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RESERVOIR EVALUATION OF THE ZHOULIANGZHUANG GEOTHERMAL FIELD, TIANJIN, CHINA

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ABSTRACT

The Zhouliangzhuang geothermal field is one of many geothermal fields in Tianjin, China. It is a conduction-dominated, low-temperature sedimentary system. At present, there is considerable interest in developing this geothermal resource further. The system is characterised by higher temperatures than most other fields in Tianjin, the highest temperature being more than 100°C. All geothermal wells drilled so far are artesian. Exploration of the field has been on-going since 2001. Assessment of the production potential of the system was carried out by using lumped parameter models as well as a simple numerical model. Similar hydro-geological conditions control the two models, such as no recharge, and according to predictions of the two models, the total allowable production of Zhouliangzhuang geothermal field is estimated to be about 7.8×10^6 m^3/year, with water level in production wells' above 150 m for 20 years. Reinjection will be essential to maintain reservoir pressure in order to enable sustainable utilization as well as to increase the production potential of the system.

1. INTRODUCTION

The Zhouliangzhuang geothermal field is located in the northeast part of the North China alluvial plain, about 35 km north of the city of Tianjin (see Figure 1). Utilization of the geothermal resources in the area, such as for space heating of villas, fish farming, and greenhouse heating, has been planned by several companies because of the convenient location and the available land. The Zhouliangzhuang field is located about 20 km northeast of Wuqing, where geothermal energy from a sandstone system has been utilized since 1994 (Wang, 1998), and about 60 km northwest of Tanggu, where a comparable sandstone resource has been utilized since 1987 (Axelsson and Dong, 1998). In addition, the city of Tianjin is the location in the P.R. of China with the most extensive and most advanced geothermal utilization in the whole country.

The Zhouliangzhuang field lies in a convex part of a sedimentary basin. Past investigations indicate that thermal energy from the deep crust is conducted through high conductivity basement into shallower formations, while a low conductivity cap rock controls the surface heatflow (Chen, 1988). Therefore, the

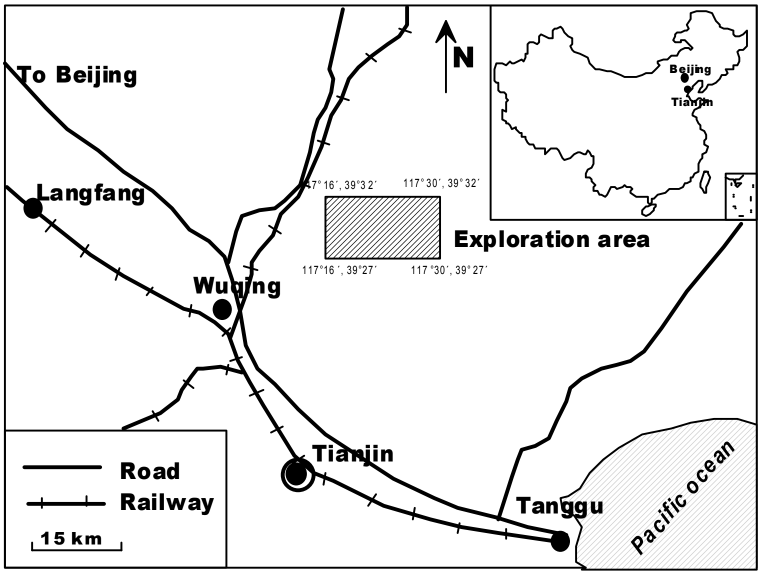

FIGURE 1: Location of the current exploration part of the Zhouliangzhuang geothermal field

field has a high thermal gradient in the cap rock and a high reservoir temperature. According to lithological data, the geothermal system can be divided into three formations or separate reservoirs, divided by impermeable layers. In the early 1980s, this geothermal field was discovered through petroleum exploration drilling; three of the wells (W2, W3 and W4) have been used for geothermal utilization at low discharge, for bathing and farming. Well W3 produces from an Ordovician formation with a nearly constant flowrate of about 1.1 l/s since 1988, well W4 produces from a Cambrian formation with a constant flowrate of about 4.2 l/s since 1987, and well W2 produces from a Proterozoic formation with constant pumping flowrate of about 8 l/s since 1990. A geothermal exploration well (ZL1) was drilled in 2002. The well was successful with a maximum pumping flowrate of about 83 l/s of 100°C hot water. The thermal water from this well will be used for space heating, bathing and agriculture.

In this report, a brief outline of the geological characteristics of the geothermal system is given to provide the reader some ideas about the nature of the field. The main emphasis is on a reservoir evaluation through modelling. Lumped parameter models and simple numerical distributed parameter models are set up based on the system's conceptual model and available long-term monitoring data. Consequently, an assessment of the production potential of the geothermal system is carried out. The utilization of reinjection as a part of the geothermal resource management in the field is also studied. It must be emphasised here that very limited data are available in the Zhouliangzhuang geothermal field; production response data, in particular, are limited. In such situations, complex numerical modelling is generally not justified. The numerical model presented here, however, should be looked upon as the first step in model development for the field, which will be extensively revised and modified as more data become available.

2. THE ZHOULIANGZHUANG GEOTHERMAL FIELD

2.1 Geological background

The Zhouliangzhuang field is located in the so-called Wancaozhuang convex, in the northern part of the Cangxian up-warping, which is located in the northern part of the Huabei sedimentary basin (Li, 2002). The convex is further divided into tectonic formations by three main faults. The northern boundary of the field is the Baodi-ninghe fault (see Figure 2); and the Dakoutun fracture is the southwest boundary separating the field from the Wuqing sedimentary basin and the Panzhuang convex. One fault on the eastern boundary of the Wangcaozhuang convex separates it from the Ninghe convex.

There are three main faults in the study area (see Figure 3) affecting the geothermal resource and the reservoir's distribution. These faults may be described as follows:

- The Dakoutun fracture is a normal fault, striking NW-SE and dipping to the southwest. Formations on the downthrown side are part of the Wuqing sedimentary basin, which is characterised by very thick Tertiary formations; while the uplifted side belongs to the Wangcaozhuang convex. The fault is believed to provide a path for hot water.
- The Wangcaozhuang fault is a normal fault, striking W-E, dipping to the south with an angle of 40°. The fault is about 30 km long and is believed to connect different geothermal formations.
- The Niutihe fault is also a normal fault, more than 10 km in length, striking approximately from east to west, and dipping to the south, with an angle of about 30°. The fault is also believed to provide channels for thermal water migrating between different formations.

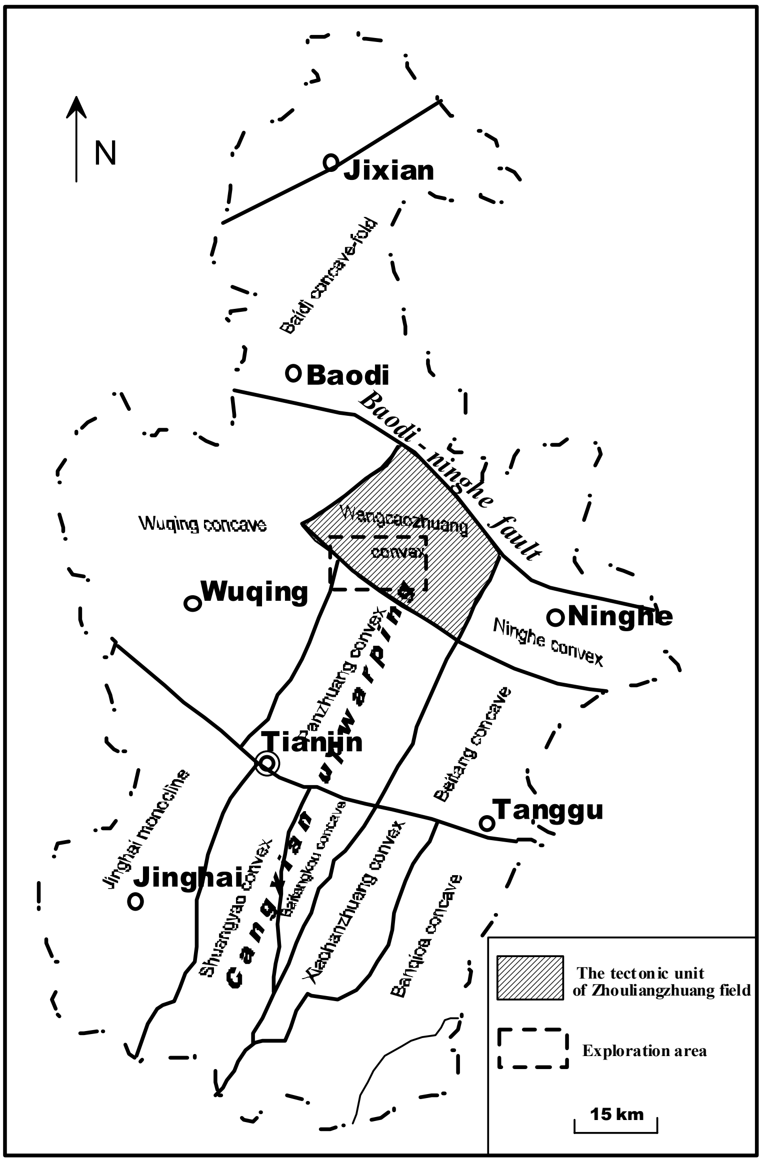

FIGURE 2: Tectonic map of the Tianjin region

2.2 Lithological structure

The information on the stratum distribution can be obtained from wells drilled in the area (Table 1). During geothermal exploration from 2001 to 2003, only one well (ZL1) was available for geological exploration. According to drill cuttings analysis and well logging, some of the usual layers are missing in well ZL1.

TABLE 1: Lithological information from boreholes in the Zhouliangzhuang field

Well No. / Stratum	W2	W3	W4	W11	ZL1
	Depth of bottom (m)	**Depth of bottom (m)**	**Depth of bottom (m)**	**Depth of bottom (m)**	**Depth of bottom (m)**
Quaternary (Q)	304	226	278		300
Neogene (N)	1383	882	736	878.5	922
Eogene (E)	2811	--	1344	1509	1977
Mesozoic (Mz)	--	--	1521	--	--
Ordovician (O)	--	1077*	--	1928	--
Cambrian (Є)	--		2072*	2677	--
Proterozoic (Pt)	2968*			2712*	2700*

* Information on depth of layer not available; -- layer missing

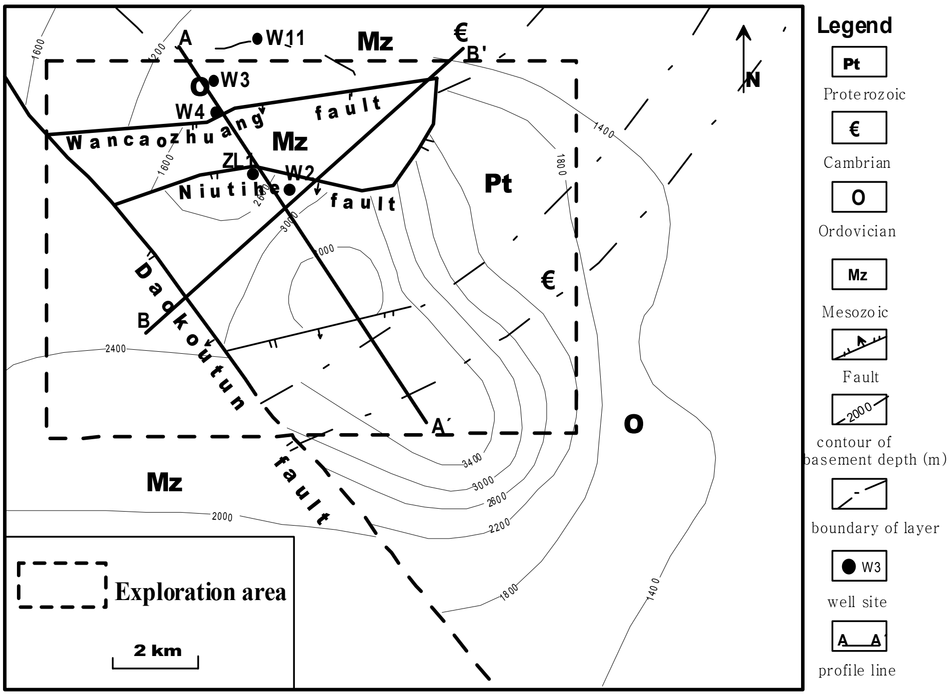

FIGURE 3: Geological map of the Zhouliangzhuang field

The lithological information is summarized in Table 2, and Figure 4 shows two cross-sections through the area.

TABLE 2: Simplified lithological structure of the Zhouliangzhuang geothermal system

Stratum	Thickness (m)	Lithology
Quaternary (Q)	200-350	Sandy cohesive soil, fine sand
Neogene (N)	500-800	Mudstone, sandstone and sandy conglomerate
Eogene (E)	~2000	Mudstone and sandstone
Mesozoic (Mz)	~700	Sandstone, volcanic rock and mudstone
Ordovician (O)	~700	Limestone, shale and dolomitic limestone
Cambrian (€)	~800	Limestone, mudstone, shale
Proterozoic (Pt)	>1000	Shale, sandstone, dolomitic limestone and dolomite

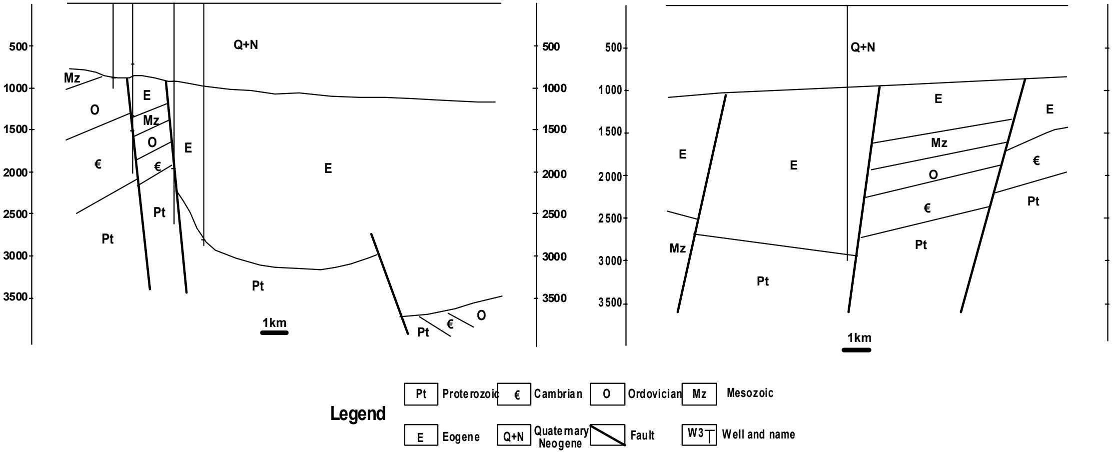

FIGURE 4: Geological cross-sections through the Zhouliangzhuang geothermal system (see Figure 3 for location)

In general, 7 layers or formations are found distributed over a 4000 m depth interval in the geothermal field, with varying thickness and lithological structure. Quaternary and Neogene formations cover the entire geothermal field, while Eogene, Mesozoic, Ordovician and Cambrian formations appear to be missing in some areas. A thick Proterozoic formation is distributed over the whole field. According to analysis of properties of rocks, the Ordovician, Cambrian, and Proterozoic formations are the main aquifers with good permeability.

2.3 The geothermal reservoirs

There are three separate productive geothermal formations, or reservoirs, in the Zhouliangzhuang geothermal system, as already mentioned:

1. The Ordovician formation (O), which is mostly composed of limestone, has average temperature in the range of 60-82˚C. This layer seems to be missing in the centre of the study area. Well W3 produces from this formation, and its wellhead pressure was 0.6-0.8 bars in 2001.
2. The Cambrian formation (€), which is mainly composed of limestone, has formation temperature higher than 80°C. Well W4 has produced from it since the 1980s. The pressure at the wellhead was about 3.8 bar in 2001.
3. The Proterozoic formation (Pt) is mainly composed of dolomite and limestone-dolomite. This layer is widespread in the field. There are two wells (W2 and ZL1) producing from this formation. The temperature of the formation is about 100˚C and wellhead pressure was about 6.0 bar in 2001.

Table 3 shows the main components in the chemical composition of fluid from three formations. The waters from the three formations appear to be similar according to chemical analysis. This indicates that the formations are connected to the same recharge zone. Higher silica content with depth reflects increasing temperature with depth.

TABLE 3: Chemical composition of water (mg/l) from the three formations in the Zhouliangzhung system

Formation / **Concentration**	**Ordovician**	**Cambrian**	**Proterozoic**
Na^+	220.0	210.0	207.0
Ca^{2+}	42.0	40.0	36.0
Mg^{2+}	8.0	6.0	6.0
Cl^-	108.0	108.0	108.0
SO_4^{2-}	175.0	182.0	158.0
HCO_3^-	345.0	357.0	354.0
F^-	8.0	7.0	10.0
SiO_2	50.0	78.0	80.0
TDS	1040	1010	1000
pH	7.5	7.5	7.8

3. MODELLING OF THE ZHOULIANGZHUANG GEOTHERMAL SYSTEM

Reservoir modelling is an integral part of geothermal reservoir assessment and management. In this report, a conceptual model based on available geological data is set up. Consequently, the LUMPFIT and TOUGH2 simulation programs are used to simulate monitoring data from two wells (W3 and W4) with production histories of nearly 15 years. The two models are set up to find the relationship between production and the historical pressure response to determine the production potential of the geothermal system. Consequently, these models should be involved in directing and managing the future geothermal development in the field.

3.1 Conceptual model of the Zhouliangzhuang reservoir

A conceptual model is a descriptive or qualitative model of a system or section of a system that incorporates the essential physical features of the system and is capable of matching the salient behaviour or characteristics of interest to the modeller (Grant et al., 1982). The conceptual model of Zhouliangzhuang geothermal system is mainly based on geological data. In the model, the structure of the geothermal system, the heat source, hot water flow paths, and recharge path are described. The conceptual model is shown in Figure 5.

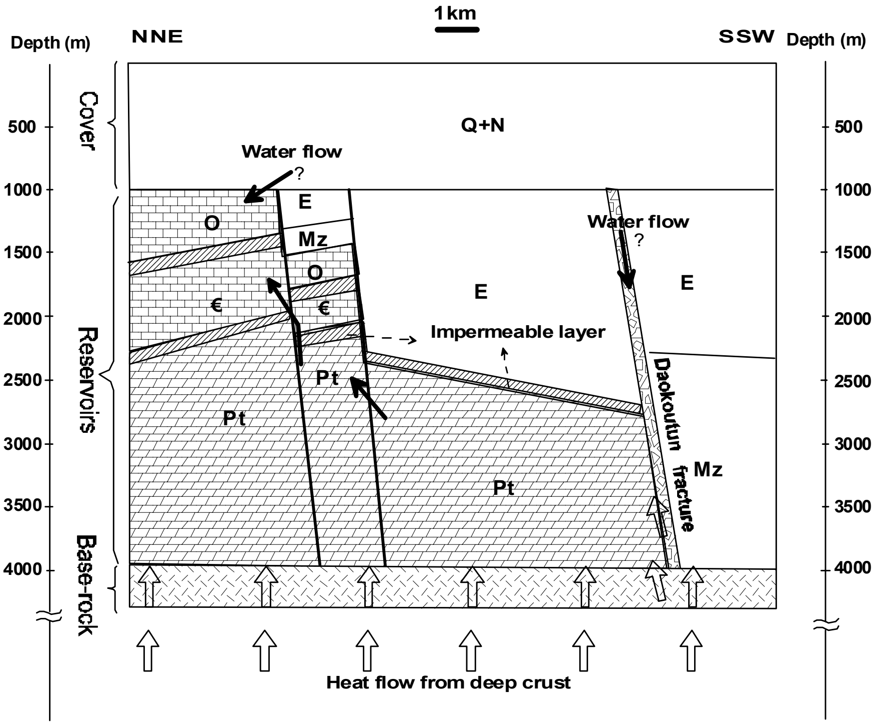

FIGURE 5: Conceptual model of Zhouliangzhuang geothermal system

The main elements of the conceptual model are as follows:

- The main reservoir formations vary in thickness. The Ordovician formation is 300-700 m, the Cambrian formation is 300-800 m, and the Proterozoic formation is more than 1000 m. The Ordovician and Cambrian formations are not found in the centre of the field.
- The thermal resource is characterised by conduction-dominated heat-flow from the deep crust.
- The Quaternary and Tertiary formations have low thermal conductivity and permeability and act as a cap rock, which causes the permeable formations below to heat up.
- Permeable faults connect the different formations and act as paths for the hot water.
- The main hot recharge fault of the system is considered to be the Daokoutun fault.
- The geothermal water is believed to be of meteoritic origin from mountains in the northern Tianjin region.

3.2 Lumped parameter modelling

The method of lumped parameter modelling has been used successfully for about two decades to simulate monitoring data from several low-temperature geothermal reservoirs in Iceland and elsewhere (Axelsson and Gunnlaugsson, 2000). The lumped simulators have been used to assess the production capacity of reservoirs by predicting future water level change for various production scenarios.

A lumped model consists of a few capacitors or tanks that are connected by conductors or resistors. Figure 6 shows an example of a closed two-tank model, which has no recharge. The two tanks simulating the geothermal system are connected by a permeable channel (resistor) with conductivity σ_1.

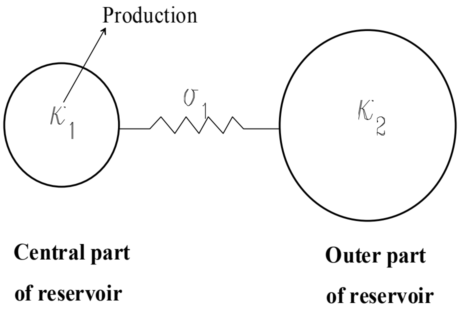

FIGURE 6: Example of a closed two-tank lumped parameter model (Axelsson, 1989; 2003a)

Lumped parameter models are set up by using the program LUMPFIT (Axelsson and Arason, 1992). The computer program automatically fits observed water-level or pressure change data with the model's production response by using a non-linear iterative least-squares technique for estimating the model parameters. The parameters characterize the response of the model to production. The two main properties of the model are the storage coefficients of a tank (κ_i), and the flow conductance of a resistor (σ_i). The storage coefficient reflects the volumetric storage of different parts of the geothermal reservoir depending on volume, porosity, and storage mechanism. The following formula is used for the storage coefficient in the case of compressibility controlled storage (Axelsson, 2003a):

$$\kappa = V\rho c_t \tag{1}$$

where V = Volume of the reservoir (m^3);
ρ = Liquid density (kg/m^3);
c_t = Total compressibility of the liquid-saturated formation (Pa^{-1}).

The total compressibility of the liquid-saturated formation is given by the equation:

$$c_t = \phi c_w + (1-\phi)c_r \tag{2}$$

where c_w and c_r = Compressibility of the water and rock, respectively (Pa^{-1});
ϕ = Porosity of the formation.

The conductance parameter (σ_i) reflects the fluid conductivity of the different parts of the reservoir and depends on permeability, viscosity, and geometry. The formula (assuming radial 2-D flow) is as follows:

$$\sigma_i = 2\pi k_i \frac{h}{\ln(\frac{r_{i+1}}{r_i})\nu} \tag{3}$$

where k_i = Permeability (m^2);
h = Thickness of the reservoir (m);
ν = Kinematic viscosity of water (m^2/s);
r_{i+1} and r_i = Radii of different model parts (m).

Figure 7 shows the measured wellhead pressure of well W3, along with the pressure simulated by LUMPFIT, due to an almost constant 1.14 l/s production from 1989 to 2001. A closed two-tank model gave the best result. Figure 8 shows the observed wellhead pressure of well W4, along with pressure simulated by LUMFIT, due to an almost constant flowrate of 4.2 l/s from 1987 to 2001. A two-tank closed model gave the best fit. This indicates that there is limited recharge to the Zhouliangzhuang geothermal system. Although the two formations are simulated separately, there might be a

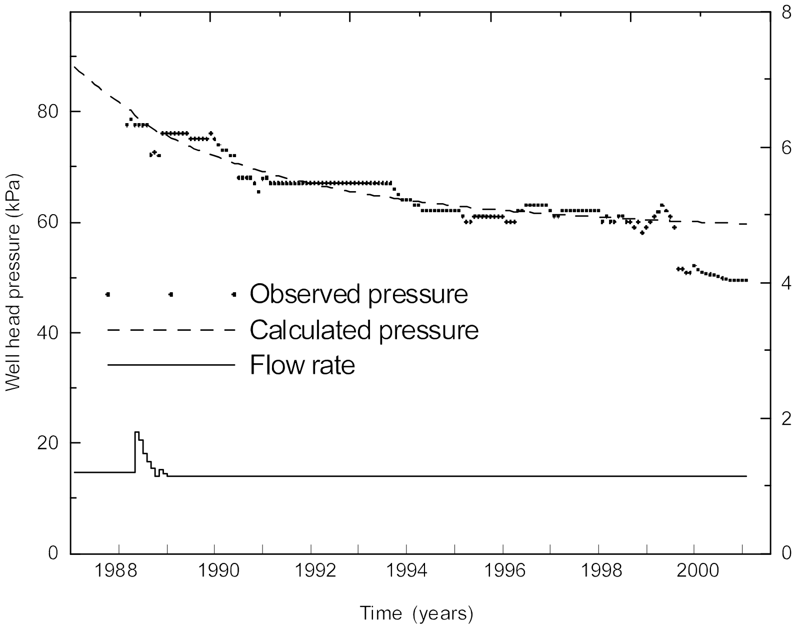

FIGURE 7: Wellhead pressure change and discharge history of well W3 simulated by LUMPFIT

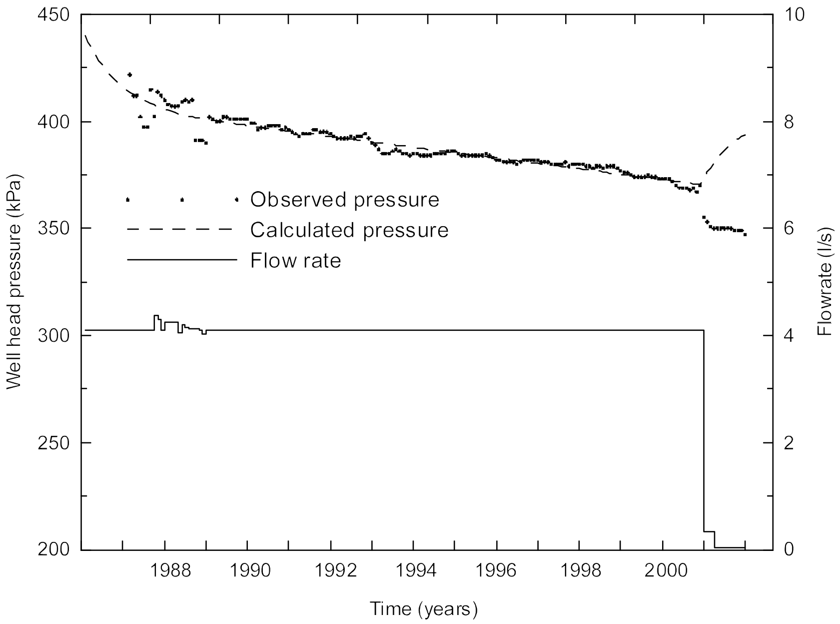

FIGURE 8: Wellhead pressure change and discharge history of well W4 simulated by LUMPFIT

connection between them through permeable faults, which might influence the simulation results. However, the effect of this possible connection is uncertain. Table 4 shows the parameters of the two models.

Changes in wellhead pressure during the last few years have been negligible. The pressure drop in well W3 in 1999 may be due to a discrepancy between pressure gauges; and the pressure drop in well W4 in 2001 is related to the flow from the well being stopped. Based on the best-fit models for the two wells, the size and permeability of the reservoirs connected to the wells can be estimated by using Equations 1- 3. The estimated reservoir parameters of models are shown in Table 4. According to the calculation results, the two formations have similar permeability, but the Ordovician formation (W3) seems to be connected to an outer part of the reservoir with a much larger volume than the Cambrian formation (W4).

TABLE 4: Parameters of the best-fitting closed two-tank lumped models for wells W3 and W4 in the Zhouliangzhuang field

Parameter		W3	W4
Model		closed 2- tank	closed 2- tank
κ_1 (ms^2)		5040	3280
κ_2 (ms^2)		657100	48500
σ_1 (ms)		0.4×10^{-4}	0.1×10^{-3}
Coefficient of determination		91.03%	91.68%
Thickness of formation (m)		500	400
Porosity of formations		5%	5%
Volume (km^3)	First tank	120	80
	Second tank	15300	1150
Permeability (m^2)		1.51×10^{-14}	1.25×10^{-14}

3.3 Simple numerical distributed parameter model

In this report, numerical distributed parameter modelling is carried out by the TOUGH2 computer program. TOUGH2 is a general-purpose numerical simulation program for non-isothermal flows of multi-component, multi-phase fluids in one, two, and three-dimensional porous and fractured media (Pruess et al., 1999). The TOUGH2 program is now being used by over 150 organizations in more than 20 countries. The major application areas include geothermal simulation, environmental remediation, and nuclear waste isolation (Elmroth et al., 2002).

Mass- and energy balance is at the heart of the TOUGH2 computation. The code practically works as a bank with a huge number of accounts, with recharge and discharge between each other (both heat and mass) (Björnsson, 2003). The fundamental mass balance equations have the following form:

$$\frac{d}{dt}\iiint\limits_{V} M^{(\kappa)} dV = \iint\limits_{\Gamma} F^{(\kappa)} \bullet \vec{n}\, d\Gamma + \iiint\limits_{V} q^{(\kappa)} dV \tag{4}$$

where, the integration is over an arbitrary volume V, which is bounded by the surface Γ. Here $M^{(\kappa)}$ denotes mass for the κ-th component (water, gas, heat, etc), $F^{(\kappa)}$ is flow through the surface, and $q^{(\kappa)}$ is the strength of sources or sinks inside V.

Based on the conceptual model, a simple TOUGH2 model of the geothermal system was set up. Due to limited geological data, inclined layers are approximated as horizontal, and fault zones are assumed to be vertical in the model development.

3.3.1 Creating the model mesh

In general, a TOUGH model consists of a number of grid blocks (elements) connected to each other. Each element is assigned an appropriable rock type, which has certain permeability, porosity, and other properties partly based on the reservoir geology.

The Zhouliangzhuang model covers an area of 1050 km^2, which is approximately the area of the Wancaozhuang convex (see Figure 9). The mesh was generated by the Meshmaker associated with TOUGH2. It consists of 640 elements (384 elements in the study area), where 160 elements are "inactive" (for the inactive elements, no mass and energy balance equations are set up, and their thermodynamic condition will remain unchanged). The model consists of 8 layers (see Figure 10). Layers 1 and 8 are inactive to set the top and bottom boundary conditions (see Table 5). Each production well produces from the centre of a relevant element.

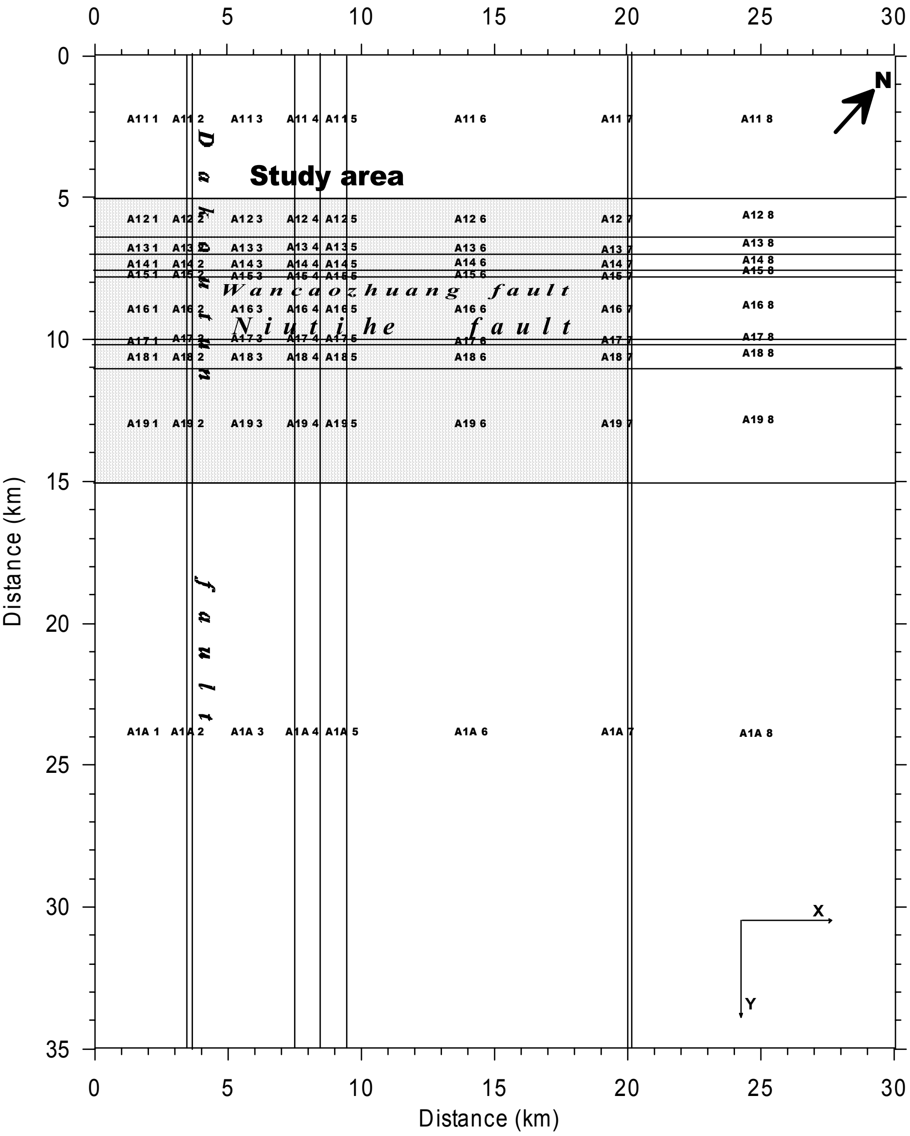

FIGURE 9: Mesh for Layer 1 of the Zhouliangzhuang geothermal system TOUGH2 model

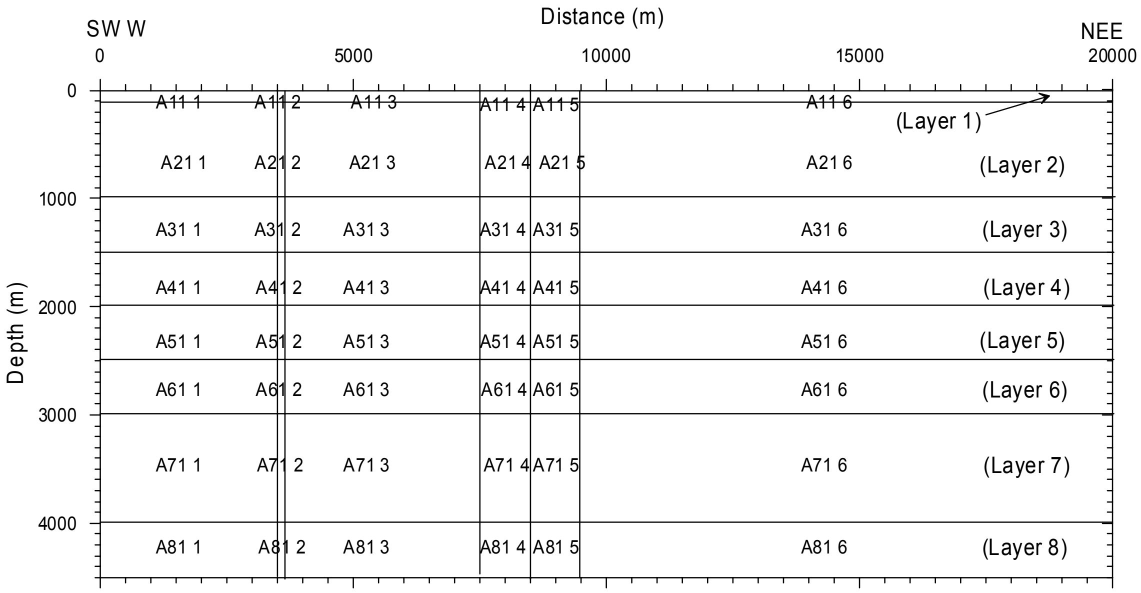

FIGURE 10: Cross-section through the TOUGH2 model

TABLE 5: Information on layers in the TOUGH2 model

Layer	Thickness (m)	Depth of centre (m)	Physical condition in layer
1	100	50	Inactive (T = 15˚C, P = 5 bar)
2	900	550	Active (T = 35˚C, P = 49 bar)
3	500	1250	Active (T = 65˚C, P = 122 bar)
4	500	1750	Active (T = 72˚C, P = 170 bar)
5	500	2250	Active (T = 85˚C, P = 218 bar)
6	500	2750	Active (T = 95˚C, P = 266 bar)
7	1000	3500	Active (T = 104˚C, P = 338 bar)
8	500	4250	Inactive (T = 114˚C, P = 410 bar)

3.3.2 Model calibration

In general, detailed data on geology, hydrogeology, temperature, pressure and long-term production and pressure response is needed for the development of a reliable detailed distributed numerical model of a geothermal system. In this case, however, only limited geological data is available and production histories are only for free discharge from wells, but not for large-scale mass production. The model developed here should, therefore, be considered as the first stage of model development. More data is needed to develop the model further before it becomes an integral part of future system management.

Table 6 lists the parameters of the TOUGH2 model. The fractures are considered as the most permeable flow channels connecting different formations. Hence, the corresponding rock type has higher porosity and permeability. The parameters in the TOUGH2 model were adjusted until a good match with the observation data from the two wells was obtained, as shown in Figures 11 and 12. The model has no recharge from the outside. However, the model characteristics are only based on a simulation with very low mass extraction rates, which can nearly be considered similar to natural discharge. The effect of production did possibly not reach the model boundaries during the 15 years of production. It should be mentioned that the well head pressures have been changed to formation pressures, to enable a comparison with the calculated pressures by TOUGH2.

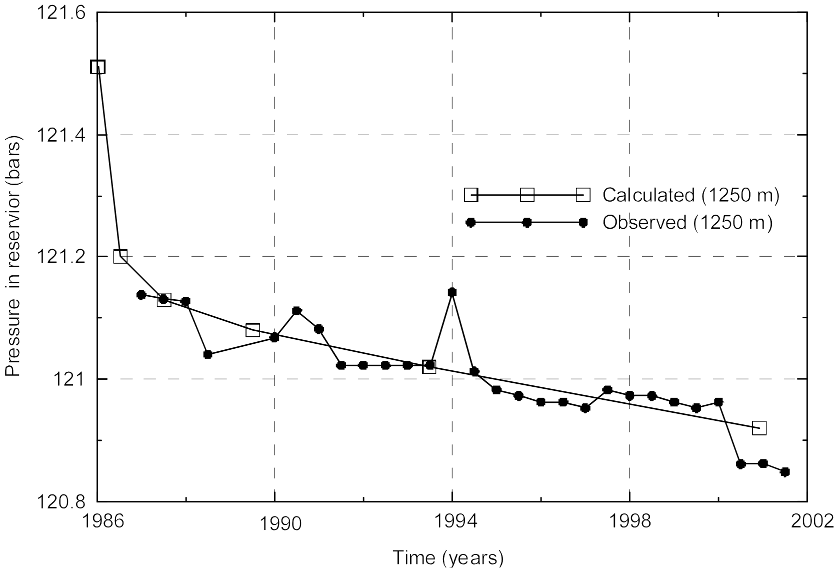

FIGURE 11: Observed and calculated pressure in well W3 at 1250 m depth (TOUGH2-model)

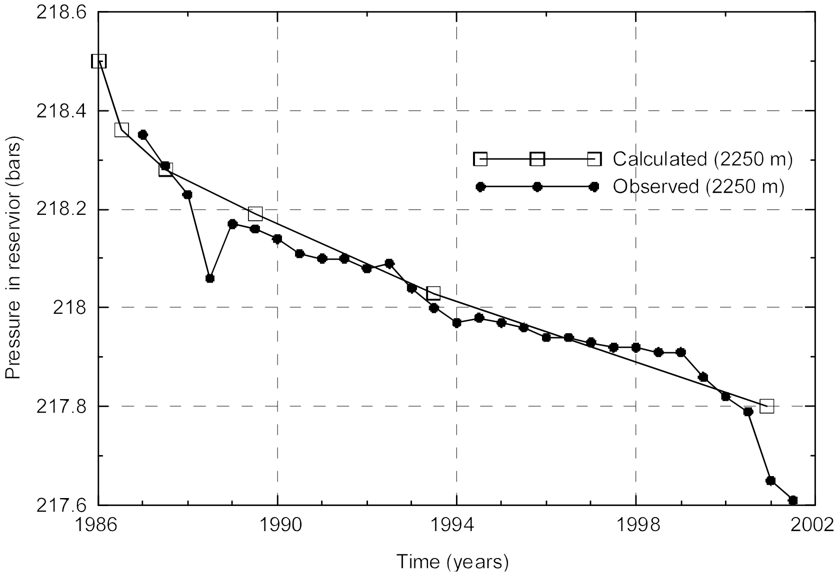

FIGURE 12: Observed and calculated pressure in well W4 at 2250 m depth (TOUGH2-model)

TABLE 6: Rock properties in the TOUGH2 model of the Zhouliangzhuang geothermal system

Rock type	**Density (kg/m^3)**	**Porosity (%)**	**Permeability (m^2)**			**Thermal conductivity (W/m/˚C)**	**Heat capacity (J/kg/˚C)**
			X	**Y**	**Z**		
Neogene	2109	20	5×10^{-13}	5×10^{13}	5×10^{-16}	1	1035
Eogene	2300	10.0	2×10^{-15}	2×10^{-15}	5×10^{-17}	1.2	878
Mesozoic	2400	10	1×10^{-16}	1×10^{-16}	5×10^{-17}	1.5	888
Ordovician	2723	5.6	1.51×10^{-14}	1.51×10^{-14}	5×10^{-16}	2	932
Cambrian	2760	5	1.25×10^{-14}	1.25×10^{-14}	5×10^{-17}	2.1	827
Proterozoic	2912	5.6	2×10^{-14}	2×10^{-14}	5×10^{-17}	2.3	930
Fracture	2100	30.0	5×10^{-12}	5×10^{-12}	5×10^{-15}	2.7	1000
Rock1	1780	30.0	20×10^{-13}	20×10^{-13}	20×10^{-18}	0.9	1350
Rock2	2700	0.6	20×10^{-40}	20×10^{-40}	20×10^{-40}	3	800

4. ASSESSMENT OF THE PRODUCTION POTENTIAL

4.1 LUMPFIT predictions

In order to assess the production potential of the Zhouliangzhuang geothermal system, the lumped parameter models were used to predict the water level change due to long-term production. Four production scenarios were calculated for both the Ordovician and Cambrian formations, using the corresponding two-tank closed models. The heating season is assumed to be 125 days and hence the non-heating season 240 days.

Table 7 presents these future production scenarios. The predictions are calculated to the year 2025, starting from 2004. The results are shown on Figures 13 and 14. According to the prediction results, the Ordovician formation should be able to sustain a production of 1,700,000 m^3/year until the year 2025, with a drawdown of less than 150 m, which is the limit set by the down-hole pumps to be used. The Cambrian formation should, however, be able to sustain a production of 2,600,000 m^3/year during the same time period. Since the models are closed, no recharge is supplied to the reservoir, reflected in a constant drawdown with time in the second model which has a much smaller volume. However, in the first model the inner part of the reservoir is connected to the outer part which has a very large volume, and supplies the inner part with recharge resulting in almost steady state pressures in the formations.

TABLE 7: Future exploitation scenarios for LUMPFIT predictions

Formation	**Scenarios**			
	Scenario no.	**Production in heating season (l/s)**	**Production in non-heating season (l/s)**	**Annual average production (m^3)**
Ordovician	1	30	5	430000
	2	60	15	960000
	3	120	20	1700000
	4	150	20	2000000
Cambrian	1	30	5	430000
	2	100	15	1400000
	3	200	20	2600000
	4	250	20	3100000

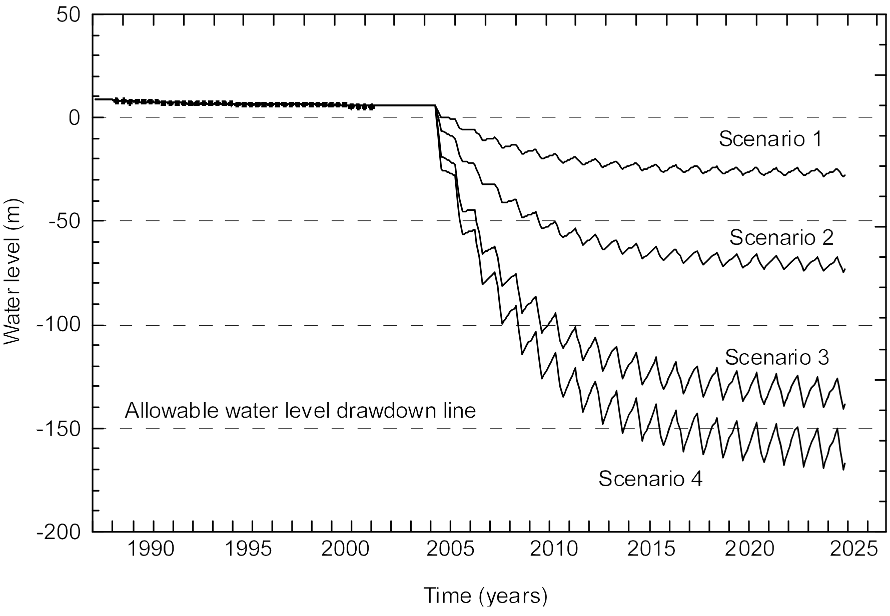

FIGURE 13: Predicted water level decline in the Ordovician formation (well W3) for production scenarios 1-4, calculated by the two-tank closed lumped model

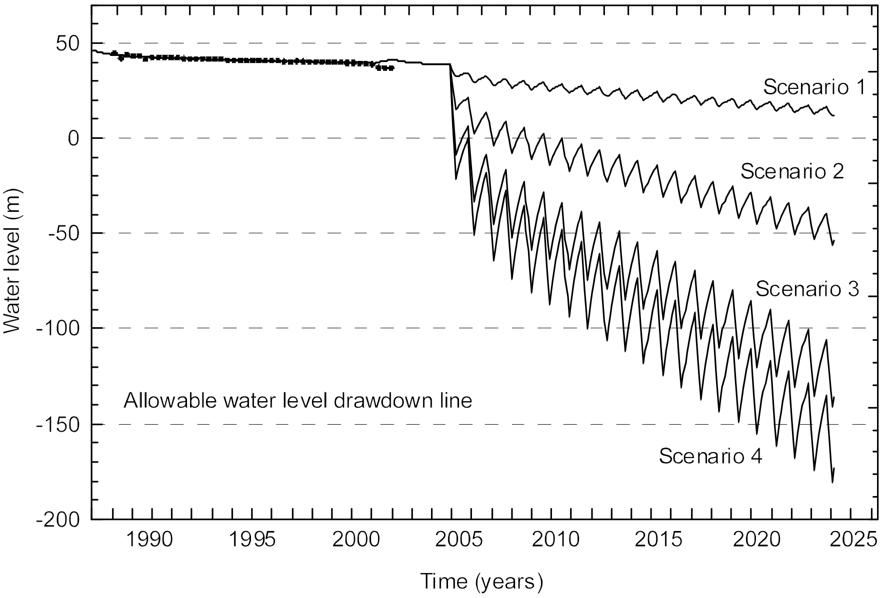

FIGURE 14: Predicted water level decline in the Cambrian formation (well W4) for production scenarios 1-4, calculated by the two-tank closed lumped model

4.2 TOUGH2 model prediction

Several production cases are considered in the TOUGH2 predictions (see Table 8). Only constant-rate scenarios are considered here to simplify calculations. Here, the 8.3 l/s production in the Proterozoic formation in Case 1 is considered to be artesian flow from wells W2 and ZL1.

TABLE 8: Future exploitation scenarios for TOUGH2 predictions

Average production (l/s) **Formation**	**Case 1**	**Case 2**	**Case 3**
Ordovician	65	65	70
Cambrian	80	80	90
Proterozoic	8.3	105	120

Figures 15, 16, and 17 show the results of predictions by TOUGH2 in the three formations, which are also done to the year 2025. It is interesting to note that even though the production is only from the upper two formations (Case 1), the water level drawdown in the Proterozoic formation is larger than in the past (see Figure 17). This results from the fact that the three formations are connected by the faults in the TOUGH2 model. Therefore, the production effect between the formations needs to be comprehensively studied.

Based on cases 2 and 3, the allowable production is as follows:

- 65 l/s or 2.0 × 10^6 m^3/year from the Ordovician formation;
- 85 l/s or 2.7 × 10^6 m^3/year from the Cambrian formation;
- 110 l/s or 3.5 × 10^6 m^3/year from the Proterozoic formation.

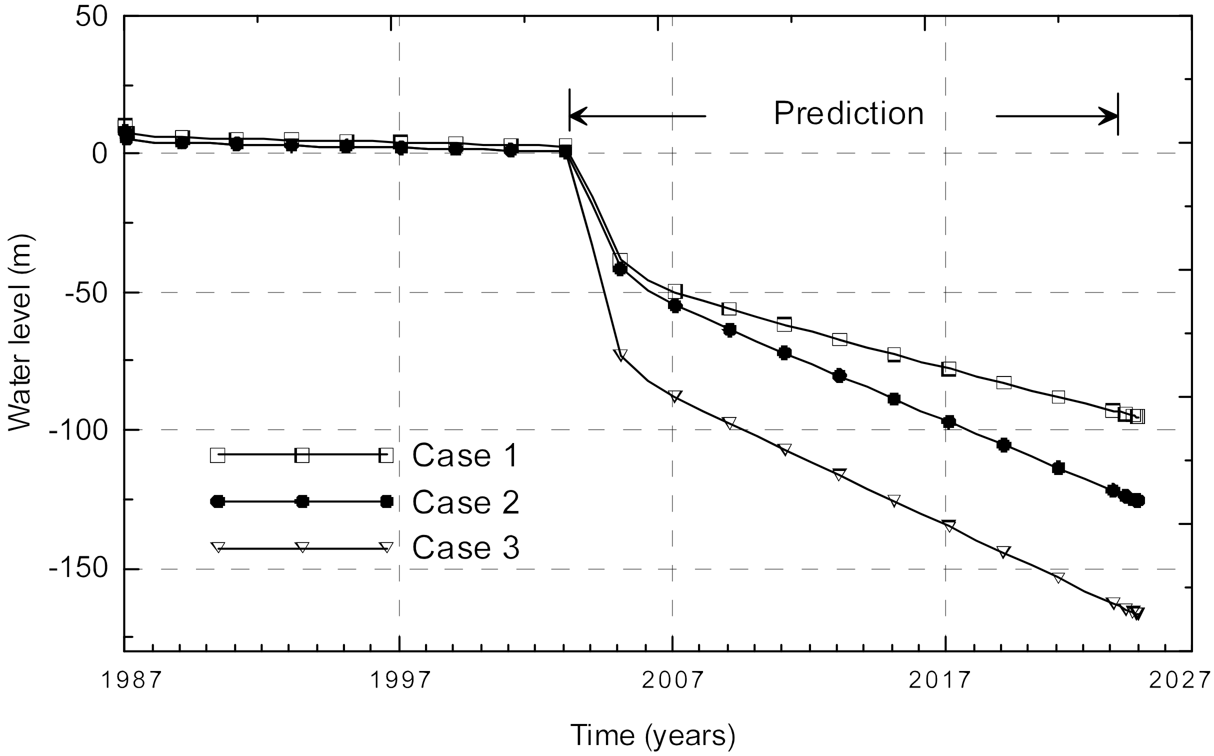

FIGURE 15: Predicted water level decline in the Ordovician formation (well W3) for production cases 1-3, calculated by the TOUGH2 model

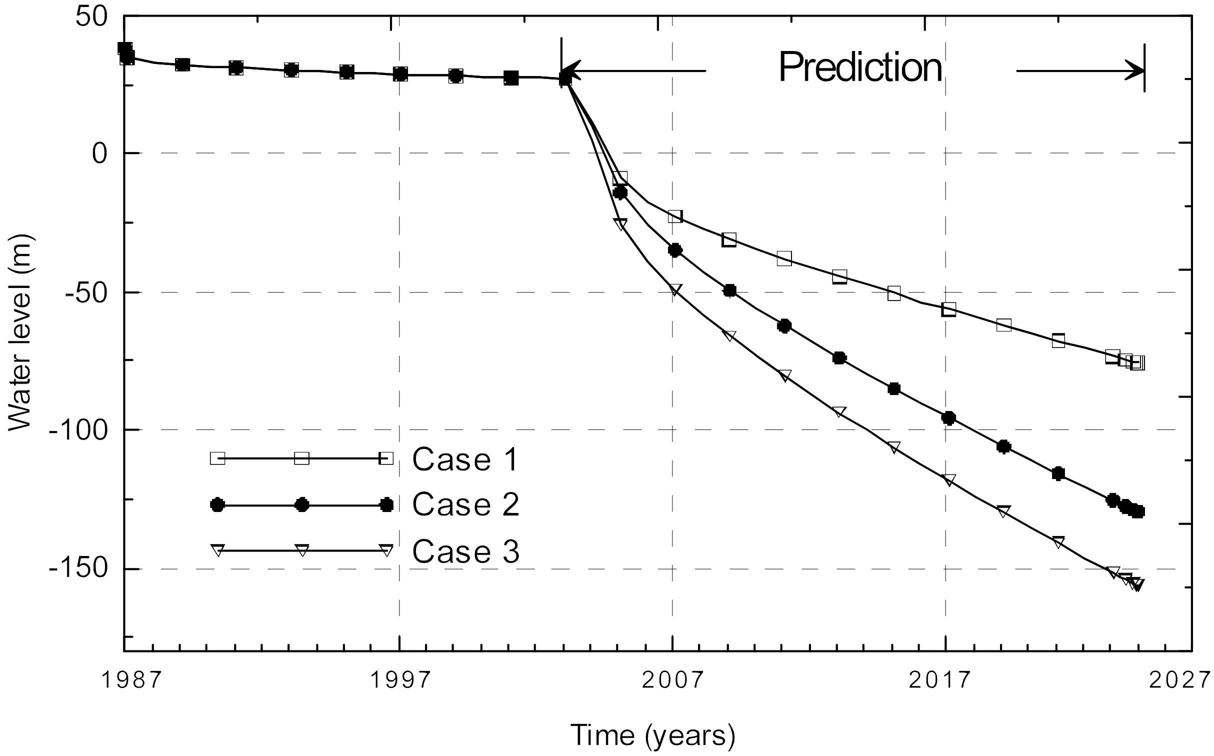

FIGURE 16: Predicted water level decline in the Cambrian formation (well W4) for production cases 1-3, calculated by the TOUGH2 model

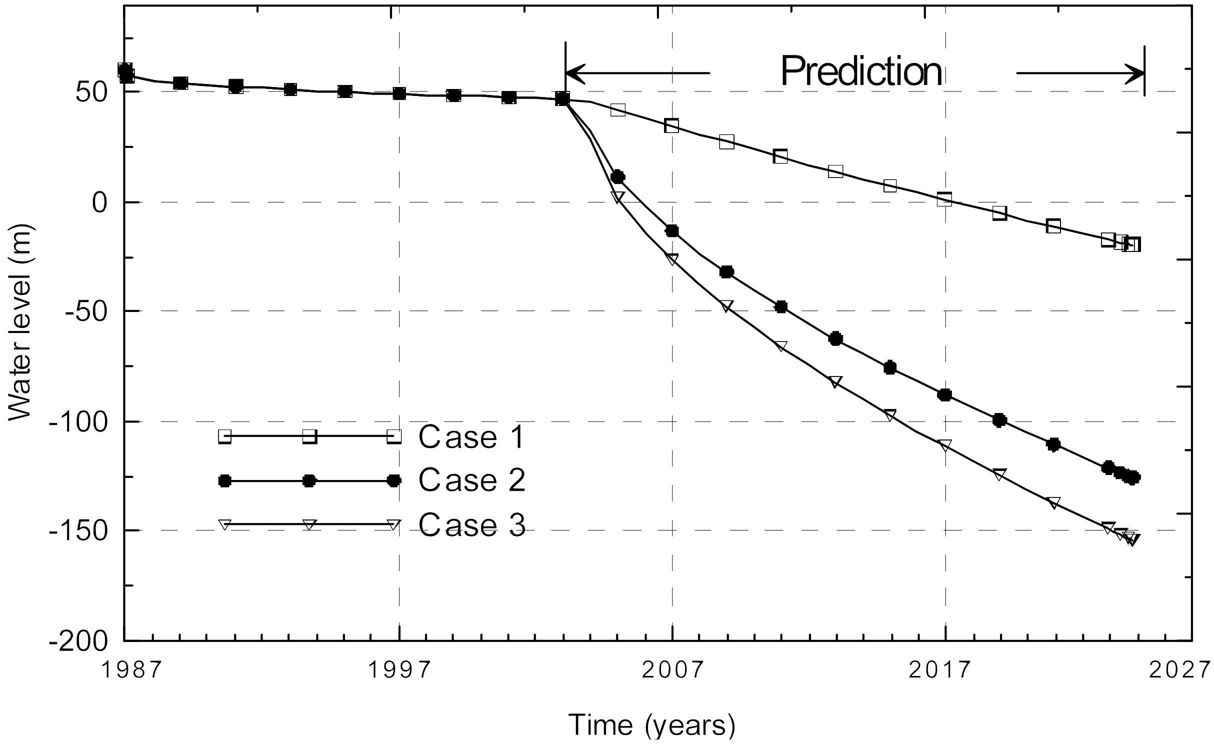

FIGURE 17: Predicted water level decline in the Proterozoic formation (well W2) for production cases 1-3, calculated by the TOUGH2 model

4.3 Production potential of the geothermal system

Based on current economic conditions (cost of extracting, etc.), the allowable maximum water level depth in production wells should be less then 150 m during the next 20 years. Based on the prediction result of LUMPFIT, the potential of the Ordovician formation is estimated to be about 1.7×10^6 m^3/year, and that of the Cambrian formation is estimated to be about 2.6×10^6 m^3/year. Based on the TOUGH2 model, however, the production potential of the Ordovician formation is estimated to be about 2.0×10^6 m^3/year, and the production potential of Cambrian formation about 2.7×10^6 m^3/year. Also, according to the TOUGH2 model, the production potential of the Proterozoic formation is about 3.5×10^6 m^3/year. Therefore, the total allowable production of all three formations is estimated to be about 7.8×10^6 m^3/year.

It must be emphasised that this production potential assessment of the Zhouliangzhuang geothermal reservoirs is only a first estimate. It is based on 15-year monitoring data histories from two artesian wells, producing from two distinct formations. The response to extensive mass extraction is, therefore, poorly known. A new production potential assessment should be done as soon as more data on the response to extensive mass production is available. Careful monitoring of production rates and water level drawdown is, therefore, very important.

5. REINJECTION IN THE ZHOULIANGZHUANG FIELD

Reinjection is currently used in many geothermal fields around the world. Its use started around the year 1970 as a method to dispose of wastewater from power plants for environmental protection. Today, it is also used for pressure maintenance, and for extracting more of the existing thermal energy in geothermal reservoirs (Stefánsson, 1997). According to the results of the lumped parameter simulation, the Zhouliangzhuang geothermal system appears to be mostly closed, at least the deeper parts. The natural recharge to the system is, therefore, limited and the water-level drawdown will increase rapidly in the future with increased production. Reinjection is, consequently, essential to maintain the reservoir pressure in order to enable sustainable utilization and increase the production potential of the system.

Since 1996, reinjection experiments have been conducted in the karst-fissure basement reservoirs in Tianjin. Experiments have verified that colder water can successfully be reinjected into this medium (Wang, 2003). Therefore, both the lumped and numerical models were used to estimate the benefits of reinjection into the Zhouliangzhuang geothermal reservoir, as discussed in the following.

5.1 LUMPFIT reinjection simulations

In the future, geothermal production may be expected to increase as the local economy improves and consumption increases. Table 9 lists the production and reinjection scenarios studied. The predictions are carried out by using the LUMPFIT program and the models already developed for the two formations. Heating season is 125 days.

TABLE 9: Reinjection scenarios used for LUMPFIT predictions

Formation	**Period (years)**	**Production in heating season (l/s)**	**Production in non-heating season (l/s)**	**Reinjection**
Ordovician	2004-2005	30	5	--
	2005-2006	60	15	--
	2006-2008	100	15	50% injection
	2008-2012	150	20	50% injection
	2012-2017	200	20	50% injection
	2017-2022	250	20	50% injection
	2022-2025	300	20	50% injection
Cambrian	2004-2005	30	5	--
	2005-2006	60	15	--
	2006-2008	100	15	50% injection
	2008-2012	200	20	50% injection
	2012-2017	250	20	50% injection
	2017-2022	300	20	50% injection
	2022-2025	400	20	50% injection

Figures 18 and 19 show the results of the lumped parameter predictions with and without reinjection. It is clear that reinjection can efficiently maintain the reservoir pressure. When the injected volume is about 50% of the produced, the production potential apparently increases quite drastically.

5.2 TOUGH2 reinjection calculations

In the TOUGH2 model, the following cases of average production and reinjection were considered:

Production:
- 100 l/s from Ordovician formation;
- 130 l/s from Cambrian formation;
- 160 l/s from Proterozoic formation.

Reinjection:
- 30 l/s into Ordovician formation;
- 40 l/s into Cambrian formation;
- 50 l/s into Proterozoic formation.

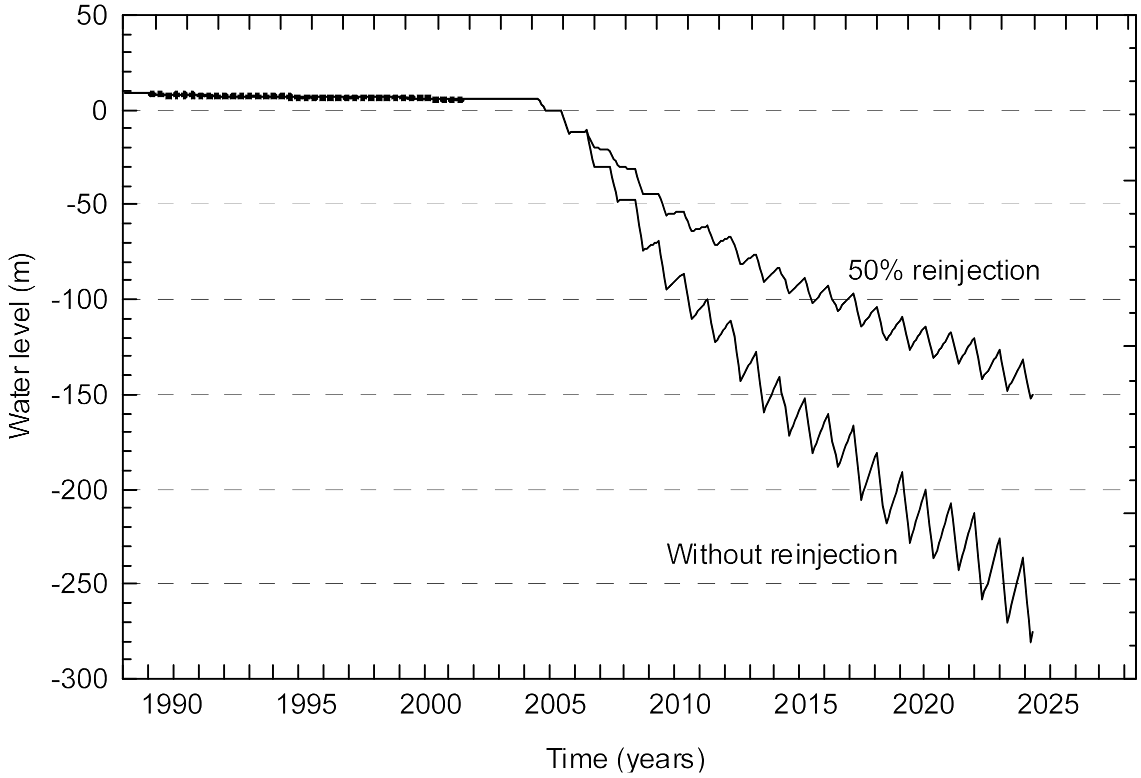

FIGURE 18: Benefit of reinjection into the Ordovician formation, according to the lumped parameter model

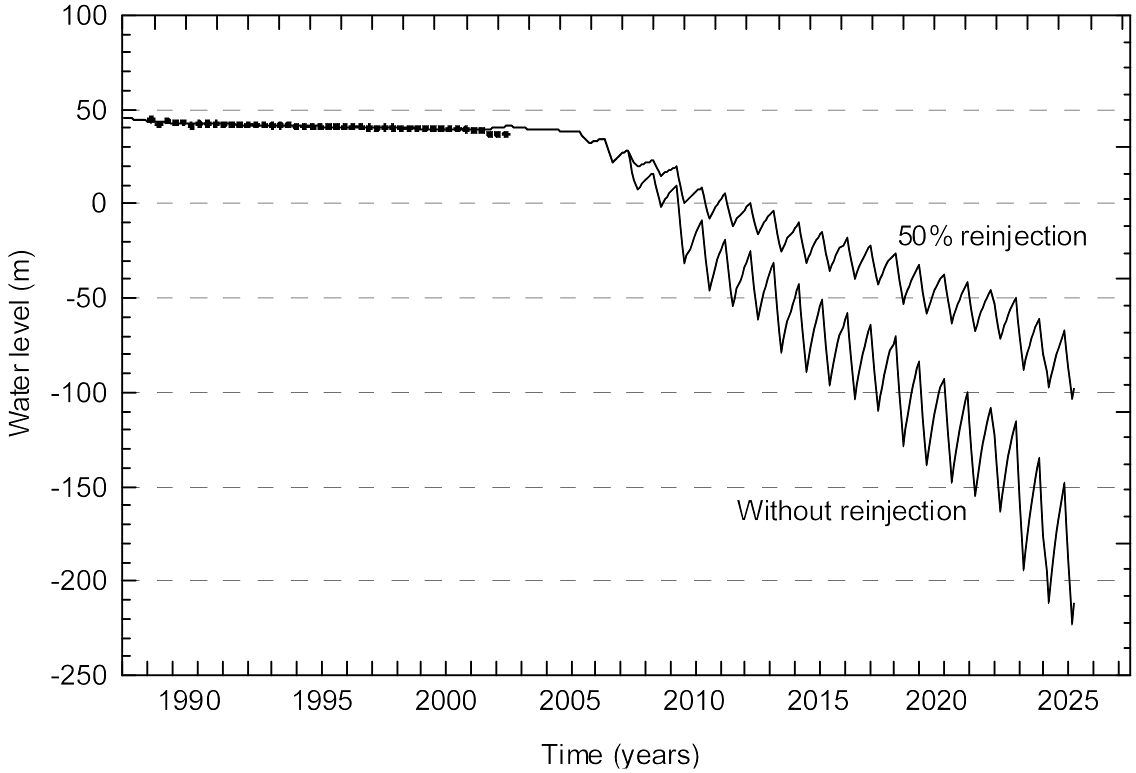

FIGURE 19: Benefit of reinjection into the Cambrian formation, according to the lumped parameter model

This is the minimum reinjection needed to keep the water level above 150 m depth during the 20-year production period.

Figures 20, 21 and 22 show the predicted water level changes with injection and without injection, in the three formations for the next 25 years, according to the TOUGH2 model. According to the predictions by the two models, reinjection appears to be a good method of maintaining the reservoir pressure.

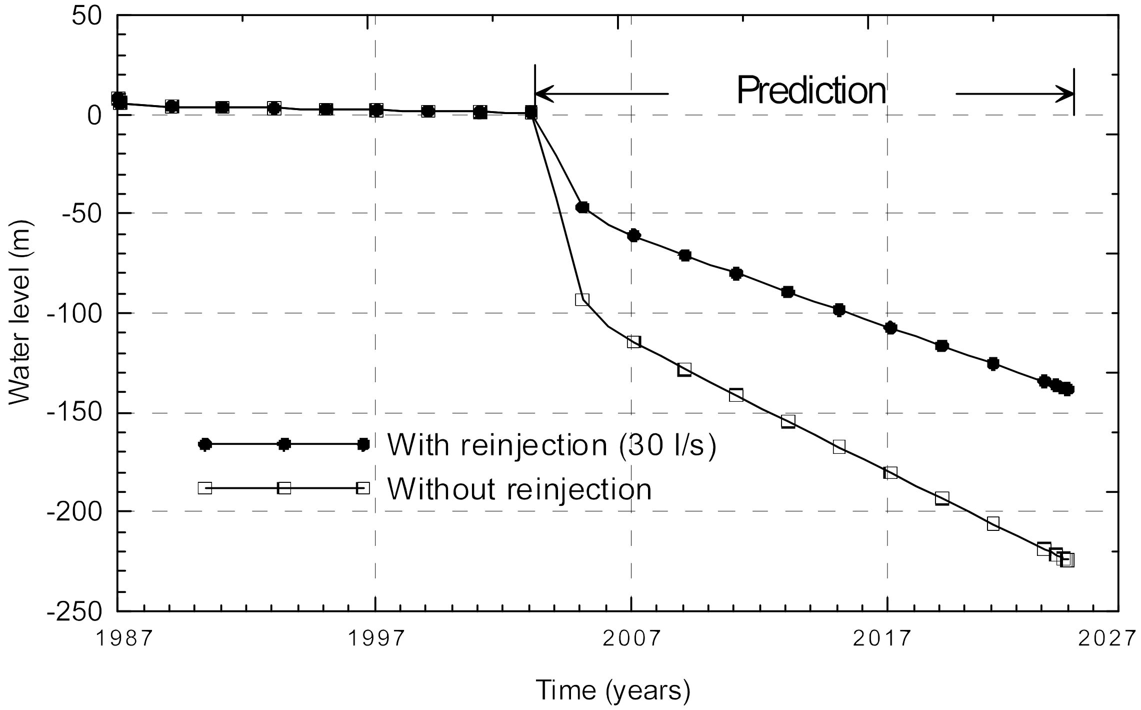

FIGURE 20: Benefit of reinjection into the Ordovician formation, according to the TOUGH2 model

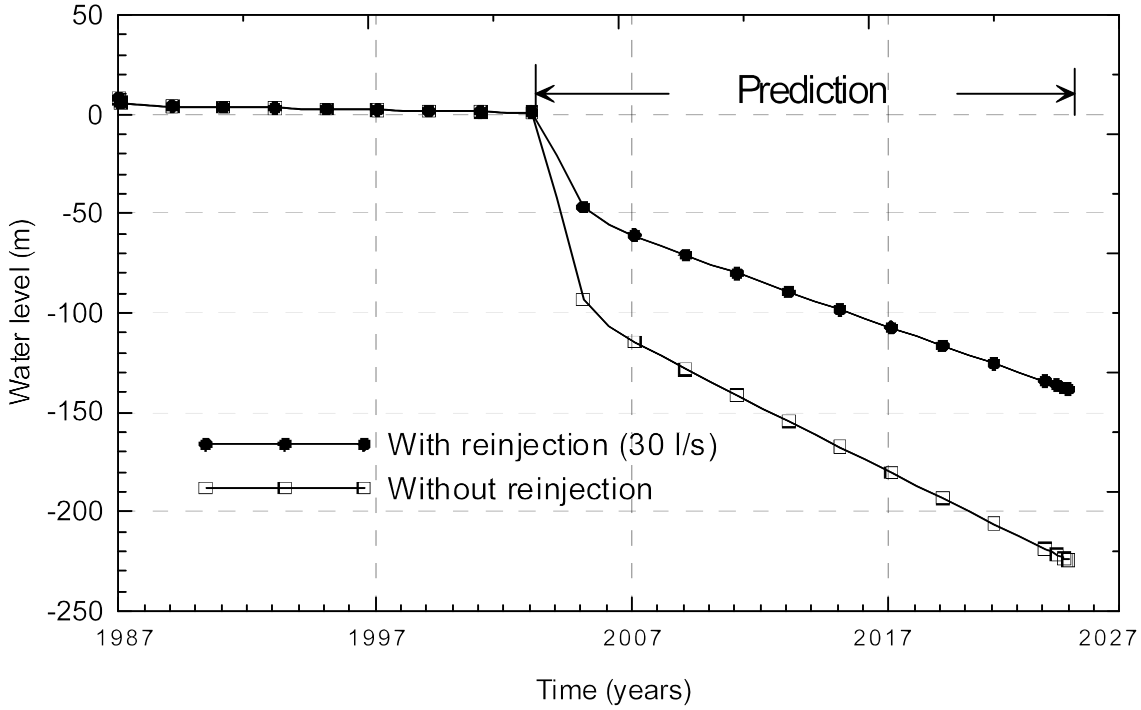

FIGURE 21: Benefit of reinjection into the Cambrian formation, according to the TOUGH2 model

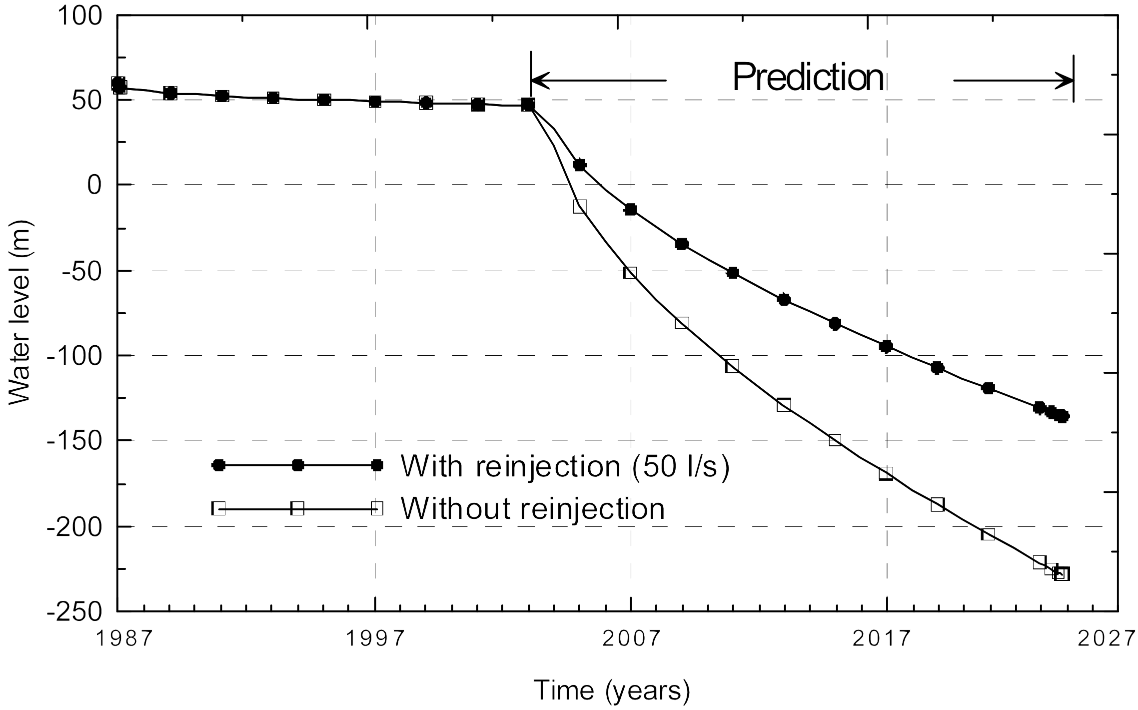

FIGURE 22: Benefit of reinjection into the Proterozoic formation, according to the TOUGH2 model

5.3 Increased production potential

According to the reinjection simulation by the lumped parameter models, the production potential of the Ordovician formation is estimated to be about 3.6×10^6 m^3/year, and the Cambrian formation to be about 4.7×10^6 m^3/year, both with 50% injection. Reinjection calculations by the TOUGH2 model, give the production potential of the Ordovician formation to be about 3.2×10^6 m^3/year; 4.1×10^6 m^3/year for the Cambrian formation; and 5.0×10^6 m^3/year for the Proterozoic formation. This leads to a total allowable production of about 12.2×10^6 m^3/year, with average injection rates of about 30, 40, and 50 l/s, respectively.

5.4 Thermal breakthrough

The main side effect anticipated from injection is the possible cooling of the reservoir and production wells involved (Axelsson, 2003b). Therefore, it was also necessary to investigate the possible cooling/thermal breakthrough in the reservoir due to reinjection, and how to plan locations of reinjection wells relative to production wells.

Thermal breakthrough time is defined as the time it takes a production well to start cooling down after reinjection starts in a nearby well. It depends on the properties of formation, such as the thermal conductivity of rock, heat capacity of the formation (water and rock), and properties and nature of flow paths, etc. Here, two methods are used to estimate the possible cooling. One is based on the theory of heat transport in a liquid-phase porous media geothermal system with radial flow; the other is based on the TOUGH2 model in which the reinjection well is located close to the production wells. These methods can simulate the possible cooling in the reservoirs based on properties of the formation in the models.

In the first method, heat transport is assumed to be by intergranular fluid flow. It is assumed that the rock grains are so small that rock and fluid are at the same temperature at any point (Axelsson, 2003c). Therefore, the temperature change in the formation can be described by the equation:

$$\frac{\partial T}{\partial t}+\frac{\beta_w}{\langle\rho\beta\rangle}\vec{q}\bullet\nabla T=0 \qquad (5)$$

where T = Temperature (˚C);
β_w = Heat capacity of water (J/m^3 ˚C);
$\langle\rho\beta\rangle$ = Volumetric heat capacity of reservoir (J/m^3 ˚C);
q = (q_x, q_y, q_z) the mass flow vector (kg/m^{3}s);
∇T = $\left(\frac{\partial T}{\partial x},\frac{\partial T}{\partial y},\frac{\partial T}{\partial z}\right)$ the temperature gradient vector.

The volumetric heat capacity of the reservoir as used in this equation equals:

$$\langle\rho\beta\rangle=\rho_w\beta_w\phi+\rho_r\beta_r(1-\phi) \qquad (6)$$

where ρ_w and ρ_r = Density of water and rock, respectively;
β_w and β_r = Heat capacity of water and rock, respectively;
ϕ = Porosity of the formation.

Then, a horizontal model with 2-D flow can be used to calculate the radial distance from injection well to the temperature front:

$$r_T=\left[\frac{\beta_w Qt}{\pi H\langle\rho\beta\rangle}\right]^{1/2} \qquad (7)$$

where β_w = Water heat capacity, which is 1000 J/m^3 ˚C;
H = Reservoir thickness (m);
Q = Injection flowrate (kg/s);
t = Time (s).

The properties of the rock in different formations are listed in Table 10 as well as injection flowrates, which are assumed to be half of the production potential. The temperature of the injected water is assumed to be about 40˚C.

TABLE 10: Rock properties in the formations of the Zhouliangzhuang geothermal system and assumed reinjection rates

Rock type	Density (kg/m^3)	Porosity (%)	Thermal conductivity (W/m˚C)	Heat capacity (J/kg˚C)	Thickness (m)	Reinjection flowrate (kg/s)
Ordovician	2723	5.6	2.1	932	500	30
Cambrian	2760	5.0	2.1	827	500	45
Proterozoic	2912	5.6	2.1	930	1000	60

Figure 23 shows how the cold front moves away from the reinjection well into the reservoir with time, according to the porous media model (Equation 7). According to these calculations, the cold front in the Cambrian formation should have moved 400 m away from the reinjection well after 100 years of constant 45 l/s injection. In the Ordovician and Proterozoic formations, the cold front should have moved about 300 m after the same time during constant 30 and 60 l/s injection, respectively. This indicates that reinjection can be sustained for a long time if the distance between reinjection and production wells is sufficient. It should be kept in mind that these results are dependent on several assumptions, a critical one is the formation thickness (Table 10). If the injected water is not distributed over the whole thickness of a formation, a more rapid cold front breakthrough is expected.

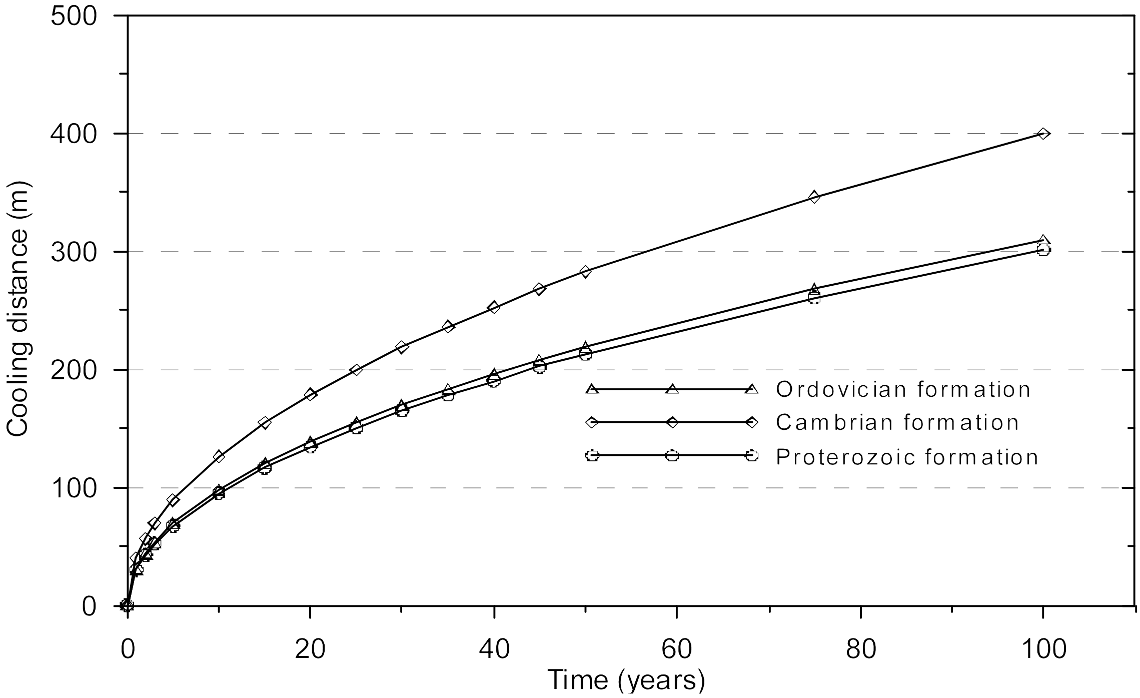

FIGURE 23: Estimated cold front movement during injection according to the porous media model

The TOUGH2 numerical model was also used to calculate the temperature of the water produced from well W4 in the Cambrian formation during constant 80 and 100 l/s production and 40 l/s injection of 30°C cold water into an injection well 1000 m away. Figure 24 shows the results, which indicate that the temperature of produced water will only cool down by about 0.15°C in one hundred years. This is in agreement with the previous calculation reflecting that the cold front has only moved about 300 m away from the injection well.

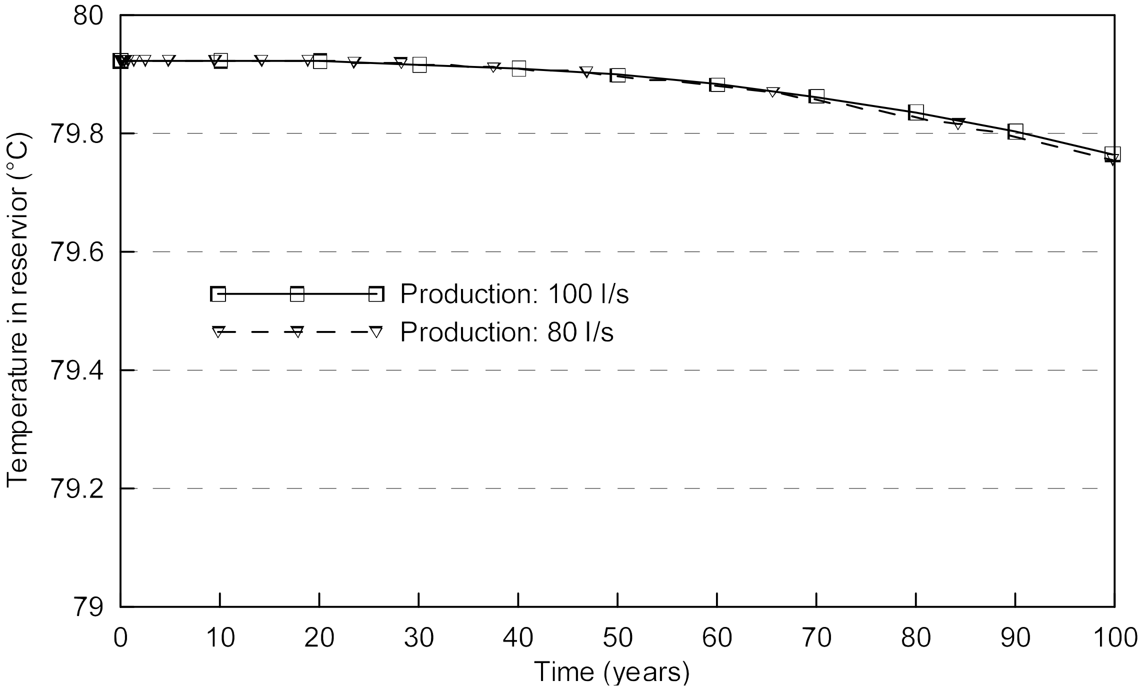

FIGURE 24: Prediction of cold front movement during injection with the Tough2 numerical model

Based on these two simple reinjection modelling studies, it seems that if a reasonable distance is kept between production and reinjection wells, the danger of premature cooling is minimized. However, these results are based on highly simplified assumptions, as already mentioned. But tracer tests are a good tool to study the connections between injection and production wells in order to enable more accurate predictions of the possible decline in production temperature due to long-term reinjection (Axelsson, 2003b). Tracer tests have not been carried out in the Zhouliangzhuang geothermal field. In the future, after reinjection starts, tracer tests should be carried out as soon as possible to estimate the thermal breakthrough time.

6. SUMMARY AND RECOMMENDATIONS

The main results of this report may be summarized as follows:

- The Zhouliangzhuang geothermal system is a low-temperature sedimentary geothermal system, with conduction dominated heatflow. The system consists of three main reservoirs associated with different formations (Ordovician, Cambrian and Proterozoic). The three aquifer formations are believed to be separated by impermeable layers and they are, hence, poorly connected hydrodynamically. The temperature of different parts of the geothermal system ranges from 60 to 102°C, and the wellhead pressure is 0.6-6 bar, increasing with well depth.

- Three geothermal wells have been subject to long-term extraction at low flowrates. Therefore, the geothermal system can be considered being close to the natural state. The only response data available are data on the well head pressure response to production for two wells, which discharge from the Ordovician and Cambrian formations.

- A lumped parameter model was set up, using the LUMPFIT program, based on the production and wellhead pressure histories of these two wells. The Ordovician and Cambrian formations are both simulated by closed two-tank models, which are believed to be in agreement with the nature of the formations, which are believed to have limited recharge. Closed models also lead to conservative predictions.

- Based on the conceptual model, a simple numerical distributed parameter model was also set up using the TOUGH2 program. It simulates the two production histories, and again the Zhouliangzhuang geothermal system is simulated as a closed system.

- According to predictions for various exploitation scenarios, calculated by both models, the production potential of the Ordovician formation is estimated to be $1.7\text{-}2.0\times10^6$ m^3/year for the next 20 years. The production potential of the Cambrian formation is estimated to be about $2.6\text{-}2.7\times10^6$ m^3/year. Based on the TOUGH2 model, the production potential of the Proterozoic formation is estimated to be about 3.5×10^6 m^3/year. The total allowable production is therefore about 7.8×10^6 m^3/year for the next 20 years with water level drawdown less than 150 m.

- Production from the geothermal system may be increased and sustained for a longer time by using reinjection to counteract the water level drawdown.

- Both a simple porous media model and the TOUGH2 model were used to estimate the cooling of the produced water during injection. It seems that if a reasonable distance between production and reinjection wells is used, cooling risk can be effectively minimized.

The study presented in this report is limited by a lack of data on the geothermal system, which also affects the reliability of the results. Therefore, the author would like to make some suggestions, which may be helpful in the future management of the geothermal resources in the Zhouliangzhuang field.

- During the distributed parameter modelling, the complex geology of the geothermal system has been simplified drastically because of limited geometrical data. Therefore, the details of the numerical model should be increased as more data becomes available.

- Cooling predictions are based on assumptions on porous media flow, which may not be in complete agreement with the real situation. Therefore, tracer tests should be carried out to study connections between wells and estimate the thermal breakthrough time.

- Careful monitoring of production parameters for the Ordovician and Cambrian formations should be continued, and a comprehensive monitoring program set up that should involve production from the Proterozoic formation as well as other possible formations, such as the Neogene formation. The data collected will be an essential guide for future management of the geothermal resources.

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