with flow rates in well DR1 are shown in Figure 15, presenting a very good agreement between observed and fitted data. The parameters of the closed three-tank model are presented in Table 1, which can also be used to derive some of the properties of the reservoir, such as volume, area and permeability. After the best fit is obtained by LUMPFIT, the parameters of the model may be used to predict future pressure changes in the reservoir for given production scenarios.

TABLE 1: Parameters of the closed three-tank lumped model of Dezhou

Parameter	Value
$A_1\,(10^{-2})$	0.1525
$A_2\,(10^{-2})$	26.1
L_1	0.074
L_2	1.623
$B\,(10^{-7})$	6.39
$\kappa_1\,(ms^2)$	0.0232
$\kappa_2\,(ms^2)$	4.36
$\kappa_3\,(ms^2)$	9521.57
$\sigma_{12}\,(10^{-4}ms)$	6.24
$\sigma_{23}\,(10^{-4}ms)$	54.36
Coefficient of determination: 97.572%	
κ: Capacitance (storage)	
σ: Conductivity	

It must be pointed out that even though the pumping test for well DR1 in 1997 was executed quite successfully, it lasted for only 7 days, which is a rather short time compared to an exploitation history to be sustained for several decades. Therefore, a lot of information on the reservoir is not revealed in the test, for example: boundary conditions, interference among wells, recharge situation, etc. As exploitation from the reservoir increases, and more data becomes available, it is suggested that the model be updated and refined by matching longer production histories, to make the model as accurate as possible. Consequently, this would result in more and more reliable predictions of reservoir behaviour.

4.2 Reservoir modelling for the Galanta geothermal system

The nature of the Galanta geothermal reservoir is similar to Dezhou in terms of reservoir type. So, the same kinds of models are adopted for simulating and predicting the reservoir behaviour. The crucial difference is that the reservoir modelling of Galanta will be based on long-term observation data rather than short-time pumping test data.

4.2.1 Distributed parameter modelling

The VARFLOW program is still selected as the tool to simulate and predict pressure changes in response to production/reinjection. Figures 16-17 show the fit between observed and simulated pressure changes in wells FGG2 and FGG3, using the monitoring data from Nov. 1, 1996 to May 15, 2000. The optimal parameters of the reservoir are determined as follows:

X-direction transmissivity:	$T_x = k_x h / \mu$	$= 9 \times 10^{-9}$ m^3 / Pa s;
Y-direction transmissivity:	$T_y = k_y h / \mu$	$= 2 \times 10^{-7}$ m^3 / Pa s;
Storage coefficient:	$S = c_t h$	$= 12 \times 10^{-4}$ m / Pa s;

A high anisotropy, $k_y / k_x = 22$, is incorporated into the model, which means that permeability in the N-S direction is 22 times that in the east-west direction. The north-south direction coincides with the main direction of geothermal water flow in the Galanta geothermal reservoir. From the above results, the average permeability-thickness and permeability of the reservoir are calculated as (assuming h = 113 m):

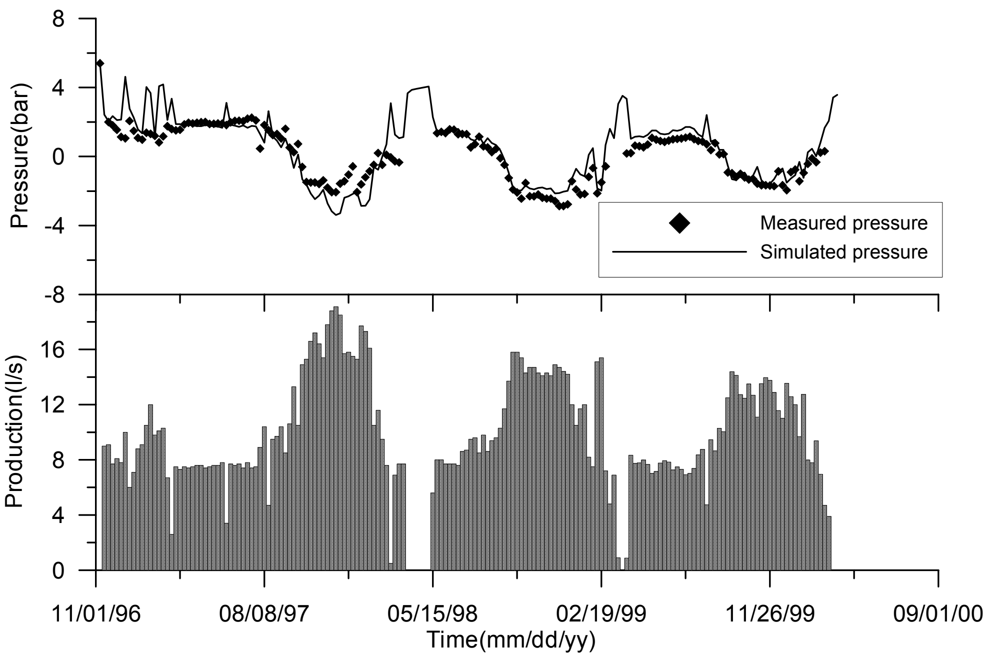

FIGURE 16: Observed and simulated (Theis-model, VARFLOW) pressure variations along with production from well FGG2

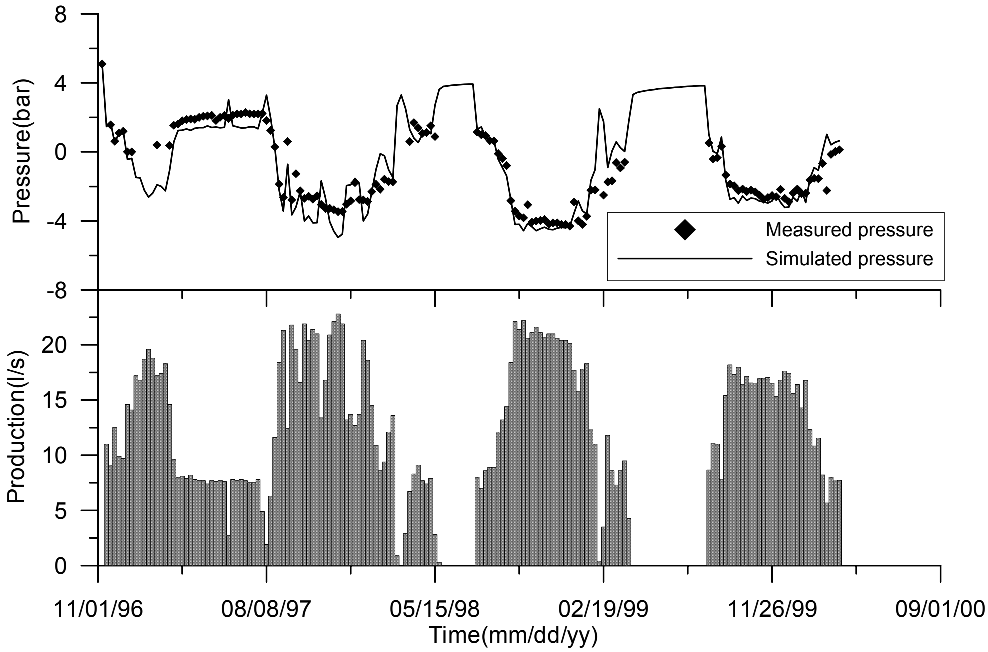

FIGURE 17: Observed and simulated (Theis-model, VARFLOW) pressure variations coupled with production from well FGG3

$k_x h$ = 3.28 Dm $k_y h$ = 72.8 Dm   Average $kh = \sqrt{(k_x h)(k_y h)}$ = 15.5 Dm

k_x = 0.029 D k_y = 0.64 D   Average k = $\sqrt{k_x k_y}$ = 0.14 D

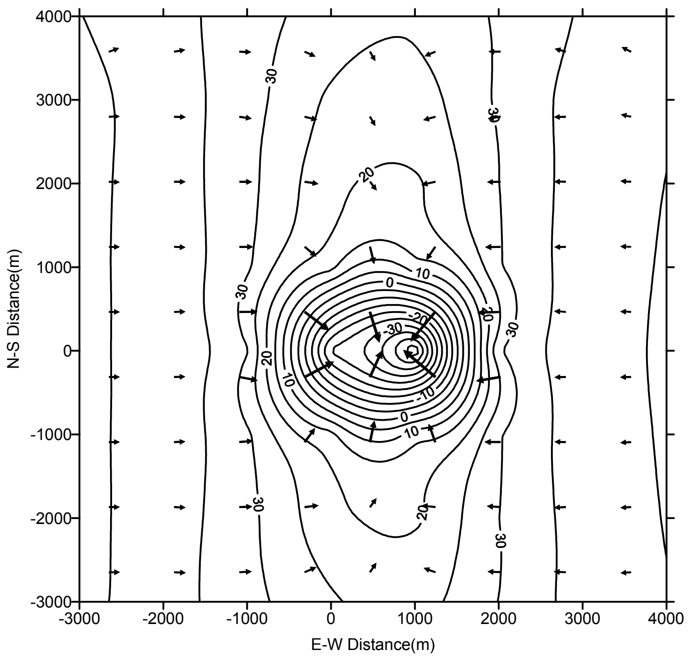

FIGURE 18: Water lever contours (m) showing the depression cone caused by production from wells FGG2 and FGG3 on Feb. 10, 1999, when the greatest water level drawdown, to date, occurred

The pressure distribution in the reservoir on Feb. 10, 1999, calculated by the distributed parameter model (VARFLOW), is shown in Figure 18.

In view of the quite accurate match between observed and calculated data, the parameters of the distributed model may be used to predict future water level performance corresponding to future production scenarios.

4.2.2 Lumped parameter modelling

Several different kinds of lumped parameter models were used to simulate the observed pressure response resulting from the 3.5-year production, by using LUMPFIT. Finally, the best fitted model, open two-tank, was selected as the model to be utilized for forecasting future behaviour of wells FGG2 and FGG3 for given production scenarios.

The simulated and monitored water level changes, together with production, are shown in Figures 19 and 20, representing a good agreement between observed and simulated data. The parameters are presented in Table 2, where some of the properties of the reservoir can be derived, such as volume, area and permeability.

It should be pointed out that the lumped parameter model (LUMPFIT) cannot simulate interference between wells, while the distributed parameter model (VARFLOW) can and does.

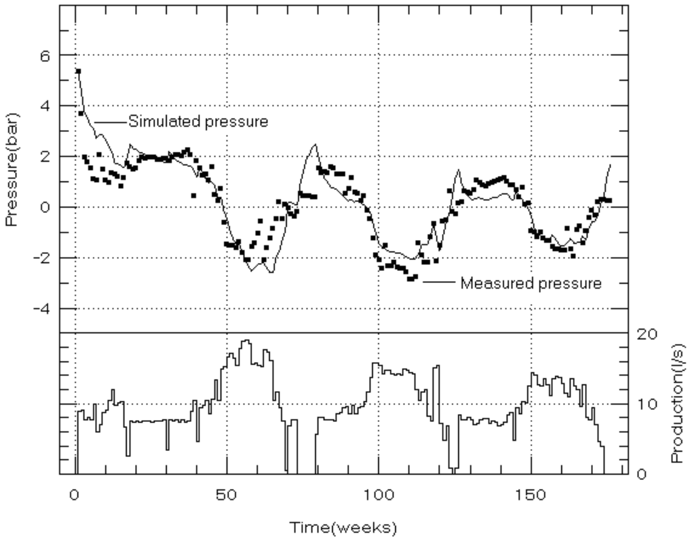

FIGURE 19: Observed and simulated (LUMPFIT) pressure changes, together with production from well FGG2, for data from Nov. 1, 1996 to May 15, 2000

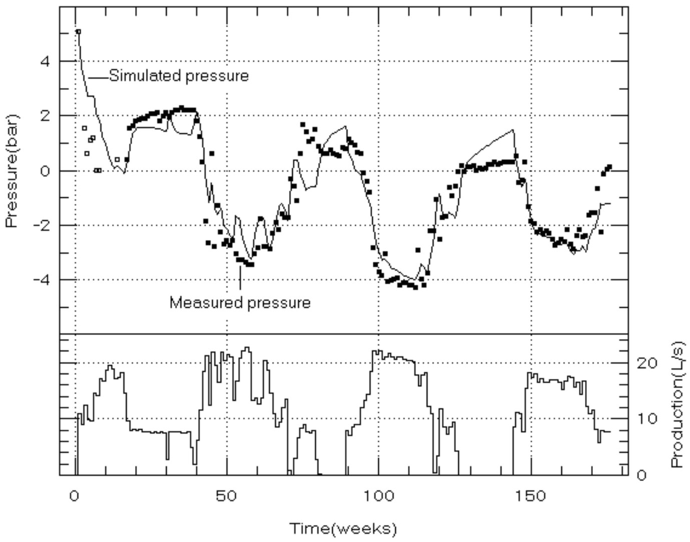

FIGURE 20: Observed and simulated (LUMPFIT) pressure changes, together with produc- tion from well FGG3, for data from Nov. 1, 1996 to May 15, 2000

TABLE 2: Parameters of open two-tank models for wells FGG2 and FGG3 in Galanta

Parameters	FGG2	FGG3
A_1	0.12	0.1789
A_2	0.01	0.008157
L_1	0.45	0.897
L_2	0.03	0.0176
B	0	0
κ_1 (ms^2)	44.94	31.4549
κ_2 (ms^2)	610.66	719.122
σ_{12} (10^{-4} ms)	0.31	0.4467
σ_{23} (10^{-4} ms)	0.34	0.219
Coefficient of determination	75%	85%
Remarks	κ: Capacitance (storage) σ: Conductivity	

5. PRODUCTION POTENTIAL

It has long been recognized that the basic tasks and main objectives of reservoir engineering are the assessment of production potential and response prediction for long-term behaviour of wells and reservoirs. This is based on information of the reservoir's nature and properties. Included in this task is designing a well distribution pattern for optimum development of the reservoir.

In view of the fact that production response of a reservoir is chiefly manifested as water level drawdown, the models established here may be used to evaluate the production potential of the two reservoirs by calculating and predicting water level performance for different future production scenarios. Both the lumped and distributed parameter models may be used to deal with the reservoir evaluation. The lumped model considers the total net production from the reservoir, but neither the interference nor the locations of individual wells. The distributed model (VARFLOW) is in general agreement with the geological conditions and permeability anisotropy of the reservoirs, and locations and interference of individual wells are taken into account. Only the predictions by the distributed parameter model are presented here.

The prerequisite of calculating production potential is to determine a rational maximum allowable drawdown of the production wells in the reservoir, since it determines the economic production potential directly. In other words, the production potential is restrained by the maximum allowable drawdown of the reservoir.

5.1 Production potential of the Dezhou geothermal reservoir

Considering constraints in the Dezhou geothermal reservoir, including the setting depths of well pumps, design of the production wells, the risk of colder water inflow, and especially the land subsidence in the area, the maximum allowable drawdown is defined as 100 m.

On the basis of the maximum allowable drawdown and the established distributed parameter model, the water level predictions were calculated for two different production scenarios:

Scenario I: Production during the pumping test for wells DR1 and DR2 is maintained for the next ten years, i.e.:

Annual average production: 62 l/s;
Production in heating season (Nov.-Mar.): 120 l/s;
Production in non-heating season: 10 l/s.

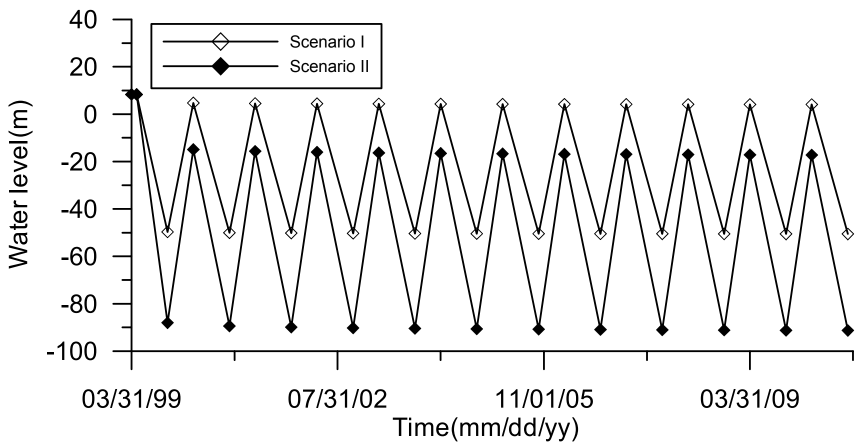

FIGURE 21: Predictions of water level trends up to the year 2010 in well DR1 for production scenario I and II for the Dezhou geothermal field, calculated by VARFLOW

The water level predictions, calculated by the analytical distributed parameter model, are presented in Figure 21, which shows the calculated water level changes in well DR1 for the next ten years. Well DR1 is located in the centre of the depression cone of the water level (Figure 22). Figure 22 represents the water level contours at the end of the prediction period on March 31, 2010, calculated by the distributed model. The water level drawdown distribution can also be seen in Figure 22.

Scenario II: Besides wells DR1 and DR2, four additional production wells are included according to geological conditions and the requirements of the Dezhou municipality. The production is increased to:

Annual average production: 220 l/s;
Production in heating season: 360 l/s;
Production in non-heating season: 120 l/s.

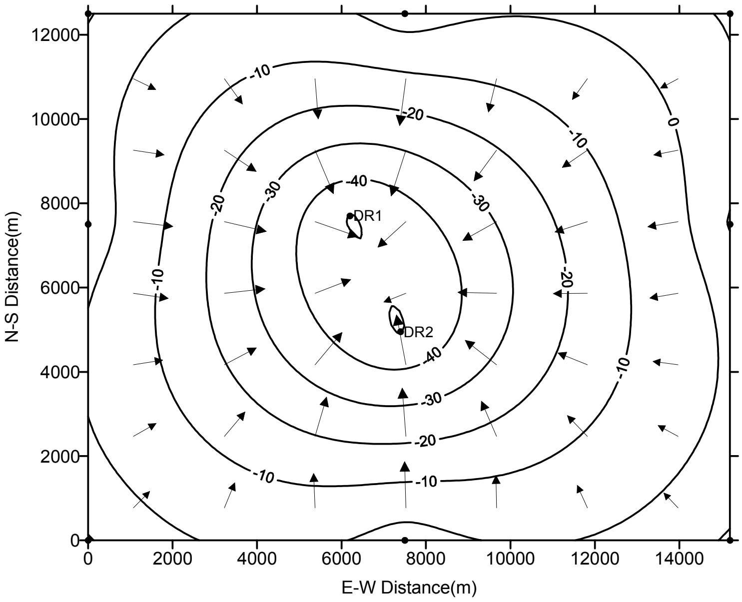

FIGURE 22: Predicted water level contours (m) on Mar. 31, 2010 for production scenario I in Dezhou, calculated by VARFLOW

The water level predictions, calculated by the distributed parameter model, are presented in Figure 21, which shows the water level changes in well DR1 for the next ten years. Well DR1 is still located in the centre of the depression cone of the water level (Figure 23). Figure 23 illustrates the water level contours at the end of the prediction period on Mar. 31, 2010, calculated by the distributed model, combined with a three-dimensional presentation of the water level surface. The water level drawdown distribution may also be seen in Figure 23. Comparing Figures 22 and 23, it is obvious that the water level drawdown for scenario II will be much greater and more extensive over the whole reservoir at the end of the prediction period.

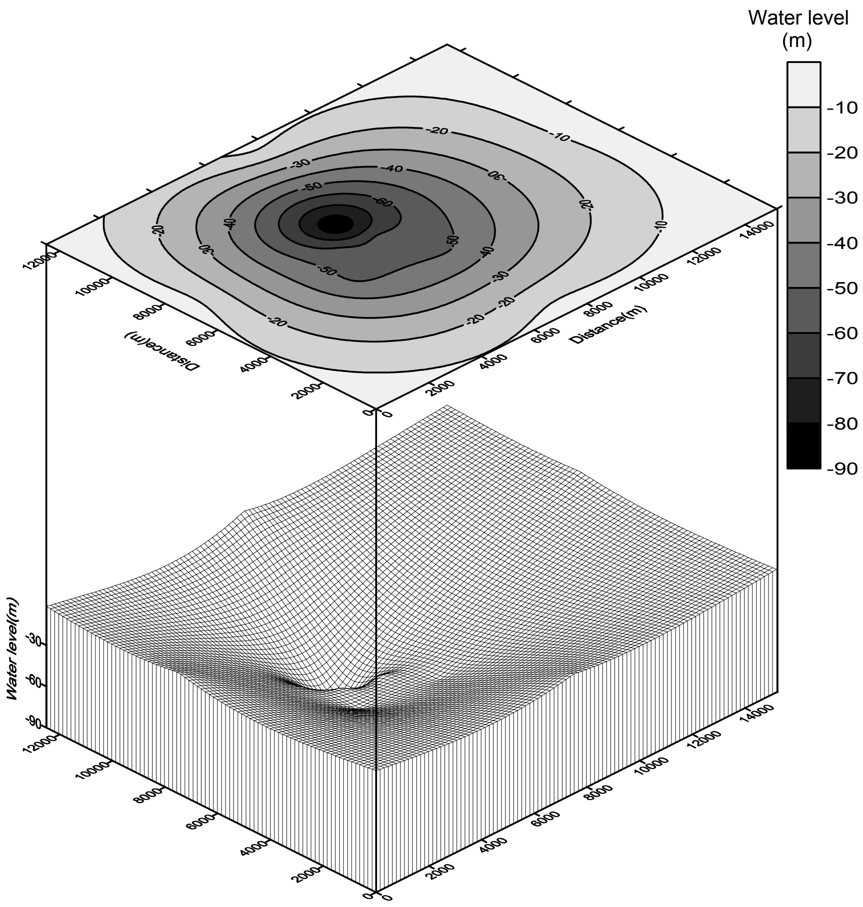

FIGURE 23: Predicted water level contours (m) (top) and 3D water level surface (bottom) in Dezhou on Mar. 31, 2010 for production scenario II, calculated by VARFLOW

Figures 21-23 show that the greatest anticipated water level drawdown for scenario I is 58 m, whereas for scenario II it is 99 m. In light of these results, and considering the maximum allowable drawdown of 100 m, the production potential of the Dezhou geothermal reservoir is evaluated to be 220 l/s on average for the next ten years, or 6.9 million tons per year. The allowable maximum production in heating seasons is 360 l/s.

5.2 Production potential of the Galanta geothermal reservoir

Considering limitations of the Galanta geothermal reservoir, including the setting depths of well pumps, design of the production wells, the risk of colder water inflow and land subsidence, the maximum allowable drawdown is defined as 200 m.

On the basis of the maximum allowable drawdown and the established distributed parameter model (VARFLOW), the water level predictions were calculated for two different production scenarios:

Scenario I: The present production for wells FGG2 and FGG3 is maintained for the next ten years, i.e.:

Annual average production: FGG2 - 9.6 l/s, FGG3 - 11 l/s;
Production in heating season: FGG2 - 17 l/s, FGG3 - 21 l/s;
Production in non-heating season: FGG2 - 2.1 l/s, FGG3 - 1 l/s.

The water level predictions, calculated by the distributed parameter model, are presented in Figures 24 and 25, which show the water level changes in wells FGG2 and FGG3 for the next ten years.

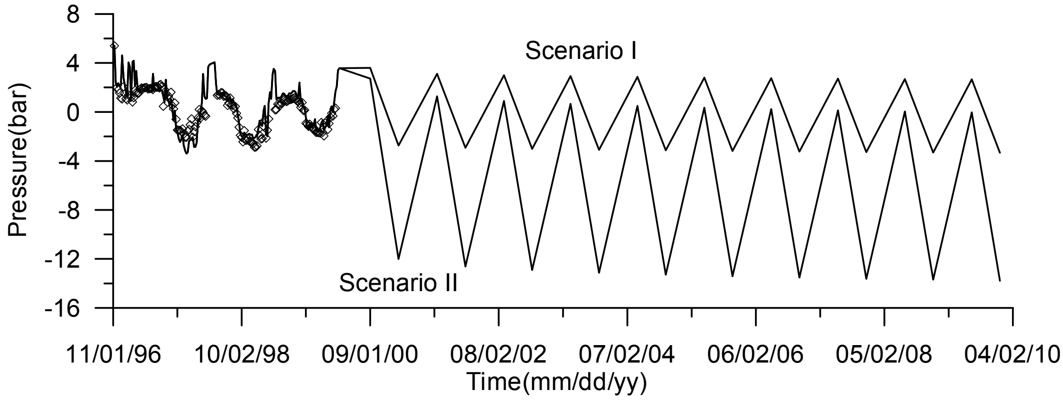

FIGURE 24: Predicted water level trends up to year 2010 for well FGG2 in Galanta for production scenarios I and II

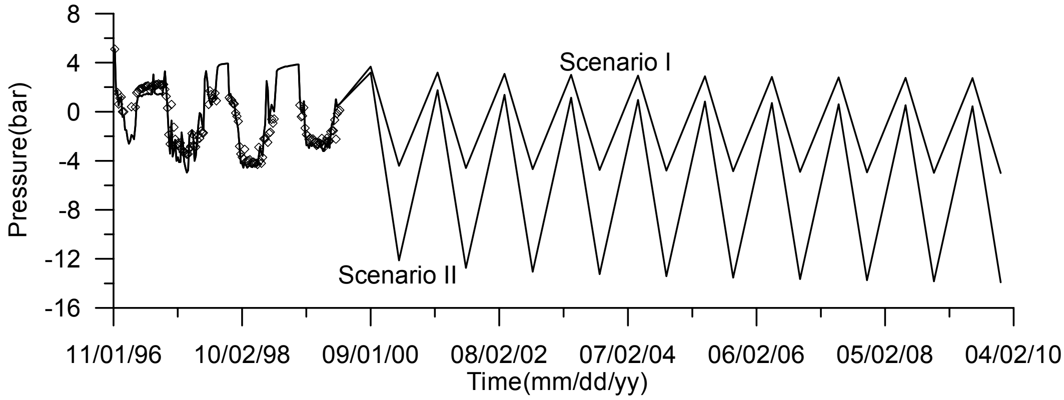

FIGURE 25: Predicted water level curves for well FGG3 in Galanta for production scenarios I and II

It is obvious that if the current production of wells FGG2 and FGG3 is maintained, the reservoir pressure will approximately stabilize, according to the model.

Scenario II: Taking the maximum allowable drawdown into account, production for the next ten years is assumed as follows:

Annual average production: FGG2 - 21.6 l/s, FGG3 - 20.3 l/s;
Production in heating season: FGG2 - 39 l/s, FGG3 - 38.5 l/s;
Production in non-heating season: FGG2 - 4.3 l/s, FGG3 - 2 l/s.

The water level predictions, calculated by the analytical distributed parameter model, are presented in Figures 24 and 25, which show the water level variations in wells FGG2 and FGG3 for the next ten years. Figure 26 illustrates the water level contours at the end of the prediction period on Mar. 31, 2010, calculated by the distributed model. Comparing Figures 26 and 18, it is clear that the water level drawdown for scenario II will be much greater and more extensive over the entire reservoir at the end of the prediction period, than is currently the case.

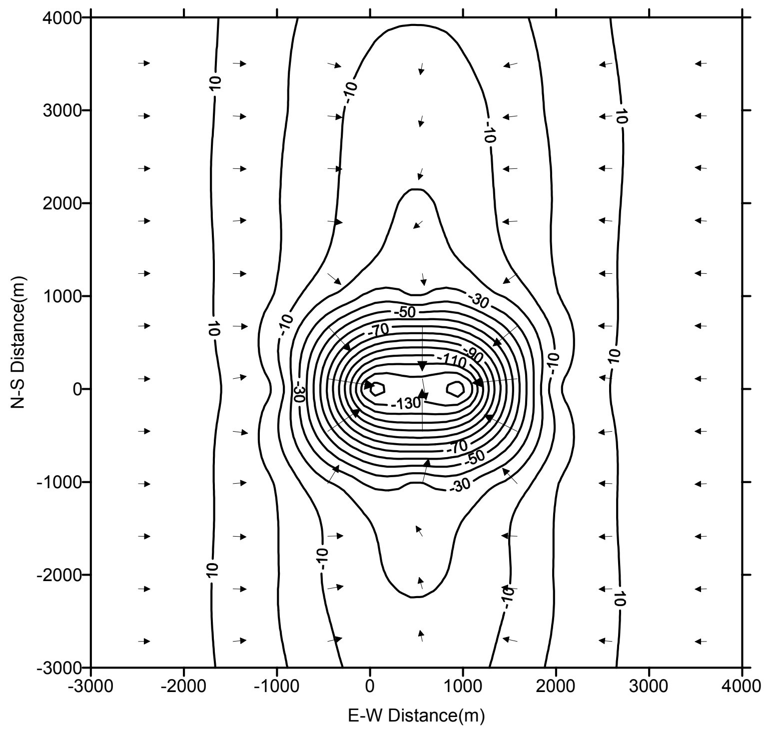

FIGURE 26: Predicted water level contours in Galanta on March 31, 2010 for production scenario II

From Figures 24-26, it can be seen that the greatest water level drawdown for scenario I is about 90 m, while that for scenario II is approximately 199 m. In light of these results, and considering the maximum allowable drawdown of 200 m, the production potential for the Galanta geothermal reservoir is assessed to be 42 l/s on average for the next ten years, or 1.3 million tons per year. The maximum extractable production in the heating season is estimated at 78 l/s.

It must be emphasized that the production potential evaluated is based solely on the present production of wells FGG2 and FGG3. No new production wells are incorporated due to the limited geological and geothermal information available. With the continuation of reservoir exploration, the exploitation extent of the whole reservoir may be evaluated, and then it is possible to determine if and where new wells can be planned. Consequently, the production potential can be updated and refined.

6. PRODUCTION POTENTIAL WITH RESPECT TO REINJECTION

6.1 Production potential with respect to reinjection for the Dezhou geothermal reservoir

In view of the land subsidence in the Dezhou area, reinjection is suggested as part of the field management in future. It would aim at:

- Maintaining reservoir pressure, i.e. to counteract the water level drawdown;
- Extracting more thermal energy from reservoir rocks;
- Improving efficiency and increasing longevity;
- Mitigating land subsidence.

As a result, reinjection would contribute to the sustainable development of the reservoir.

The analytical distributed parameter model already established is used to estimate the effects of long-term reinjection. Two cases are considered:

- Three reinjection wells, with a 30 l/s injection rate for each well in the heating season (Nov.-Mar.), are considered in the model. The distances between production and injection wells are no less than 1000 m. The calculated water level recovery in well DR1 is shown in Figure 27.
- Six injection wells, with a 30 l/s injection rate for each well in the heating season (Nov.-Mar.), are considered in the model. The distances between production and injection wells are no less than 1000 m. The water level recovery in well DR1 is shown in Figure 27.

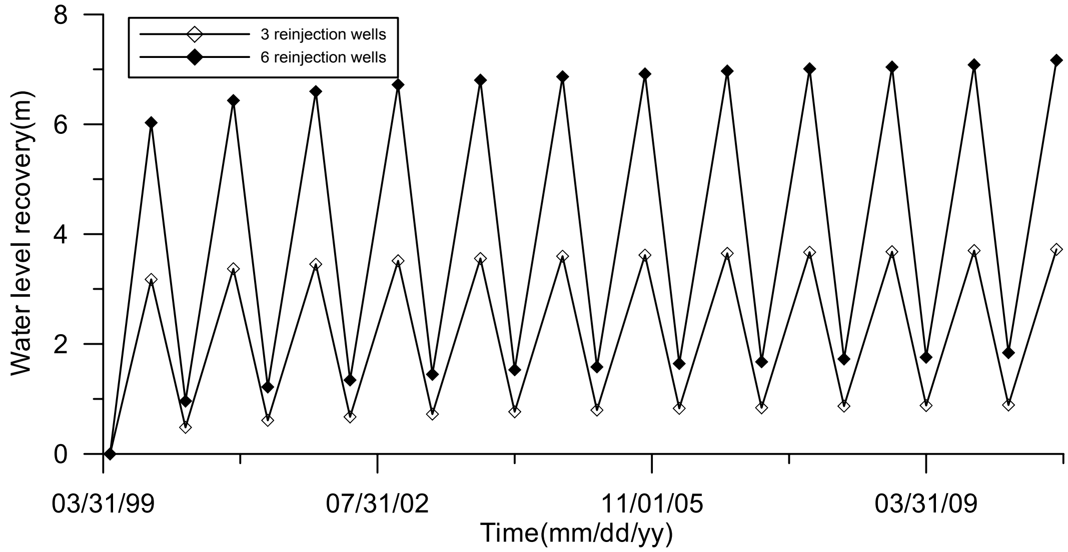

FIGURE 27: Predicted water level recovery in well DR1 in Dezhou resulting from three and six reinjection wells with 30 l/s injection rate each in the heating season

From Figure 27, it is obvious that the water level recovery for three reinjection wells is approximately 4 m in the long run and 8 m for six wells. As a result, the production potential of the Dezhou reservoir is approximately increased by 3% and 7%, respectively.

It should be noted that both the positive and negative effects of reinjection must be taken into account, simultaneously. On the one hand, benefit is maximized by locating injection wells as close as possible to production wells; on the other hand, cooling is minimized by siting injection wells far away from production wells. A proper equilibrium between positive and negative requirements must be selected (Axelsson et al., 1998), i.e. the locations of reinjection wells must be chosen to balance these two effects.

The thermal breakthrough time of an extensive horizontal sedimentary reservoir may be estimated by:

$$t = -\frac{r_o^2 \pi H <\rho\beta>}{\beta_w Q} \tag{6}$$

where t = Thermal breakthrough time [s];
r_o = Radial distance from reinjection well [m];
H = Reservoir thickness [m];
$<\rho\beta>$ = Average volumetric heat capacity of reservoir, i.e. $\phi\beta_w\rho_w + (1-\phi)\beta_r\rho_r)$ [J/m^3/°C];
β_w = Heat capacity of water [J/kg/°C];
ρ_w = Water density [kg/m^3];
ϕ = Rock porosity;
β_r = Heat capacity of rock [kg/m^3];
ρ_r = Rock density [kg/m^3].

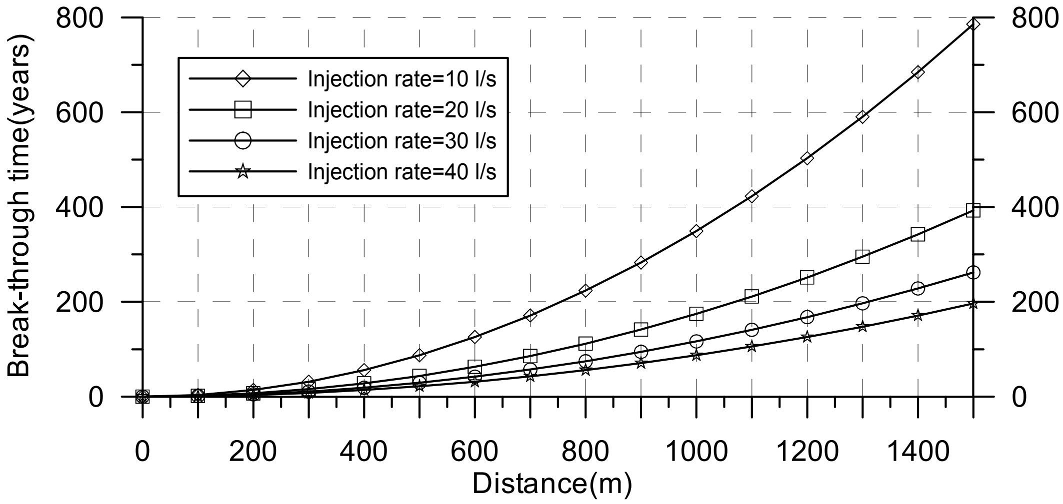

FIGURE 28: Estimated cold front breakthrough time as a function of distance from reinjection to production wells, for different average reinjection rates, in a horizontal sedimentary reservoir 56.7 m thick

The breakthrough time is calculated as a function of the distance between reinjection and production wells for assumed average injection rates of 10, 20, 30, 40 l/s, respectively. The results are presented in Figure 28. It should be pointed out that the thickness of the reservoir used in the above equation is 56.7 m, approximately 1/3 of the actual thickness of the reservoir. This is for safety reasons to minimize the danger of actual colder water intrusion through flow channels in feed-zones.

In accordance with a conservative criterion that the cooling front breakthough time must not occur until 100 years hence, and an average reinjection rate of 30 l/s, the minimum distance between reinjection and production wells must be on the order of 1000 m.

Another side effect of reinjection besides cooling is the significant decrease of injectivity in sandstone reservoirs. The aquifers next to the injection well, or slotted liners, become clogged with fine sand and precipitation particles, causing reduction of permeability. One of the maintenance solutions used is flow-reversal, i.e. to install a down-hole pump in the injection well, which is used to produce the well for a few hours once its injectivity has dropped after a period of reinjection. During a reinjection test in the Tanggu field in NE-China in 1996, the injection well needed to be cleaned after 7-11 days of injection (Axelsson and Dong, 1998). After cleaning, its injectivity was fully restored. Another solution involves a sophisticated closed loop system wherein the reinjection water is kept completely oxygen-free and passes through very fine filters (one micron) before it is injected (Axelsson, 2000). This later, more advanced solution, is now being applied in several sandstone reservoirs.

6.2 Production potential with respect to reinjection for the Galanta geothermal reservoir

In accordance with the great water level drawdown, approximately 85 m, which has occurred in wells FGG2 and FGG3, reinjection should also be considered for the Galanta reservoir.

The already established analytical distributed parameter model is used here to evaluate the influence of long-term reinjection. Two reinjection wells, each with a 30 l/s injection rate during the heating season (Nov.-Mar.), are assumed in the model. The distance between production and reinjection wells is about 1000 m. The pressure changes with two injection wells and water level recovery along with the pressure changes under the condition of scenario II are presented in Figure 29.

It can be seen from Figure 29 that the water level recovery for two injection wells is about 58 m over a ten-year long run. As a consequence, the production potential of the Galanta reservoir will be increased by approximately 29%.

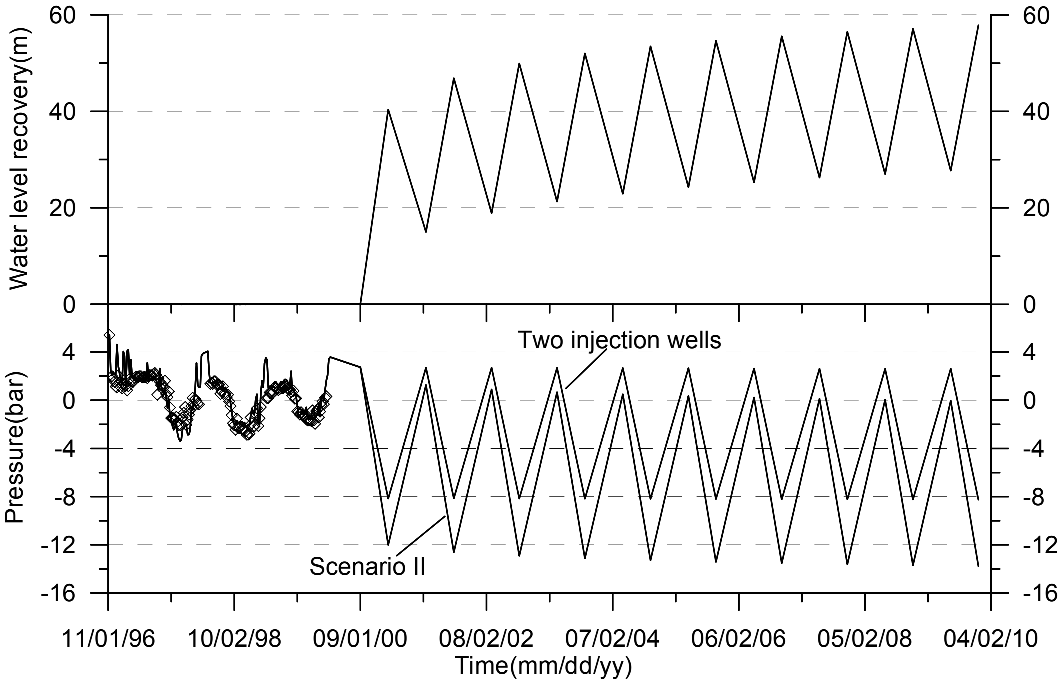

FIGURE 29: Pressure fluctuations with two injection wells and its water level recovery for well FGG2, combined with pressure variations under the condition of scenario II

7. SUMMARY

7.1 Summary for the Dezhou reservoir

- The Dezhou geothermal reservoir is a low-temperature sedimentary sandstone reservoir, with conduction-dominated thermal flow. The main aquifer is in the Upper Tertiary Guantao formation, with an average permeability of 6.6 Darcy. Its thickness varies from 160 to 180 m at depths between 1350 and 1650 m, covering an area of 169 km^2. The reservoir temperature ranges from 46 to 58˚C. In its initial state, the reservoir is artesian, with an initial pressure of approximately 0.7 bars.
- The Dezhou geothermal reservoir is still in its natural state. Only two wells have been drilled, with small production. The reservoir evaluation is based on a seven-day pumping test.
- On the basis of the conceptual model and analyses of pumping test data from the Dezhou geothermal reservoir, an analytical distributed parameter model, approximately in agreement with the reservoir conditions, and a lumped parameter model, have been established to estimate the production potential and to predict the reservoir response to long-term production and reinjection. Both models simulate the observed water level variations quite accurately. Based on a maximum allowable drawdown of 100 m, the production potential is estimated as 220 l/s on average for the next ten years, or 6.9 million tons per year. The allowable maximum production in the heating season is 360 l/s.
- Considering both the positive (water level rise) and negative (cooling) effects, the allowable minimum distance between production and reinjection wells is determined as 1000 m. Based on this, three reinjection wells and six reinjection wells were considered in the distributed model, respectively. The corresponding water level rise is approximately 4 m and 8 m, respectively, over a ten-year period. As a result, the production potential of the Dezhou reservoir would be approximately increased by 3% and 7%, respectively.

- As there are only a few geothermal production wells, and limited field observation data is available at this time, the modelling is based on a seven-day well test. It should be pointed out that the model must be updated and refined as new production and response data becomes available.
- Monitoring is essential for model updating and refining, and is also one of the most important parts of geothermal management. Hence, it is recommended that with the exploitation of the geothermal reservoir, a comprehensive observation system be established, not only including water level, flow rate, and water temperature, but also water chemistry, corrosion, scaling and land subsidence.
- Reinjection is an important option for reservoir management, especially as subsidence has already occurred in the Dezhou field. A tracer test is suggested prior to reinjection to confirm the current model of the reservoir.

7.2 Summary for the Galanta reservoir

- The Galanta geothermal reservoir is also a low-temperature sedimentary reservoir, with conduction-dominated thermal flow. The reservoir aquifer is in sandstone of Pliocene age, with an average permeability of 0.14 Darcy. Its average thickness is 113 m at depths between 1000 and 2500 m. The reservoir temperature ranges from 49 to 126˚C corresponding to depths from 1000 to 3000 m. In the initial state, the reservoir is artesian, with an initial pressure of approximately 5.2 bars.
- The Galanta geothermal reservoir is produced by wells FGG2 and FGG3, with an average total production of 20.6 l/s. The reservoir evaluation is based on long-term observation data of wells FGG2 and FGG3 from Nov. 1, 1996 to May 15, 2000.
- On the basis of the conceptual model and long-term observation data of wells FGG2 and FGG3, an analytical distributed parameter model, approximately in agreement with reservoir conditions, and a lumped parameter model, were established to estimate the production potential and to predict the reservoir response due to long-term production and reinjection. Both models simulated the observed water level variations quite well. Based on a maximum allowable drawdown of 200 m, the production potential is estimated to be 42 l/s on average for the next ten years, or 1.3 million tons per year. The allowable maximum production in the heating season is 78 l/s.
- Considering both the positive (water level rise) and negative (cooling) effects, the allowable minimum distance between production and reinjection wells is determined as 1000 m. Based on this, two reinjection wells were considered in the distributed model, resulting in a water level rise of approximately 58 m over a ten-year period. Consequently, the production potential of the Galanta reservoir would be increased by approximately 29%.
- As there is only a limited amount of subsurface geothermal information available, it should be noted that the model must be updated and refined as new exploration information, and production and response data become available.
- Reinjection is an essential option for the reservoir management, especially since a great water level drawdown of approximately 85 m has already occurred in the Galanta field. A tracer test is suggested prior to reinjection to confirm the current model of the reservoir.

7.3 Summary for sedimentary reservoirs

- Sedimentary geothermal reservoirs, distributed worldwide, are characterized by large areal extent, fairly homogeneous and quite productive aquifers, as well as great energy potential, compared with many smaller fractured geothermal reservoirs.
- Both analytical distributed analytical models and lumped parameter models are able to calculate and evaluate reservoir potentials, with acceptable accuracy. Comparatively, the distributed parameter model is more suitable for a well field composed of several production and/or reinjection wells, since it can calculate the interference between different wells; but it needs much

more data and requires more time. A lumped parameter model is more appropriate either for a single well, or for taking the reservoir as a whole. It is quite effective and requires very little time for calculation of either long-term production monitoring data over several decades or short pumping test data for several days.

- The basic tasks and main objectives of sedimentary reservoir engineering are the assessment of production potential and response prediction for the long-term behaviour of wells and reservoirs, including water level or pressure changes and their side effects, such as land subsidence. To fulfil this aim, the maximum allowable water level drawdown should be determined carefully as a precondition of reservoir evaluation. In other words, production potential is drawdown dependent.
- The following factors should be emphasized in determining maximum allowable drawdown of sedimentary reservoirs: the setting depths of well pumps, design of the production wells, the risk of colder water inflow and land subsidence.
- Sustainability is a primary concern in any geothermal field development (Sarmiento, 2000). Monitoring provides up-to-date information of the equilibrium situation between reservoir withdraw and recharge. Hence, continuous monitoring should be undertaken to enable operators to discern negative or positive signatures on variations of field characteristics.
- It should be noted that reinjection is a very effective countermeasure for the sustainable development of geothermal reservoirs in order to maintain reservoir pressure, counteract water level drawdown, extract more thermal energy from reservoir rocks, improve efficiency, increase longevity, and mitigate land subsidence. Therefore, one of the main priorities of comprehensive management strategies for sedimentary reservoirs is reinjection. Another option is improving energy efficiency, in part through cascaded utilization of geothermal water.
- Economic instruments (O'Shaughnessy, 2000) are also very effective in achieving positive environmental results during the development of sedimentary reservoirs. Economic instruments associated with environmental management generally take two forms: (i) punitive: a cost (usually a tax) is imposed on an environmentally unacceptable activity so that, as a result of its magnitude, a person or organisation carrying out the activity either accepts the penalty, abandons the activity, or modifies the activity such that the penalty is applied with less severity; (ii) incentive: a reward is provided for implementing a specific action, which either avoids or mitigates an adverse environmental effect.

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