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ASSESSMENT OF GEOTHERMAL RESOURCES IN XIANYANG, SHAANXI PROVINCE, CHINA: LUMPED PARAMETER MODELLING AND PREDICTIONS

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ABSTRACT

The Xianyang geothermal field, located in Shaanxi province in the People´s Republic of China, is rich in low-temperature geothermal resources, having considerable flow-capacity, with the Wei River northern bank fault playing a key role in geothermal activity. Today more than 30 wells, ranging in depth from 1602 to 4080 m, have been drilled in the region with temperatures ranging from 55 to 120°C. The geothermal water is suitable for district heating and balneology. Since the first well was drilled in 1993, geothermal space heating has been developed to take the place of coal boilers and so far approximately 3 million m^2 of geothermal space heating have been established , which is equivalent to reducing 120,000 tons of CO_2 emissions annually; these numbers are continually increasing. A conceptual reservoir model was set up that explains the heat source, recharge zone and reservoir size, based on the available geological and geophysical information. Lumped parameter modelling is used for simulating pressure response data and predicting future water level variations. The results of a 20-year prediction show that the water level of Sanpu 1, Sanpu 2 and WR 3 will drop 1.1, 5.0 and 2.0 m per year according to pessimistic closed models, respectively, if the present production rate is maintained. In contrast, predictions with open models shows an optimistic future in which the water level of Sanpu 1, Sanpu 2 and WR 3 will remain stable at 0.36 MPa, 0.05 MPa and 53 m under the ground, respectively. A prediction with 30% injection results in a tendency where the water level decline slows down. The permeability of the Xianyang reservoir is estimated to be in the range of 6-24 mD according to simulation parameters. The results of pressure interference calculations indicate that over the past ten years considerable interference should have occurred between wells.

1. INTRODUCTION

The city of Xianyang (Figure 1) lies in the centre of Shaanxi Province of the People´s Republic of China and is located at latitude 34°11′ to 35°32′ and longitude 107°98′ to 109°10′. It is around 25 km northwest of Xian, the Shaanxi capital today. Xianyang city is the capital of the prefecture-level division of Xianyang, an administrative area of the Shaanxi province with 5 million inhabitants in 13 counties. There are around 600,000 inhabitants in Xianyang City and its vicinity, the city being located at the confluence of the Wei (a branch of the Yellow River) and Feng Rivers. Xianyang is

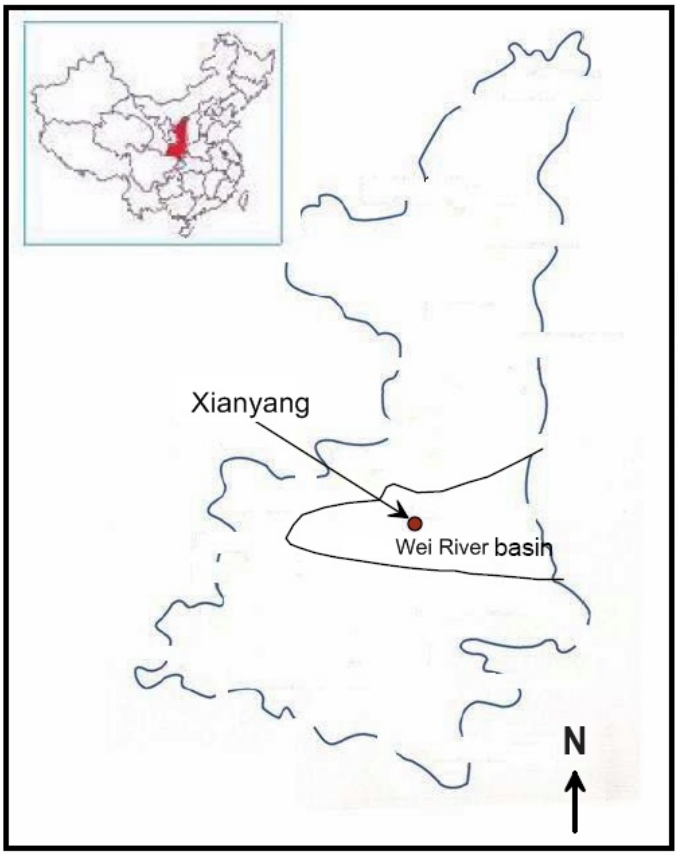

FIGURE 1: The location of Xianyang geothermal field

devoted to industrial activities, with a focus on the textile and electronics industries. Xianyang was the capital of China more than 2000 years ago. Today this region is well known, a.o.t. for its large man-sized terracotta warrior army located in the Mausoleum of the First Qin Emperor.

The southeast of Xianyang Division is rich in low-temperature geothermal resources. Geothermal water has been produced from 1993 in the Xianyang geothermal field for house heating in the cities of Xianyang and Xingping, and the towns of Wugong, Liquan and Sanyuan, which are located southeast of this Division. The exploitation and utilization of geothermal resources in the Xianyang geothermal field has had obvious economic, social and environmental benefits. The geothermal water has been used for space heating during the wintertime, as well as for hot tap water, balneology and medical purposes. In the year 2006, Shaanxi Green Energy Geothermal Development Co. Ltd. was established. The company is an Iceland-China joint venture, whose shareholders are ENEX-China and the Sinopec Group. Sinopec Group is the biggest state-owned enterprise in China and climbed to No. 9 among the Fortune 500 companies in 2009. This company has already set up a district heating network providing heating to 1 million m^2 of housing in Xianyang City, based on Icelandic geothermal techniques with a computerized automatic monitoring system for the purpose of reservoir management.

Axelsson and Ármannsson (2005) present the results of an initial resource feasibility and potential assessment study for the Xianyang City geothermal resource. A series of data has been collected and is analysed in the study. Erlingsson et al. (2009) describe Xianyang geothermal district heating system.

The main purpose of this study is to evaluate pressure changes in the reservoir since 2005, estimate reservoir properties and predict future pressure changes in order to estimate production capacity. This is mainly done by lumped parameter modelling. First, a conceptual model will be established based on the geological information. Then simulation is done using a lumped parameter model to estimate reservoir properties and obtain parameters for further prediction. Finally, pressure changes of different scenarios in the coming 20 years will be predicted. Additionally, some important properties of the reservoir, such as permeability and pressure interference between wells, will also be calculated.

2. BACKGROUND

2.1 Wei River sediment basin

The Wei River Basin lies on the Middle and Lower Wei River in central Shaanxi Province. It spreads east to Tongguan, west to Baoji, north to Beishan, and south to Qinling. It’s about 300 km long from

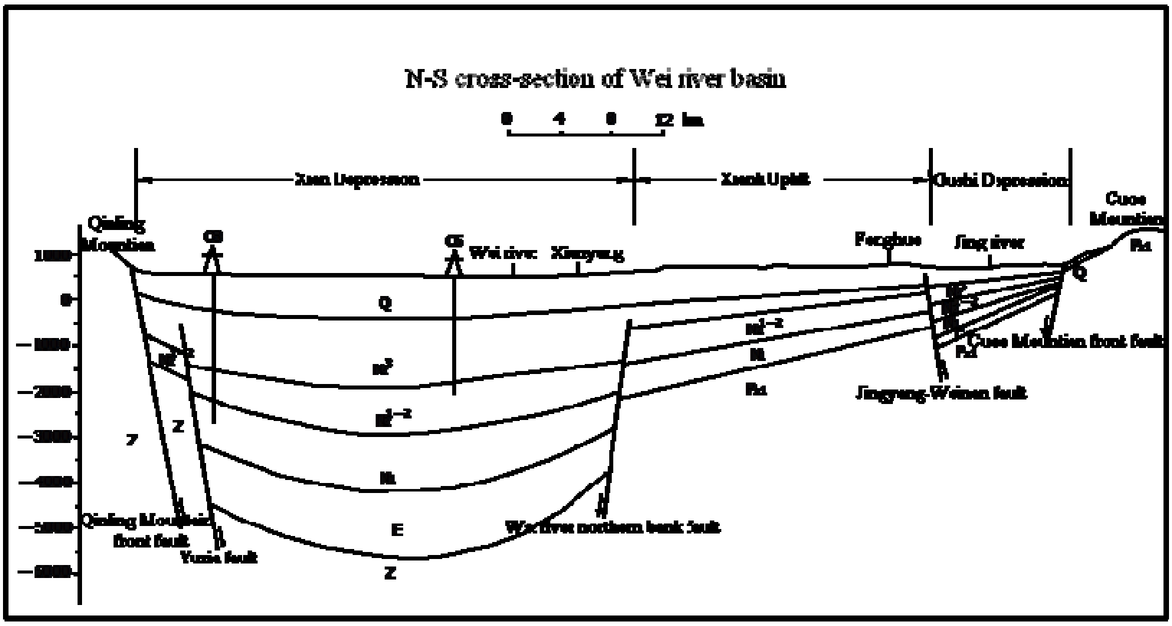

FIGURE 2: N-S geological cross-section of the Wei river sediment basin

east to west and 60 km wide from north to south, covering an area of about 20,000 km^2. As shown in Figure 2, the Wei river basin is a symmetrical half graben basin, deep in the south and shallow in the north, lying between the steep Qinling Mountain and a gradual northern hilly region. A fault developed in the basin, and divided it into many structural units with different protruding or depressive shapes. Xianyang urban area lies on a gradual slope on the northern Xian depression, a second order unit of Wei River basin. The whole northern gradual slope belt is divided into three third order fault steps by the Wei River northern bank fault and the Liquan fault. The northernmost fault step is Qianxian higher fault step. The southernmost is the Xianyang lower fault step. Between them is the Liquan middle fault step. All of them consist of a gradual slope, which decreases from north to south in turn with an approximate east-west strike and a south dip. Wei River northern bank fault is 170 km long, its strike is north-northeasterly, and it is a tensile normal fault with an upward foot wall, a downward hanging wall and a dip angle of 80°. Low-temperature springs are distributed along the fault line. Quite a few geothermal wells have been drilled near the fault belt (Zou, 2007).

At the same time, the Wei River northern bank fault divides the bedrock into two parts. Bedrock north of the fault is lower Paleozoic carbonate rock, and bedrock in the south is Proterozoic metamorphic rock and intrusive rock formed during the Yanshan period (Wang, 2006). There is an obvious difference between the two. There is a thicker Lower Tertiary stratum south of the fault but this stratum is lost in the north. Upper Tertiary strata in this area are thick in the south and thin in the north, and show a great difference in thickness, up to 700 m. This fault is also a Quaternary landform boundary between a second erosion-accumulation terrace and a third erosion terrace on the northern bank of the Wei River, demonstrating that the fault has been active recently (Chen et al., 1977).

Considering the Wei River northern bank fault as a boundary, the thickness of the Cenozoic strata is in the range of 4000-5000 m above the southern Proterozoic metamorphic bedrock and thickens from the area near the fault to the southern area. The basin contains Tertiary sediments; later on sedimentation accelerated gradually and formed very thick Cenozoic sediments which are widely distributed. They are divided into several stratigraphic formations or groups: Quaternary Qinchuan group ($Q_{2\text{-}4}$qc), Sanmen formation (Q_1s), the Upper Tertiary Zhangjiapo formation (N_2^2z), the Upper Tertiary Lantian-bahe formation (N_2^1l+b), the Gaoling group (N_1gl), the Lower Tertiary Bailuyuan formation (E_3b), and the Lower Tertiary Honghe formation (E_2h). Four of these are considered to comprise a good hot water reservoir and now yield geothermal water. They are:

1) The Upper Tertiary Zhangjiapo formation with a thickness in the range of 580-1100 m with an average porosity of around 26%. It is composed of isopach alternating layers of mudstone and siltstone with the colour of mostly light brown-red mudstone, at intervals blue-gray, light gray fine sandstone siltstone and sandstone with a characteristic of diagenesis and muddy cement**.**
2) The Upper Tertiary Lantian-Bahe formation with a thickness in the range of 600-1000 m, with an average porosity of around 24%. The upper and middle part of the formation is non-isopach alternating layers composed of brown mudstone and sandstone and gray-white fine- to medium-grained sandstone. The lower part is an isopach alternating layer composed of gray-white coarse pebbled and argillaceous sandstone and brown mudstone with a characteristic of diagenesis and muddy cement**.** This formation is the most productive.
3) The Upper Tertiary Gaoling formation with a thickness in the range of 600-800 m with an average porosity of around 21%. It consists of non-isopach alternating layers composed of brown mudstone and silty mudstone and gray-white pebble coarse sandstone, fine sandstone, siltstone and argillaceous sandstone with a characteristic of diagenesis and muddy cement. The upper part of the sandstone is finer than the lower part.
4) The Lower Tertiary Bailuyuan formation, found below them, also consists of alternating layers of sandstone and mudstone. It has even higher temperatures and has been tapped by a limited numbers of wells in Xian. The thickness of the information is between 500 and 600 m. The upper part of the formation is a non-isopach alternating layer of dark brown and gray-yellow mudstone, silty mudstone and light gray and gray-white siltstone, fine sandstone and medium-grained sandstone. The lower part is composed of brown mudstone and silty mudstone and gray-white pebble coarse sandstone (Zhang et al., 2007).

North of the fault, the depth of the bedrock face (consisting of Lower Paleozoic carbonate rock) changes gradually from 3000 m by the southern boundary near the fault to 2000 m in Liquan County in the northern basin, due to the Xianli Uplift which is a slope with dip towards the south. It has lost the Lower Tertiary rock and developed Upper Tertiary and Quaternary rock. The thickness of the sediment has reduced; the lithology becomes gradually coarse from south to north. Thickness of the same stratum is 200-300 m thicker than that north of the fault. Minerals identified in the reservoir rocks include analcime, Na-feldspar, calcite, dolomite, quartz, clinochlore, fluorite, muscovite, chalcedony, goethite, anhydrite, and chrysotile (Tian and Zheng, 1995).

The Wei River northern bank fault is believed to be the most important fault. The fault and the limestone beneath the Tertiary stratum, and north of the fault, play a role of weak recharge for the main production layer. In addition, the geothermal field is divided into two parts by the Wei River northern bank fault due to the different reservoir properties on either side.

2.2 Pressure and temperature information

The pressure of most wells demonstrates a relatively stable drop after production starts. The pressure of the wells north of and close to the Wei River northern bank fault declined 1.1-2.8 m per year, but those south of Xianyang declined more severely. Several extreme examples include: the well head pressure of well Pianzhuan, which declined 13.6 m per year, and well Tianyun which declined 5.7 m per year. The worst well is Lvlang. Its wellhead pressure of 1.2 MPa changed to 60 m water level depth. The location of all wells presented in this report is shown in Figure 3.

The wellhead temperature in Xianyang is between 55 and 120°C. The granite rock mass of over 8000 km^2, containing radioactive isotopes ^{235}U, ^{238}U, ^{232}Th and K, underlies the west side of the Wei River basin. It is a heat resource of the geothermal basin and leads to a weak anomaly of thermal gradient west of Wei River basin. The overall thermal gradient is in the range of 32-37 °C/km in the whole basin. The thermal gradient of any location increases linearly in the basin. Figure 4 shows a perfectly constant thermal gradient for one of the production wells.

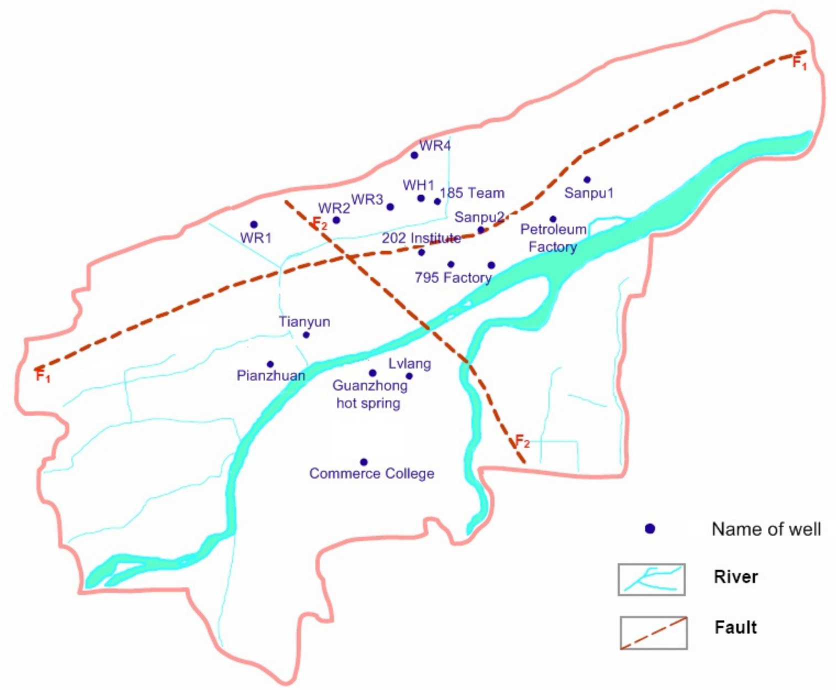

FIGURE 3: Location of wells in Xianyang City discussed here

2.3 Analysis of the well test data

Pumping test data of 12 wells, collected at the end of drilling, were selected from the wells of Xianyang city in order to estimate the hydrological properties of the reservoir. Their locations are presented in Figure 3. These data were used to simulate the relationship between the water level and the flow rate to correct for the friction and turbulent flow in the wells. The water level in the flowing wells is described by the following equation (Han, 2008):

$$H = H_0 + B \times Q + C \times Q^2 \tag{1}$$

where Q is the flow rate;
H_0 is the water level in the well at zero flow (static well);
$B \times Q$ is the linear drawdown in the reservoir;
$C \times Q^2$ is the pressure loss caused by turbulent flow at the location of inflow into the well and in the well itself.

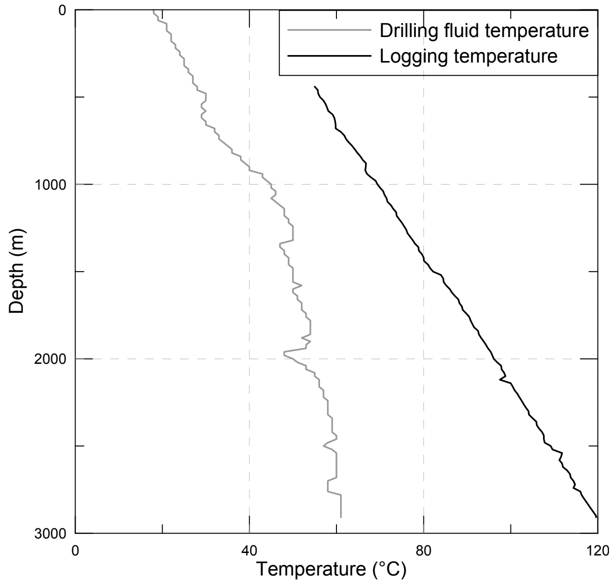

FIGURE 4: Temperature profiles for well WR 4

The simulation results, using the well test data, can be used for estimating the relationship between the water level and flow rate. The coefficients of each well are as follows:

WR 4: $H = -4.536 + 0.3221Q + 0.002144Q^2$
WR 3: $H = -3.890 + 0.5619Q + 0.003751Q^2$
WR 2: $H = -1.867 + 0.1315Q + 0.01325Q^2$
WR 1: $H = -1.072 + 0.08095Q + 0.009297Q^2$
Sanpu 2: $H = 34.46 - 1.669Q + 0.03816Q^2$

Sanpu 1: $H = -5.835 + 0.8117Q + 0.008220Q^2$
Guanzhong hot spring: $H = 53.23 - 1.334Q + 0.03683Q^2$
Commerce College: $H = -16.79 + 1.181Q + 0.004120Q^2$
185 team: $H = 11.28 - 0.8180Q + 0.05801Q^2$
Pianzhuan: $H = 64.20 - 5.935Q + 0.1989Q^2$
795 factory: $H = 6.331 - 0.2380Q + 0.01037Q^2$
202 institute: $H = 3.690 + 0.5754Q + 0.01005Q^2$

The simulation results are shown in Figure 5. There it is observed that the results for the geothermal wells have almost the same shape and that the geothermal wells located south of Xianyang City have a relatively poorer production potential and recharge than wells north of the city. The production capability of Xianyang reservoir is rather high and behaves similarly to that of a basalt reservoir, which is rarely seen in sandstone reservoirs.

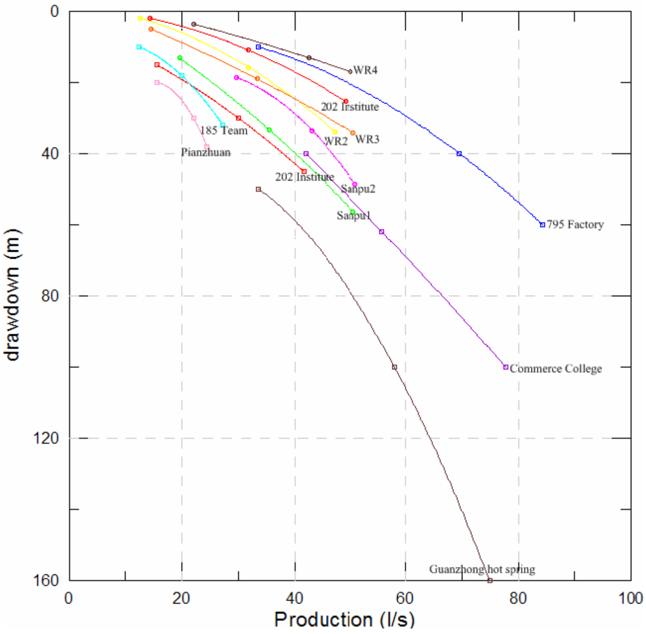

FIGURE 5: Simulation results of well test data in Xianyang

2.4 Geothermal fluid chemical features

The chemical composition of the geothermal water of the wells discussed here is shown in Table 1. Concentrations of K^++Na^+, Ca^{2+}, Cl^-, mineralization degree and total hardness decrease gradually from

TABLE 1: Chemical components of geothermal water (mg/l) of wells discussed in this report

	Sanpu 1		**Sanpu 2**		**WR 3**	
	1998.10	**2008.02**	**2004.07**	**2008.02**	**2007.10**	**2008.02**
K^+	37	20	85	20	40	20
Na^+	2315	1884.4	1850	1884.4	1932.4	2011.1
Ca^{2+}	94.2	75.2	82.2	75.2	76.2	83.2
Mg^{2+}	20	22.5	16.6	21.3	23.1	18.8
$NH4^+$	1.1	1	1	1	0.8	0.8
Fe^{2+} & Fe^{3+}	0.088	0.098	0.67	0.179	0.123	0.139
Cl^-	3190.5	3013.2	2570.1	2446	2632.2	2711.9
SO_4^{2-}	386.6	437.1	438	456.3	398.7	427.5
HCO_3^-	329.5	326.4	353.9	381.4	317.3	335.6
F^-	2.57	1.74	2.04	1.82	1.29	1.7
Mineralizat. degree	6436.8	6281.2	5941	5660.7	5882.7	5839.8
COD	-7.1	10.4	13.3	11.4	42.1	11.5
H_2SiO_3	69.9	60.4	70.2	69.2	22.9	61.4
CO_2	26.4	15.4	4.4	13.2	17.6	8.8
Sulphide			0	0.2	0	
H_2S			0	0.1	0	
HBO_2	166	217.2	252.9	314.2	248.4	298
Br-	15.7	19.4	21	16.1	16.7	16.8
I-	12.4	15.5	14.1	13.9	13.4	14.6
H_3BO_3		306.3	355.9	443	350.2	420.2
Li	0.861	0.71	1.01	0.8	0.7	0.71
pH	7.3	7.5	8	7.5	7.6	7.7

the Wei River northern bank fault to the south part. These components, also, decrease slowly from the upper part to the lower part of the region. The horizontal variation is larger than the vertical one. In contrast, the concentration of SO_4^{2-} tends to increase gradually from the Wei River northern bank fault to the south, and also increases slowly from the upper part to the deeper part. Consequently, the chemical components of the geothermal water change. It is Cl-Na type along the fault, then gradually changes southward to $Cl - HCO_3 - Na$ type, and finally to $HCO_3 - SO_4 - Na$ type along the Wei River southern bank. Concentrations of various ions tend to decrease from the upper part to the deeper part of the area, but the chemical type of geothermal water does not change.

In addition, the concentrations of micro elements in the geothermal water in Xianyang, such as F, Sr, Ba, I, Si, As and B, are enriched and play multiple roles in balneology. The water brings great economic benefits to the local population. At the same time, return water treatment is quite important before reinjection is executed.

3. MODELLING OF XIANYANG GEOTHERMAL FIELD

3.1 Conceptual reservoir model

The conceptual reservoir model of the Xianyang geothermal system incorporates all the available physical features that have been obtained through exploration drilling, geophysical surveys and other investigations. Temperature and pressure data are the essential data for constructing a good model. A good model can provide information on the heat source mechanism, recharge conditions and other important information concerning the reservoir. The basic geological structures behind the conceptual reservoir model of the Xianyang geothermal system are shown in Figure 2. This information was acquired by a petroleum geological survey and drilling during earlier times and from a geothermal feasibility study and drilling in recent years. The basic structures of the conceptual model Xianyang conceptual model are:

1) Quaternary Qinchuan group ($Q_{2\text{-}4}qc$), considered the caprock of the Xianyang reservoir. The thickness is in the range of 350-550 m.
2) The Upper Tertiary Zhangjiapo formation (N_2^2z), Upper Tertiary Lantian-bahe formation (N_2^1l+b) and Gaoling group (N_1gl) are considered the main reservoirs of the Xianyang geothermal system. These layers are composed of alternating sandstone and mudstone layers and the total thickness is in the range of 1780-3000 m. Details are presented in Section 2.1.
3) Wei River northern bank fault, Chang'an-lintong fault, Qinling Mountain front fault and limestone beneath the Tertiary stratum and north of Wei River northern bank fault contribute a weak recharge for the main production layer and effectually control distribution of the geothermal fluid; for details see Section 2.1.
4) The Xianyang reservoir is a typical low-temperature liquid-dominated sedimentary reservoir. The measured heat flux from the crust is up to 71.6 mW/m^2 and the thermal gradient is 3.2-3.7°C/100 m.

Xianyang city is located in the centre of the Wei river sediment basin; the Xianyang reservoir is artificially separated from the Wei river basin so it is convenient for study. It is a typical confined liquid-dominated reservoir and a part of the Wei river basin. A significant characteristic is the alternating beds of sandstone and mudstone in the Xianyang reservoir, which are considered a single reservoir in this report. The Wei river sediment basin is regarded as a very weak recharge reservoir by most geologists in the region, so here it will be simulated as both a closed reservoir and an open reservoir. Xianyang reservoir will be regarded as a two-dimensional model in the simulation.

3.2 Available data

The data used is from the Shaanxi Green Energy Company. The company was established in late 2006; all its wells were drilled after 2006 except for Sanpu 1 and Sanpu 2, which were purchased from another company. These two wells have a relatively long production history and complete data. These data were selected for analysis. The company has also established an automatic monitoring system, for the production, wellhead pressure and temperature. Well WR 3 has also a fairly complete data set. Therefore, it was also chosen for the study. Basic information on the wells is shown in Table 2. Data used in the report is daily data except where otherwise noted. It includes:

1) Observed wellhead pressure and temperature of Sanpu 1 from 29-Nov-2005 to 18-Mar-2009;
2) Observed wellhead pressure and temperature of Sanpu 2 from 15-Oct-2004 to 25-Jul-2009;
3) Observed water level and temperature of WR 3 from 1-Dec-2007 to 10-May-2009.

TABLE 2: Basic information on wells discussed here

Name of well	**Year drilled**	**Depth (m)**	**Prod. layers (m)**	**Well-head temp. (°C)**
Sanpu 1	1998	2975.5	1806.5-2937.7	90
Sanpu 2	2004	3558	2570.7-3299.3	94
WR 3	2007	2899.5	2060.9-2724.9	84

3.3 Lumped parameter modelling

Axelsson (1989) describes an efficient method that tackles pressure change simulation with lumped parameter models as an inverse problem and can simulate such data very accurately, if the data quality is sufficient, including long data sets (several decades). It automatically fits the analytical response functions of the lumped models to observed data by using a non-linear iterative least-squares technique for estimating the model parameters. Axelsson's paper describes the theoretical basis of this automatic method of lumped parameter modelling.

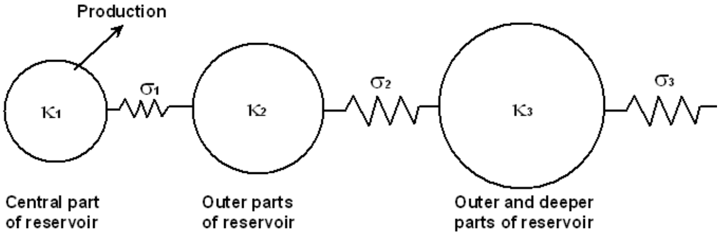

FIGURE 6: An open three-tank lumped parameter model (Axelsson, 1989)

A general lumped model is shown in Figure 6. It consists of a few tanks and flow resistors. The tanks simulate the storage capacity of different parts of a geothermal system; the water level or pressure in the tanks simulates the water level or pressure in corresponding parts of the system. A tank has a storage coefficient (capacitance) κ when it responds to a load of liquid mass m with a pressure increase $p = m/\kappa$. The resistors (conductors) simulate the flow resistance in the reservoir, controlled by the permeability of its rocks. The mass conductance (inverse of resistance) of a resistor is σ when it transfers $q = \sigma\Delta p$ units of liquid mass per unit time, at the impressed pressure differential Δp. The first tank in the model in Figure 6 can be looked upon as simulating the innermost (production) part of the geothermal reservoir, and the second and third tanks simulate the outer parts of the system. The third tank is connected by a resistor to a constant pressure source, which supplies recharge to the geothermal system. The model in Figure 6 is, therefore, open. Without the connection to the constant pressure source the model would be closed. An open model may be considered optimistic, since equilibrium between production and recharge is eventually reached during long-term production, causing the water level draw-down 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 steadily with time, during long-term production. In addition, the model presented in Figure 6 is composed of three tanks; in many instances models with only two tanks have been used.

The *LUMPFIT* program has been developed by employing iterative nonlinear inversion techniques to fit a corresponding solution to the pressure or water level data. In the models, coefficients A_j, L_j and B are functions of the capacitance coefficient κ_j and the conductance coefficient σ_j. The pressure response p of a general open lumped model with N tanks, to a constant production Q since t=0, with initial pressure p_0, can be described by Equation 2 (Axelsson and Arason, 1992):

$$p(t) = p_0 - \sum_{j=1}^{N} Q \frac{A_j}{L_j} [1 - e^{L_j t}] \tag{2}$$

And the pressure response p for a general closed model with N tanks can be described by Equation 3:

$$p(t) = p_0 - \sum_{j=1}^{N-1} Q \frac{A_j}{L_j} [1 - e^{L_j t}] + QBt \tag{3}$$

By using these parameters, the main reservoir properties of the Xianyang geothermal system can be estimated. Water compressibility β_w was estimated to be 5×10^{-10} Pa^{-1}, and the compressibility of the rock matrix β_c, composed of sedimentary rock, is approximately 2×10^{-11} Pa^{-1}. The storativity of a liquid-dominated confined geothermal system can then be estimated using Equation 4:

$$s = \frac{\Delta m}{\Delta p V} = \rho_w [\phi \beta_w + (1 - \phi) \beta_r] \tag{4}$$

Then the value of reservoir storativity can be used to estimate the principal properties and characteristics of the reservoir by assuming two-dimensional flow (Figure 7).

In accordance with the following series of equations, such as the volume of different parts of the reservoir, their area and permeability can be deduced based on the two-dimensional flow model (Guo, 2008):

$$\kappa_1 = V_1 s; \quad \kappa_2 = V_2 s; \quad \kappa_3 = V_3 s \tag{5}$$

where $\kappa_1, \kappa_2, \kappa_3$ are the capacitances of different tanks;
V_1, V_2, V_3 are the volumes of different tanks; and
s is the storativity of the reservoir.

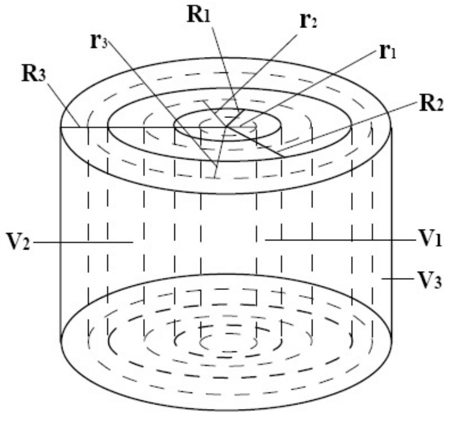

FIGURE 7: Three-tank model with two dimensional flow

Also:

$$R_1 = \sqrt{\frac{V_1}{\pi H}}; \quad R_2 = \sqrt{\frac{V_1 + V_2}{\pi H}}; \quad R_3 = \sqrt{\frac{V_1 + V_2 + V_3}{\pi H}} \tag{6}$$

where R_1, R_2, R_3 are the radiuses of different tanks;
H is the thickness of the reservoir.

Furthermore:

$$r_1 = R_1/2; \quad r_2 = R_1 + (R_2 - R_1)/2; \quad r_3 = R_2 + (R_3 - R_2)/2 \tag{7}$$

where r_1, r_2, r_3 are the half radiuses of different tanks.

Finally:

$$k_i = \sigma_j \frac{\ln \left({}^{r_{i+1}}/_{r_i}\right) v}{2\pi H} \tag{8}$$

where k_i is the permeability of the different parts of the reservoir;
r_i is the half radius of different tanks;
σ_j is the conductance between tanks; and
v is the viscosity of geothermal fluid.

3.4 Simulation

The production potential of a geothermal system is predominantly determined by pressure decline due to production. If the energy supply is sufficient, the drawdown becomes the unique influence on the production capacity of a geothermal system. In order to evaluate the potential of the Xianyang geothermal field, lumped parameter models were used to simulate and predict pressure variations in this report. The parameters obtained from the simulations were used to calculate reservoir properties, such as reservoir volume and average permeability.

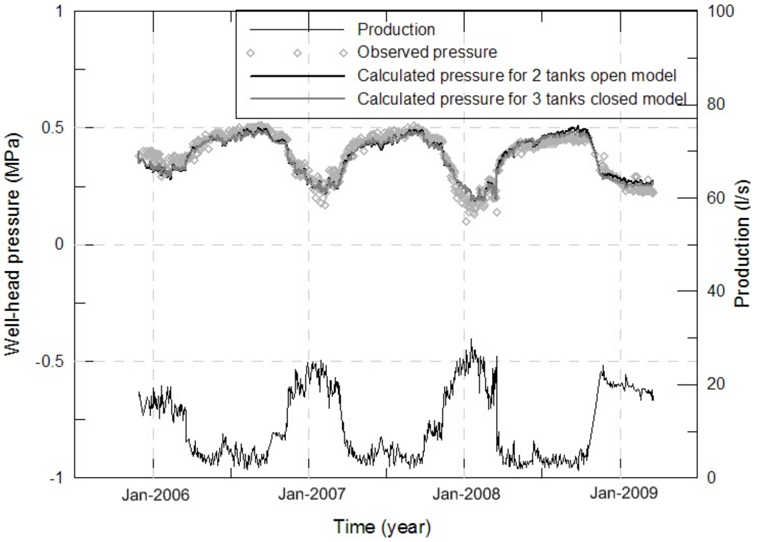

FIGURE 8: Simulation result of well Sanpu 1 using a two-tank open model and a three tank closed model

3.4.1 Simulation of well Sanpu 1

Well Sanpu 1 is located south of the Wei River northern bank fault. The well is mainly used for space heating during winter time and bathing during summer time, so the production during the two seasons is quite different. The data of the summer of 2006 could only be estimated according to the usage of other summers and the experience of engineers, due to a loss of data. The open model and the three-tank closed model were found to be best for simulating the variation of wellhead pressure, respectively. Figure 8 shows good agreement between the observed data and the calculated data for well Sanpu 1. The parameters of the two models are listed in Table 3 and Table 4 for comparison.

TABLE 3: Parameters of a lumped model for the production of well Sanpu 1

Parameter	Two-tank open model	Three-tank closed model
A_1	0.006569	0.01359
L_1	0.7251	2.067
A_2	0.00009277	0.00016287
L_2	0.006931	0.02253
B	0	0.00001801
κ_1 (ms^2)	12.68	6.132
κ_2 (ms^2)	915.4	470.1
κ_3 (ms^2)		4212
σ_1 (10^{-5}ms)	0.0001049	0.0001448
σ_2 (10^{-5}ms)	0.00007445	0.0001116
Initial pressure (MPa)	0.4	0.4
The past average production (l/s)	10	10
Root mean square misfit	0.02936	0.02809
Estimate of standard deviation	0.02944	0.02820
Coefficient of determination	**89.84%**	**90.66%**

TABLE 4: Reservoir properties according to the lumped parameter model of well Sanpu 1

Model	Properties	First tank	Second tank	Third tank	Total
2-tank open	Reservoir volume (km^3)	0.1517	10.95		11.10
	Area (km^2)	0.1341	9.682		9.682
	Permeability *k* (mD)	10.67			
3-tank closed	Reservoir volume (km^3)	0.07337	5.625	50.4	56.10
	Area (km^2)	0.06486	4.973	44.56	49.60
	Permeability *k* (mD)	14.90	6.599		

3.4.2 Simulation of well Sanpu 2

Well Sanpu 2 was drilled at the Wei River northern bank fault. Similarly with Sanpu 1, well Sanpu 2 is used for space heating in winter and bathing in summer. A two-tank open model and a three-tank closed model were found the best fitting models by simulation. The results of the simulations are shown in Figure 9. The parameters of the two models and the reservoir are listed in Tables 5 and 6 for comparison.

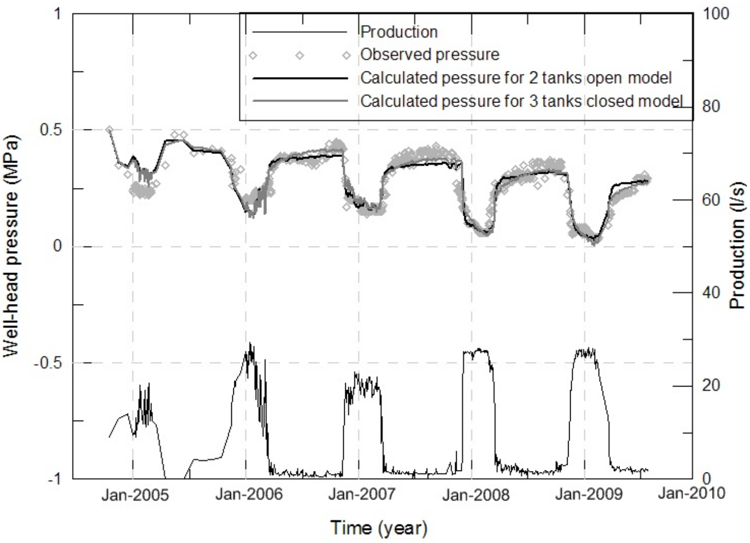

FIGURE 9: Simulation result of well Sanpu 2 using a two-tank open model

It should be emphasized that data used in this case is daily data except for data between Nov-2004 and Nov-2005 which is monthly data. This influenced the simulation results and made the simulation curve not fit very well at the beginning.

TABLE 5: Parameters of a lumped model for the production of well Sanpu 2

Parameter	Two-tank open model	Three-tank closed model
A_1	0.002482	0.02244
L_1	0.2551	2.896
A_2	0.00002637	0.00008044
L_2	0.0008937	0.01521
B	0	0.00001268
κ_1	32.62	3.737
κ_2	3093	908.5
κ_3		5724
σ_1	0.00009530	0.0001247
σ_2	0.00003233	0.0001385
Initial pressure (MPa)	0.5	0.5
The past average production (l/s)	0	0
Root mean square misfit	0.05092	0.04830
Estimate of standard deviation	0.05107	0.04847
Coefficient of determination	**77.93%**	**80.15%**

TABLE 6: Reservoir properties according to lumped parameter model of well Sanpu 2

Model	Properties	First tank	Second tank	Third tank	Total
2-tank open	Reservoir volume (km^3)	0.3326	31.54		31.87
	Area (km^2)	0.2426	23.00		23.25
	Permeability k (mD)	7.898			
3-tank closed	Reservoir volume (km^3)	0.0381	9.263	58.37	67.67
	Area (km^2)	0.02779	6.756	42.58	49.36
	Permeability k (mD)	12.21	6.013		

3.4.3 Simulation of well WR 3

Well WR 3 is located north of the Wei River northern bank fault and is only used for production in winter. A two-tank closed model and a two-tank open model were used in the simulation of this well. A more complex model could not be developed. The two models have the same coefficient of determination and the curves of the two models coincide with each other as shown in Figure 10. Other parameters are presented in Tables 7 and 8.

It is obvious that the calculated water level is higher than the observed water level during winter time (Figure 10), in spite of applying a correction for turbulence. This indicates that the water level of well WR 3 was influenced by other nearby wells that were extracting at the same time.

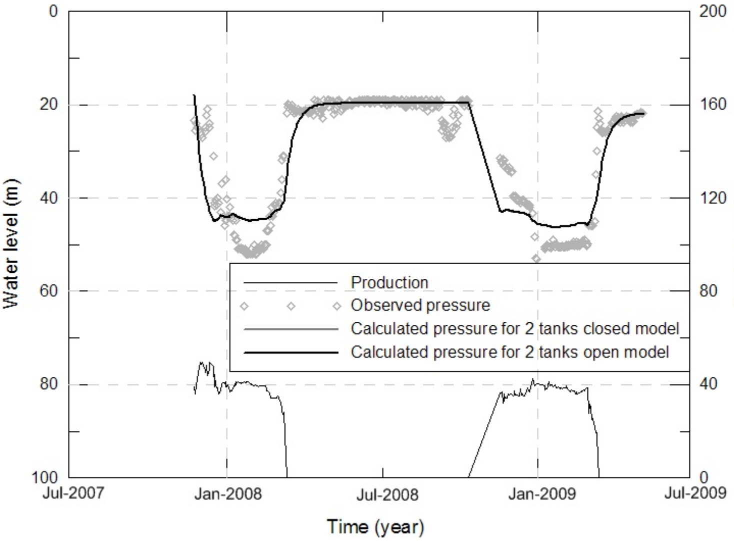

FIGURE 10: Simulation result for well WR 3 using a two-tank open model and a three-tank closed model

TABLE 7: Parameters of lumped model for production of well WR 3

Parameter	Two-tanks open model	Two-tanks closed model
A_1	0.06247	0.06225
L_1	0.09831	0.09785
A_2	0.0004223	
L_2	0.0001765	
B	0	0.000404
K_1	140.2	140.7
K_2	20810	21680
K_3		
σ_1	0.0001584	0.0001583
σ_2	0.00004281	
Initial water level (m)	18	18
The past average production (l/s)	0	0
Root mean square misfit	4.609	4.609
Estimate of standard deviation	4.630	4.624
Coefficient of determination	**86.34%**	**86.34%**

TABLE 8: Reservoir properties according to lumped parameter model of Well WR 3

Model	Properties	First tank	Second tank	Total
2-tank open	Reservoir volume (km^3)	1.674	248.5	250.1
	Area (km^2)	1.870	277.6	279.5
	Permeability k (mD)	24.02		
2-tank closed	Reservoir volume (km^3)	1.680	258.6	260.5
	Area (km^2)	1.877	289.3	291.1
	Permeability k (mD)	24.17		

3.4.4 Discussion

The properties of conductors can be used to estimate the reservoir permeability by assuming a given reservoir geometry. Based on calculations, the permeability of the three wells is shown in Tables 4, 6 and 8. It shows two important points. Firstly, well WR 3 has a higher permeability than the other two wells. This is in accordance with pumping test results shown in Figure 5. Actually, the geological survey and drilling results show that the grain size of sedimentary rock beneath Xianyang gets smaller and smaller towards south, a feature especially noticed on both sides of the Wei River northern bank fault. This is in agreement with calculated permeability. Secondly, the reservoir appears to have fairly good internal permeability but a lower external permeability. This means that the inner part of the reservoir has good connectivity but is almost closed to the outside of the reservoir. It can also be concluded that the decline of wellhead pressure will continue even if constant production is maintained in the future.

It should be pointed out that the permeability calculated from the simulation results is the mean permeability because the lumped model assumes that the entire Xianyang system is one reservoir. The calculated permeability is also lower than the true one due to the assumption that pressure change of one well is only induced by the production of the well itself.

3.5 Predictions

In order to reassess the production potential of the Xianyang field, lumped parameter models were used to predict future water-level variations of long term production. A future production period of 20 years was appended to the input file. The study process can be described as follows: Firstly, select the best fitting parameter model which can best represent the actual situation of the reservoir, from simulation to the prediction model. Then, design different production scenarios as input files. Three scenarios (listed in Table 9) have been designed for this work. The first one maintains the mean production of the past few years without any change. It can predict what will happen in the future if we continue our present production behaviour. The second one increases production by 30%. This is just what space heating companies in Xianyang want to do because of the growth of the market. The third one maintains present extraction but initiates 30% injection, which has the same effect as decreasing production by 30%. Here, both an open model and a closed model are used for predicting the reservoir response. The results of the predictions for the closed and open models are two extreme conditions for the lumped parameter modelling and the geothermal reservoir. The real behaviour of the reservoir would be somewhere between these two simulated responses. The difference between the predictions of the open and closed models is noteworthy and reflects the nature of the Xianyang reservoir.

TABLE 9: Scenarios used to predict pressure change for the three wells in the study

Well name	Present production kept (l/s)	Production increased 30% (l/s)	Production decreased 30% (l/s)
Sanpu 1	11.77	15.30	8.24
Sanpu 2	11.40	14.82	7.98
WR 3	14.27	18.55	9.99

3.5.1 Prediction for Sanpu 1

A two-tank open model and the three-tank closed model proved to be the proper parameter models for Well Sanpu 1. This well has, on average, had a production of 11.77 l/s in the past four years. The prediction was done assuming that this flow rate would continue. As shown in Figure11, the open model gave a more optimistic forecast than the closed model. The wellhead pressure was maintained at 0.36 MPa. The wellhead pressure would decline to about 0.11 MPa for the case of a closed model after 20 years, equivalent to a water head decline of 1.1 m every year.

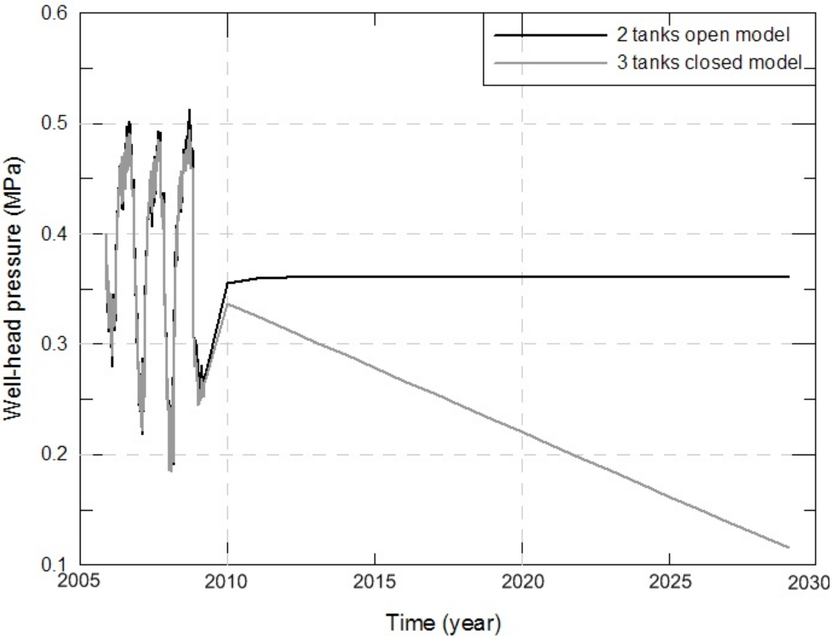

FIGURE 11: Comparison between predictions of the closed and open models for 11.77 l/s production of well Sanpu 1

The other two scenarios were to increase production by 30% or decrease it by 30%, resulting in 15.30 and 8.24 l/s production, respectively. The prediction results are presented in Figure 12. The three-tank closed model with 15.30 l/s is the most pessimistic prediction. Wellhead pressure will decline to about -0.4 MPa. It will be necessary to install a pump to obtain water from the well at that time.

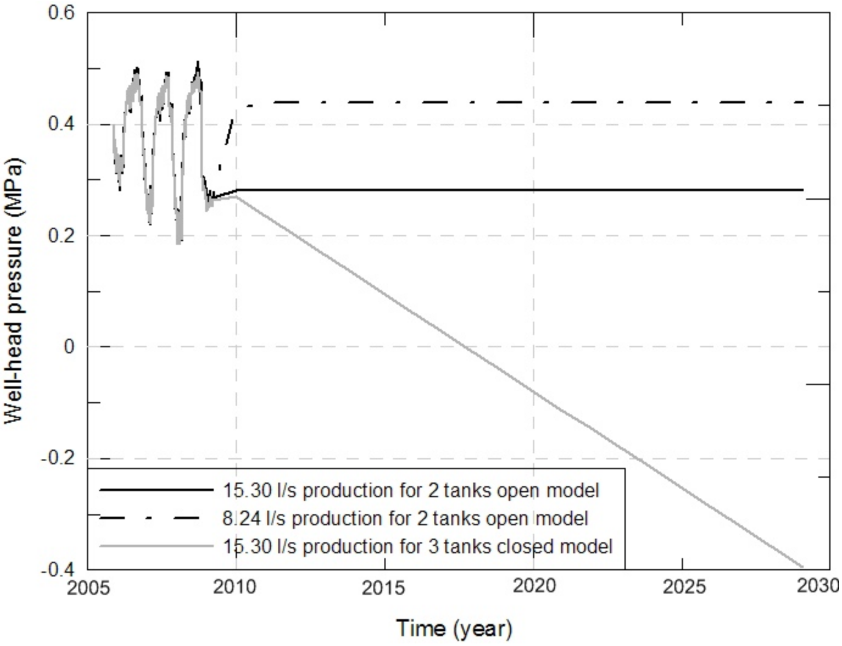

FIGURE 12: Comparison between predictions of the closed and open models for 15.30 l/s and 8.24 l/s production of well Sanpu 1

3.5.2 Prediction for Sanpu 2

The results of the simulation of Sanpu 2 show that a two-tank open model and a three-tank closed model are the best fit for well Sanpu 2. The first prediction scenario was done for unchanged production, with the flow rate maintained at 11.40 l/s. Here, the water level will gradually decline at a rate of 0.05 MPa/y with the water level sinking to 86.4 m below ground level after 20 years according to the closed model. It is obvious that this well is already overexploited if the closed nature is real (see Figure 13).

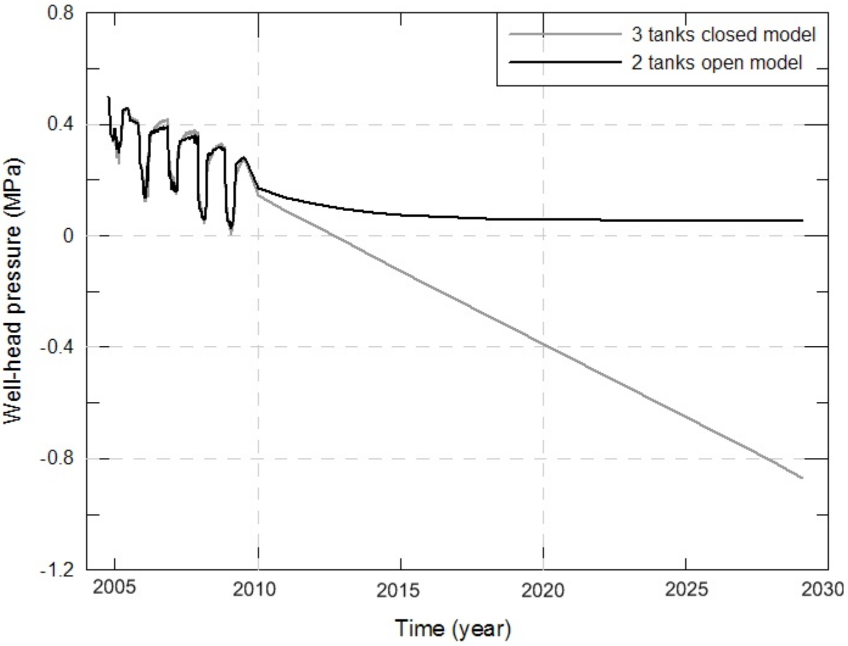

FIGURE 13: Comparison between predictions of the closed and open models for 11.40 l/s production of well Sanpu 2

As shown in Figure 14, for the scenarios of 14.82 l/s and 7.98 l/s production, the water level for the three-tank closed model will be at 122 and 51 m below ground level in 20 years, assuming production of 14.82 and 7.98 l/s, respectively.

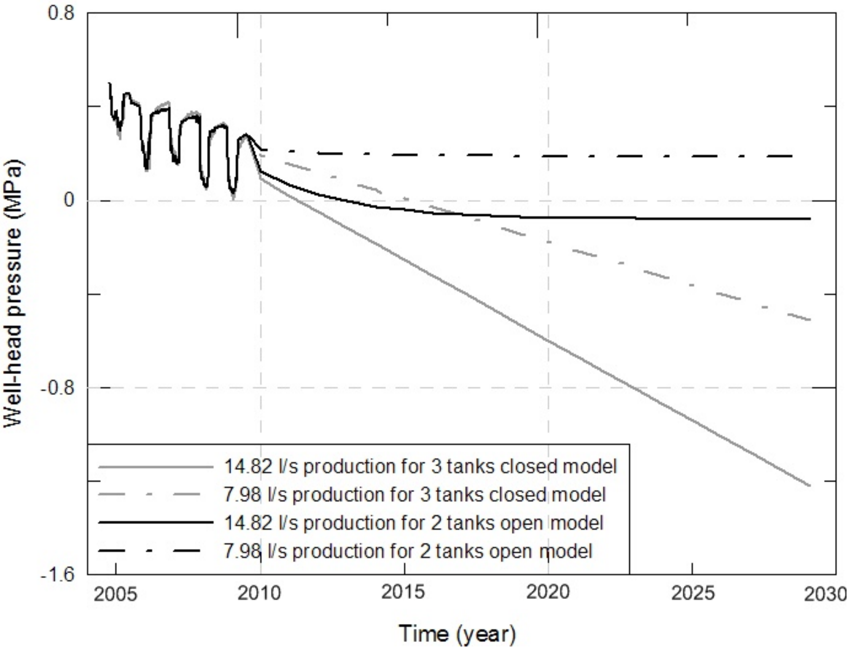

FIGURE 14: Comparison between predictions of the closed and open models for 14.82 and 7.98 l/s production of well Sanpu 2

3.5.3 Prediction for WR 3

A two-tank open model and a two-tank closed model were also used to predict the pressure variations in well Sanpu 1. This well has had a mean production of 14.27 l/s over the past two years. This scenario is presented in Figure 15, while the other two scenarios are shown in Figure 16, an increase of 30% and a decrease of 30% production, or 15.30 and 8.24 l/s production, respectively.

Due to the potential local market, the local space heating companies want to extract more and more geothermal water from wells. Hence, the decline of the water level and pressure will accelerate in the future.

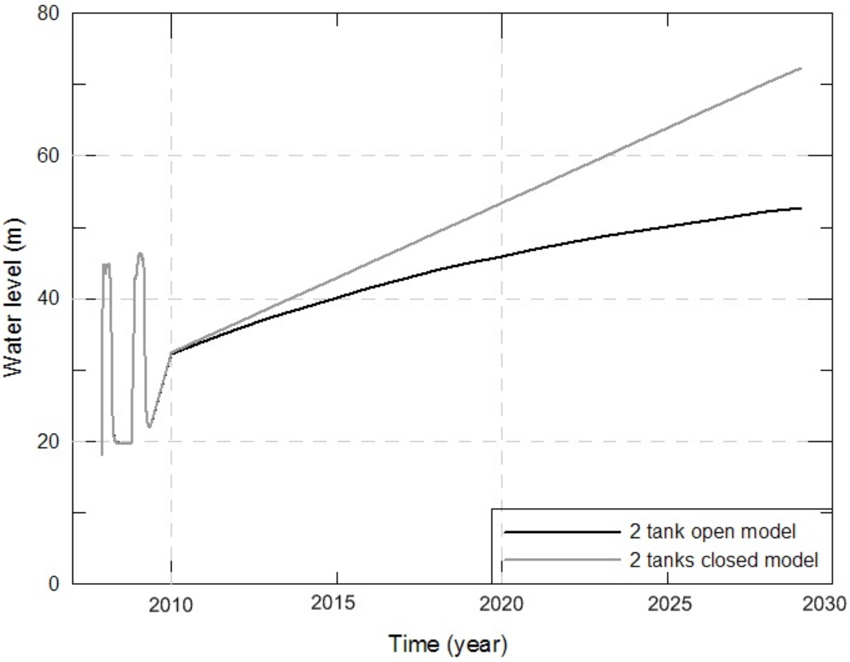

FIGURE 15: Comparison between predictions of the closed and open models for 14.27 l/s production of well WR 3

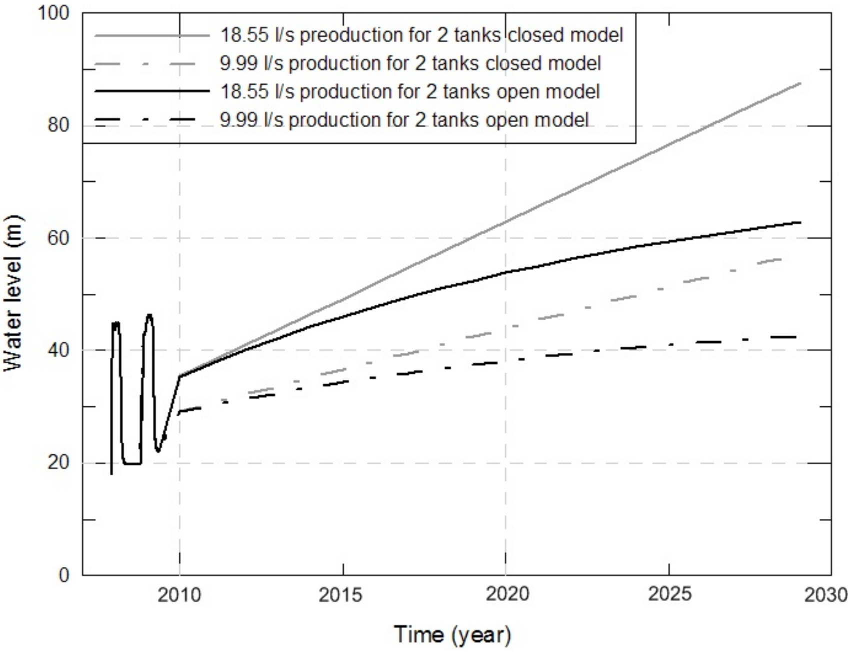

FIGURE 16: Comparison between predictions of the closed and open models for 18.55 and 9.99 l/s production of well WR 3

3.6 Calculation of pressure interference

When one well discharges, the pressure around the well will change causing the pressure of nearby wells also to change. As a basis for conventional well test analysis, the solution to the pressure diffusion equation for Theis-model of a confined reservoir of two-dimensional flow can be expressed by the following equation (Jónsson and Hjartarson, 2009):

$$p(r,t) = -\frac{vQ}{4\pi Hk}Ei\left(-\frac{r^2}{4at}\right) \tag{9}$$

where a = k/s;

$Ei()$ is the exponential integral.
r is distance between the two wells (m);
t is exploitation time (s);
v is kinematic viscosity of geothermal water (m^2/s);
Q is mass flow rate (kg/s);
H is the thickness of the reservoir (m);
k is the permeability of the reservoir (m^2); and
s is the storativity of the reservoir (kg/m^3Pa).

With the approximation that $t \gg r^2sv/4k$, the equation can be expressed as:

$$\Delta p(r,t) = \frac{vQ}{4\pi Hk}\left(0.5772 + ln\frac{r^2sv}{4kt}\right) \tag{10}$$

According to Equation 10, the pressure interference between two wells can be calculated using parameters gotten from both the open and closed models. The calculated cumulative values of pressure change are shown in Tables 10 and 11. The wellhead pressure was converted to water level for convenience.

TABLE 10: Calculated results of pressure interference between wells using open-model parameters

Well 1	**Well 2**	**Distance of two wells (m)**	**Duration of production (years)**	**Pressure change (m)**
Sanpu 1	Petroleum factory	2780	11	-8,97
Sanpu 2	Petroleum factory	810	5	-12,19
	J 1	1060	5	-10,87
	202 institute	1590	5	-8,89
	795 factory	1190	5	-10,31
	185 team	1580	5	-8,92

TABLE 11: Calculated results of pressure interference between wells using closed-model parameters

Well 1	**Well 2**	**Distance of two wells (m)**	**Duration of production (years)**	**Pressure change (m)**
Sanpu 1	Petroleum factory	2780	11	-7,01
Sanpu 2	Petroleum factory	810	5	-8,57
	J 1	1060	5	-7,72
	202 institute	1590	5	-6,44
	795 factory	1190	5	-7,36
	185 team	1580	5	-6,46

The pressure changes show that considerable interference should have occurred over the past ten years (Tables 10 and 11). But at the same time, the wells also indicate there is a close hydrological connectivity I nside the reservoir. It is obvious that the results from the open model indicate a more intense interference and a more pessimistic hydrological connection. Based on the assumption that the pressure change of one well is induced by the well itself, the pressure interference between wells will result in the calculated pressure being higher than the measured one. Consequently, the calculated permeability is lower than the actual one. Currently, over 30 wells extract water from the same geothermal reservoir during the heating months in Xianyang City. The cumulative effect of pressure interference among the wells will cause the wellhead pressure to decline rapidly during the heating months. Therefore, injection appears quite imperative.

4. CONCLUSIONS AND RECOMMENDATIONS

The main conclusions of this work may be summarized as follows:

- Xianyang geothermal system is one of the most important geothermal fields in China, and is credited with higher production per well than seen in usual sedimentary geothermal reservoirs. The Wei River northern bank fault and limestone which lies beneath the Tertiary stratum and along the north side of the fault contribute weak recharge to the main production layer. The main production layer, the Lantian-Bahe formation and the Gaoling group, consists of sedimentary rock with high porosity and permeability. The geothermal fluid in the region has a high degree of mineralization and micro elements which have a significant effect with regards to balneology.
- Both open two-tank model and three-tank closed lumped models are used to simulate the monitored production data and wellhead pressure. The two models are also used to predict different production scenarios. The real behaviour of the water level is likely to be closer to the predicted results of the closed lumped models.
- The prediction results obtained with a pessimistic closed model indicate that the water level of Sanpu 1, Sanpu 2 and WR 3 will drop 1.1, 5.0 and 2.0 m per year, respectively, if kept at the present production rate. With 30% injection, the water level will continue to decrease but more slowly than in the scenario without injection. In contrast, the predictions with the open models shows an optimistic future in which the water level of Sanpu 1, Sanpu 2 and WR 3 will remain stable at 0.36 MPa, 0.05 MPa and at 53 m below ground level, respectively.
- The fluid flow coefficients of the models reflect an average permeability ranging from 6 to 24 mD. The Xianyang reservoir thus appears to have fairly good internal permeability. In contrast, the reservoir appears to have a relatively low external permeability. This indicates that the decrease of wellhead pressure will accelerate.
- The calculated results of pressure interference show that considerable interference should have occurred wells over the past ten years. It also indicates that there is a close hydrological connection inside the reservoir.

The following recommendations are put forward based on the results of this study:

- Data on the Xianyang geothermal system is still limited. The continued monitoring of geothermal wells should be strengthened. Monitoring should be applied on all wells instead of only on some of them. A full year of data needs to be collected instead of data only being collected during the heating months.
- Modelling plays a key role in understanding the nature of geothermal systems and is the most powerful tool for predicting their response to future production (Axelsson, 2008a). The nature of a system also determines how beneficial injection can be.
- Reinjection has become an essential part of sustainable and energy-efficient geothermal utilization. It is used to counteract pressure draw-down (i.e. provide additional recharge), to dispose of waste-water and to counteract surface subsidence (Axelsson, 2008b). The results of the simulations and predictions in this report demonstrate that reinjection should be implemented for the Xianyang geothermal resource, as the current extraction of geothermal water is difficult to replace and the extraction is actually increasing year by year.
- Sandstone injection is delicate because of possible clogging of the reservoir. The crystallization and oxidation of chemical components in the geothermal fluid and the precipitation of fine solid particles in the geothermal fluid are the main factors in clogging. The cold front of injection water would affect the usage of nearby wells. Therefore, studies on this must be done before injection starts.
- Unified and centralized management is vital for massive and long-term extraction, when many different companies and institutions are utilizing the same reservoir.

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