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EVALUATION OF THE SILAPU GEOTHERMAL FIELD, LIAONING PROVINCE, CHINA

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ABSTRACT

The Silapu geothermal system is a fracture controlled low-temperature system, located in Liaoning Province, Northeast China. Wells drilled in this area are not deep enough to reach a sedimentary geothermal reservoir believed to exist at greater depth. Water temperature is in the range of 90-100°C. Total usable heat energy estimated by the volumetric method is 3.1×10^{-16} J. Geothermal exploration started in 1980 and lasted for more than three years. The properties of the geothermal field were estimated by analysing well test data. The average transmissivity is estimated to be about 1.2×10^{-7} m^3/Pas corresponding to a permeability-thickness of 35 D-m. Assuming a maximum allowable water level drawdown of 75 m, the production potential of the field is estimated to be 2.52 Mm^3/year corresponding to 22 MW_t. The water level drawdown may be reduced by reinjection. Further exploration for the deeper reservoir is recommended as well as comprehensive thermal field monitoring during utilization.

1. INTRODUCTION

The Silapu geothermal field is located in the south part of Liaoning Province in Northeast China, about 30 km south of Yingkou City (Figure 1). Geothermal water was utilized in the 1950´s, and initially for bathing and swimming. After several wells were drilled in the 80´s, the utilisation changed mainly to space-heating and greenhouse heating.

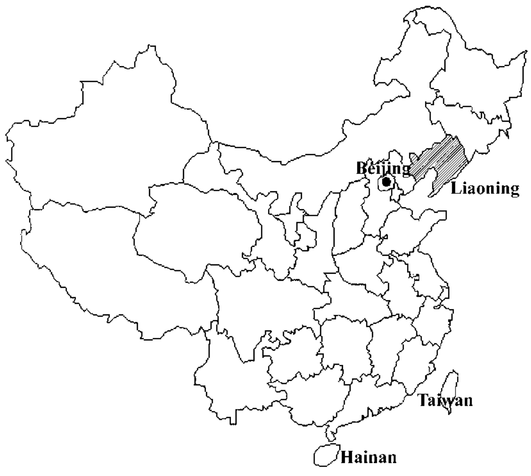


FIGURE 1: A map of China showing location of the Liaoning Province

Exploration for geothermal water through drilling started in Silapu in 1980. From 1981 to 1983, five production wells were drilled in this area to depths between 200 and 500 metres. All the wells had artesian flow and water temperature of about 100°C. This is the highest temperature for thermal water found so far in Liaoning Province.

This report presents an evaluation carried out for the Silapu geothermal field. The volumetric method is first used to calculate the usable total heat energy. There is no long-term production data available, but well test data is used to estimate the hydrological properties and predict water level changes in the geothermal field. The most important question here is how the geothermal field will respond to future production and what the production potential of the field is. Two computer models, VARFLOW and LUMPFIT, are used to answer these questions. Reinjection is also discussed in this report as a method of enabling some water level recovery.

As the five wells drilled in Silapu geothermal field are too shallow to reach the proposed sedimentary geothermal reservoir, prediction of the temperature of the deeper reservoir is carried out using both geochemical methods and by extrapolation of shallow temperature gradients.

2. THE SILAPU GEOTHERMAL FIELD

2.1 Geological outline

Geological conditions are rather simple in the Silapu area. *Quaternary sedimentary formations* are widely distributed in valleys and lowlands, mainly formed by diluvium and alluvium. The Quaternary sediments are composed of clay, middle-thick sand, gravel and scree. The thickness is generally between 10 and 40 m, but the maximum is 46 m.

The so-called *Cretaceous Wangershan formation* is rather thin and distributed in an E-W direction. It cannot be seen on the surface, only in the boreholes. It is mainly composed of sandy-conglomerate or sandstone. Its thickness varies between 1 and 3.9 m.

Intrusive rock is widely distributed on the surface or under the Quaternary sediments. It has hoar or white colour. The composition is mainly quartz, feldspar and some black mica etc. Magma intrudes through faults and fractures. Intrusive veins are usually 0.3-2 m across, but the maximum is 200 m in the eastern part.

2.2 Tectonism

The Silapu area is tectonically active. Some faults or fractures can be seen in this area in NNE-SSW and E-W direction. Magma intrusion and frequent seismic activity make it easy for water to warm up and flow through the faults.

There are several north-northeasterly faults in this area, almost parallel to each other (see Figure 2). The faults are granitic and their obliquity is between 60° and 90°. E-W faults can also be seen in this area. The

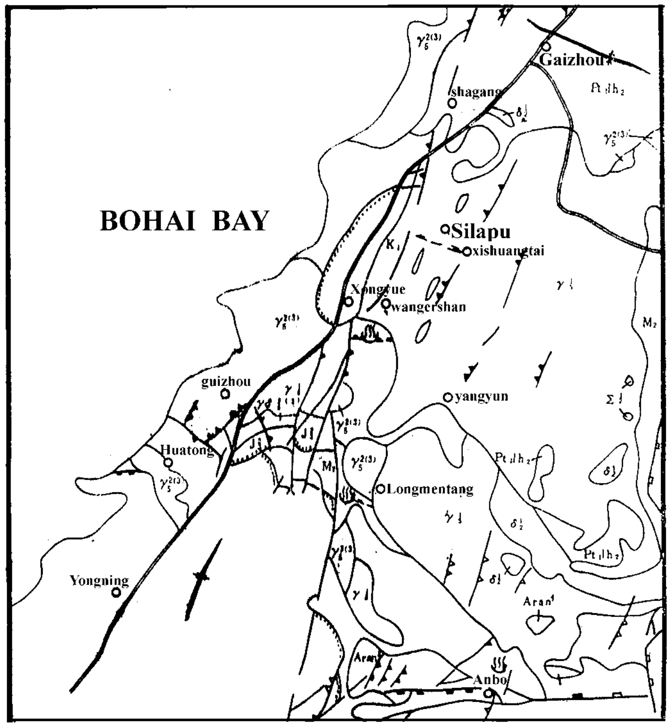


FIGURE 2: Tectonic map of the Silapu area in Northeast China (Cong et al., 1983)

faults cut through Cretaceous formations, showing that the tectonic movement is rather recent. These faults are cut by the more recent north-northeasterly trending faults (see also Figure 2).

2.3 Hydrological and chemical conditions

From Silapu and to the south, some hot springs are found in the towns of Xongyue, Huangshao and Longmentang. These are almost on a line in the same direction as the north-northeasterly faults. So we can hypothesize that there must be a deep geothermal reservoir in the area and that hot water rises by convection through faults to the surface. According to well test data, the reservoir porosity is 10% and its hydraulic conductivity 0.88-0.92 m/day (Cong et al., 1983).

The chemical composition of the water is quite variable between the wells, but is similar in the five production wells SL3, SL11, SL13, SL17 and SL35. Table 1 shows the chemical composition of the water in different wells.

TABLE 1: Chemical composition of geothermal water in the Silapu area (mg/l)

Well no.	T (°C)	K^+	Na^+	Cl^-	SO_4^{-2}	F^-	Soluble CO_2	TDS	pH
SL1		30.4	600	952.0	110.4	7.6	104	1932.6	8.86
SL2	46		173.3	200.0	55.0	3.5	61.8	704.0	7.49
SL3	96	31.2	600	942.6	111.0	7.0	135.2	1970.8	8.55
SL4	83.6	26.0	580.0	922.8	110.5	7.0	94.4	1889.9	8.47
SL5	38.0	7.4	51.4	87.7	9.0	0.4	32.0	244.1	8.15
SL6	66.0	4.6	220	350.1	51.8	3.0	56.0	813.0	7.3
SL7	31		328.8	303.5	54.1	0.4	10	970.0	7.99
SL8	33	5.6	218.0	310.1	0	3.6	108.8	777.8	8.22
SL9	57	15.2	200	420.1	34.4	4.0	62.5	1020.1	8.1
SL10	41	18.1	584	927.8	94.5	6.6	74.4	1881.6	7.76
SL11	86.4	26.2	614	917.5	117.3	8	100	1158.1	7.62
SL12	91.5	32.1	584.0	929.8	83.6	6.6	80.4	1893.9	7.9
SL13	96	27	584.0	935.9	145.6	8.0	122.4	1967.6	8.48
SL14	92	33.1	588.0	934.6	105.4	7	84.8	1915.4	7.60
SL16	34	10	193.6	303.0	30.2	2	57.6	809.5	8.04
SL17	99.5	26.6	600	938.5	111.6	0.1	68.4	1881.3	8.62
SL18	25	22.0	504	661.7	83.8	6.5	73.2	1637.3	7.96
SL19	51.5	11	500	816.7	67.9	6.4	60.8	1657.7	8.12
SL20	22.5	23	520	837.8	5.7	7.5	20.4	1576.4	7.67
SL28	27	9	303	412.2	42.1	7	22.1	964.3	8.09
SL31	34.5	8.6	290	355.6	70.4	4	52.4	936.5	7.76
SL32	41.5	8.8	518.0	827.3	75.7	0.6	7	1588.8	7.5
SL33	20	2.6	184.0	172.0	26.2	1.0	21.6	670.9	8.00
SL34	27.5	3.4	48.0	26.2	33.7	0	27.6	339.5	8.02
SL35	97.0	32.8	590.0	913.6	116.6	7	115.6	1918.3	8.86

2.4 Exploration history

Geothermal water in this province was discovered a long time ago. Several hot springs are found in Silapu, Xongyue, Huangshao, and Longmentang. An intensive exploration for geothermal water started in the autumn of 1980. At first, the exploration area was large, extending from Silapu to the Longmengtang area. A prospect report was finished after a study on the geohydrology and a resistivity survey at the end of the year.

In 1981, 12 shallow boreholes about 20-30 m deep and a deeper well about 250 m were drilled. After analysing the data from temperature measurements and drawdown tests, the exploration area was reduced to just the Silapu area. In 1982, 8 shallow boreholes (20-30 m deep) and 3 deeper wells (200-250 m deep) were drilled in the Silapu area. Water temperature in well SL17 (99.5°C) is the highest temperature found yet in Liaoning Province. The last well was drilled in 1983 to the depth of 501 m. From 1981 to 1983, 20 shallow boreholes and 5 deeper wells were successfully drilled. All the five production wells have artesian flow with water temperature from 88.5 to 99.6°C (see Table 2).

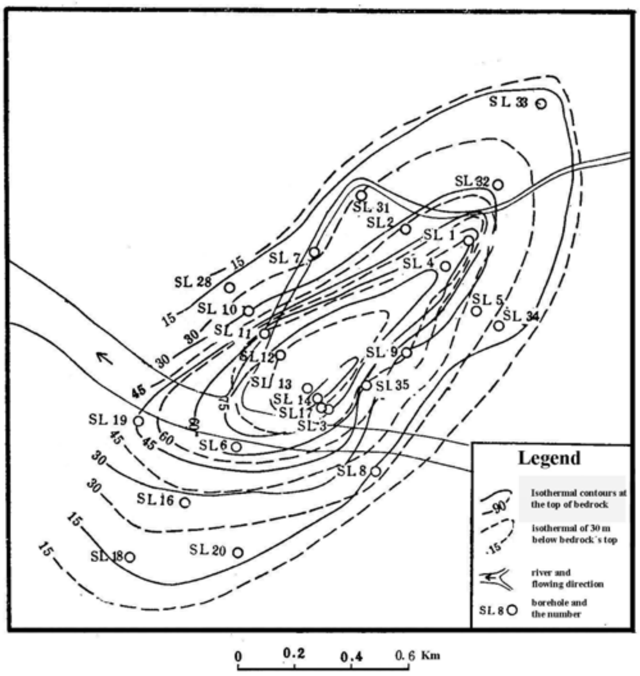


FIGURE 3: Isothermal map of the Silapu area (Cong et al., 1983)

TABLE 2: Information on the deeper wells in the Silapu geothermal field

Well no.	Depth (m)	Free-flow (l/s)	Temperature (°C)
SL3	251.2	4.0	94
SL17	250.7	1.5	99.6
SL11	208.4	0.72	84
SL13	240.7	3.0	93
SL35	501.0	1.2	88.5

Figure 3 shows the results of temperature measurements at the top of the bedrock and 30 m below the bedrock´s top as temperature contours. The figure indicates that the surface extension of the temperature anomaly is about 10.5 km^2.

2.5 Volumetric resource assessment

The volumetric method is used to assess the potential of the geothermal resource. The volumetric method involves the calculation of thermal energy contained in a given volume of rock and water, and then the estimation of how much of this energy might be recoverable. The thermal energy in the subsurface is calculated as follows:

$$E = E_r + E_w = V C_r \rho_r (1-\phi)(T_i - T_o) + V C_w \rho_w \phi (T_i - T_o) \qquad (1)$$

where E = Total thermal energy in the rock and water [kJ];
V = Reservoir volume [m^3];
T_i = Initial reservoir temperature [°C];
T_o = Reference temperature [°C];
C_r = Heat capacity of rock [kJ/kg °C];
C_w = Heat capacity of water [kJ/kg °C];
ρ_r = Density of rock [kg/m^3];
ρ_w = Density of water [kg/m^3];
ϕ = Porosity.

For the Silapu geothermal field the following assumptions were made (Holman, 1989):

T_i = 100°C; T_o = 25°C; ϕ= 0.1; ρ_r = 2640 kg/m^3;
ρ_w = 960 kg/m^3; C_r = 0.82 kJ/kg °C; C_w = 4.20 kJ/kg °C,; $V = 1.75\times10^8$ m^3.

Thermal water is expected to be first used for space-heating and then for cascaded use in swimming pools or fish farming. Therefore, an average waste water temperature of about 25°C (T_o) is assumed. Inserting the above values in Equation 1 results in an estimate for total heat energy of 3.09×10^{16} J.

The space-heating potential of the reservoir is calculated as follow:

$$Reserve(MW_t) = \frac{heat\ energy \times recovery\ factor}{plant\ life \times load\ factor} \qquad (2)$$

Assume 35°C hot water is discharged from houses, so heat energy which can be used by space-heating is 2.68×10^{16} J. Here we assume a *recovery factor* of 0.25, a *load factor* of 0.33 and a *plant life* of 20 years. This gives a space-heating potential estimate for the Silapu geothermal field of 32.7 MW_t. Based on an average requirement of 40 W/m^2 for space-heating (Axelsson and Dong, 1998), this should be sufficient power to heat more than 800,000 m^2 of living space, or about 10,000 average- sized apartments (assuming 80 m^2 for each apartment).

3. ANALYSIS OF WELL TEST DATA

Some well tests were carried out after wells were completed in the Silapu area. Production and build-up data from these tests have been used to estimate the hydrological properties of the Silapu geothermal field.

3.1 Correction of water level for flow rate characteristics

In a production well, water level or pressure can be affected by pressure losses due to friction during turbulent flow. The water level or pressure, H, in a flowing water well often follows the relation:

$$H = H_o + B\times Q + C\times Q^2 \qquad (3)$$

where Q = Flow rate;
H_o = Water level in the well at zero flow (static well);
$B\times Q$ = Linear drawdown in the reservoir;
$C\times Q^2$ = Pressure loss caused by turbulent flow at the location of inflow into the well and in the well itself.

Corrected water level H' is then approximated by:

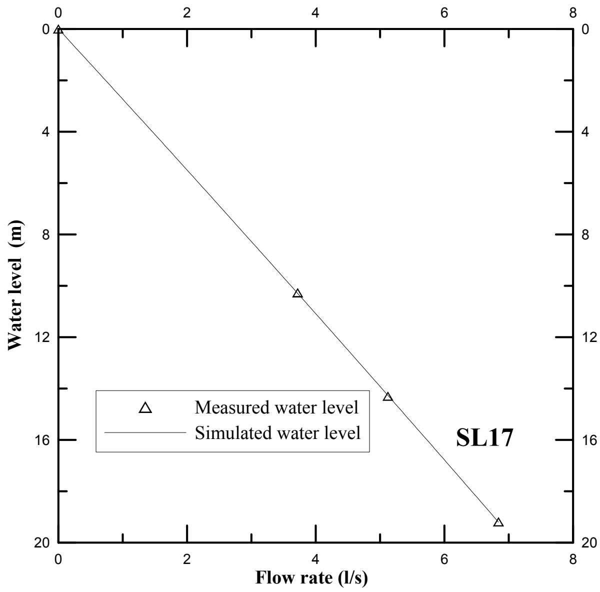
$$H' = H - C\times Q^2 \qquad (4)$$

Two well test data sets will be used to estimate the hydrological properties of the Silapu geothermal field. The two wells, SL17 and SL35, are both production wells but used also as observation wells. Therefore, water level must be corrected before estimations are made.

A simulation has been carried out to find the relationship between the water level and the flow rate (see Figure 4.). The relations for the two wells are as follows:

SL17: $H = H_o + 2.72Q + 0.012Q^2$
SL35: $H = H_o + 1.26Q + 0.190Q^2$

The water level in each well can consequently be corrected by using Equation 4.



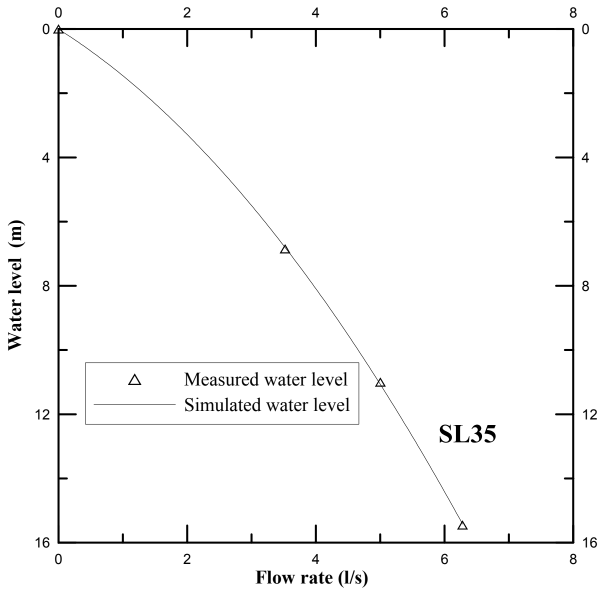


FIGURE 4: Simulated results of water level correction of wells SL17 and SL35

3.2 Pressure transient analysis

Pressure transient tests provide information on the hydrological conditions of the well/reservoir system and form a basis for future prediction of well yield and pressure drawdown in the reservoir. During a well test, the flow rate from an active well is changed. This will cause a time-dependent pressure change in the reservoir, which is either monitored in the active well itself (single well test) or in an observation well (interference test). Well known methods of analysing the test data are based on the Theis solution to the pressure diffusion equation.

Several simplifying assumptions are made in the Theis model:

1. Prior to the well test, the reservoir pressure is uniform;
2. The reservoir is homogeneous, isothermal and isotropic and the well fully penetrates the reservoir;
3. The reservoir is horizontal, of uniform thickness and infinite in radial extent, and has impermeable boundaries at the top and bottom;
4. The reservoir fluid flow follows Darcy´s law.

3.2.1 Computerized analysis using VARFLOW

VARFLOW calculates pressure changes in response to fluid production/injection from/into an idealized reservoir system, which is based on the Theis-model (EG&G Idaho Inc. and Lawrence Berkeley Laboratory, 1982). The program is set up to calculate pressure changes of up to 25 observation wells. These observation wells may be interference monitoring wells or production wells.

In an isotropic reservoir, pressure changes caused by production/injection from a single well with a variable flow rate can be calculated from Equation 5 below. The VARFLOW computer code, which is based on this equation, can be used to analyse pressure transient data by varying the parameters (such as transmissivity, storativity, skin factor and boundary conditions) until a satisfactory match is obtained.

$$P(r,t) - P_o = \frac{\mu}{4\pi k h}\int_0^t \frac{q(\tau)}{t-\tau}\exp\left[\frac{-\mu c_t r^2}{4k(t-\tau)}\right]d\tau \tag{5}$$

where P = Pressure [Pa];
P_0 = Initial reservoir pressure [Pa];
T = Time [s];
r = Radial distance from the well [m];
k = Permeability [D, 10^{-12} m^2];
h = Aquifer thickness [m];
ì = Dynamic viscosity of geothermal water [kg/m s];
ô$_n$ = Time at which the flow starts [s];
ô$_{n+1}$ = Time at which the flow stops [s];
$q(\tau)$ = Volumetric flow rate at time τ [m^3/s];
c_t = $\phi c_t + (1-\phi)c_r$ = Compressibility of the reservoir [1/Pa];
ϕ = Reservoir porosity;
c_w = Compressibility of water [1/Pa];
c_r = Compressibility of rock [1/Pa].

If r is small and t is large, Equation 5 with $r = r_w$, can be approximated by

$$P(r_w,t) = P_o - 0.1832\frac{q\mu}{kh}\left[\log(t) + \log\left(\frac{k}{\mu c_t r_w^2}\right) + 0.3514 + 0.8686s\right] \tag{6}$$

In Equation 6, a so-called skin factor, s, is also introduced, representing an additional pressure drop in the active well because of near well effects. The skin factor is estimated from a rearranged form of the above equation and can be used in the analysis with VARFLOW, as follows:

$$s = 1.1513\left[\frac{\Delta P}{m} - \log\left(\frac{k}{\mu c_t r_w^2}\right) - 0.3514\right] \tag{7}$$

where m = $0.1832\, q\mu/kh$;
ΔP = $P_o - P(r_w, 1)$.

3.2.2 Computerized analysis using LUMPFIT

A powerful program used to analyse pressure changes in a geothermal reservoirs as well as in other hydrological reservoirs is LUMPFIT (Axelsson and Arason, 1992). Lumped parameter modelling of pressure changes in hydrological reservoirs is probably most powerful of the simple modelling methods. Lumped models are simply models where the hydrological properties of a reservoir, or the major parts of a reservoir, are lumped together in one or two quantities for each part. Simple lumped parameter models can be used to predict responses of a reservoir to different future production schemes. In addition, a lumped model can give some insight into the properties of the reservoir being simulated. Lumped models consist of a few capacitors or tanks that are connected by conductors or resistors (Figure 5). The tanks simulate the storage of different parts of the reservoir in question, whereas the resistors simulate the permeability.

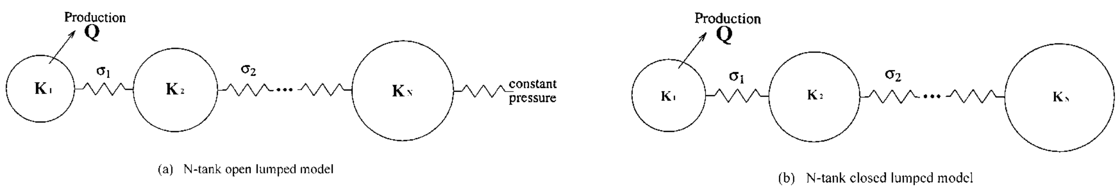


FIGURE 5: Lumped models of hydrological reservoir

The mass conductance of a resistor in a lumped model is σ

$$\sigma = \frac{kA}{\nu L} \tag{8}$$

with A = Area of reservoir [m^2];
L = Length of reservoir [m];
k = Permeability [D] or [10^{-12} m^2];
ν = Kinematic viscosity [m^2/s].

The mass storage coefficient in a lumped model is Κ:

$$K = Vs = Ah\rho_w(\phi c_w + (1-\phi)c_r) \tag{9}$$

with V = Volume of tank [m^3];
s = Storativity [1/Pa];
and other parameters as defined before.

The pressure response, p, of a general open lumped model with N tanks (see Figure 5), to a constant production, Q, since time t = 0, is given by the equation

$$p(t) = -\sum_{j=1}^{N} Q\frac{A_j}{L_j}\left[1-e^{-L_j t}\right] \tag{10}$$

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

$$p(t) = -\sum_{j=1}^{N-1} Q\frac{A_j}{L_j}\left[1-e^{-L_j t}\right] + QBt \tag{11}$$

The coefficients A_j, L_j and B are functions of the storage coefficients of the tanks K_j, and the conductance coefficients of the resistors σ_j in the model. The A_j´s may be termed amplitude coefficients, whereas the L_j´s are eigenvalues of the problem or decay rate coefficients.

3.3 Results of well test analysis

Analysis of water level (pressure) changes in wells SL17 and SL35 were carried out using the above-mentioned methods. Table 3 shows the parameters used in VARFLOW. The angle is the azimuth to the boundary measured from the positive y-axis and the distance is the perpendicular distance to the boundary from the origin. The average transmissivity obtained is 1.2×10^{-7} m^3/Pa s. The simulated results of the well test data with LUMPFIT and models of variable size are given in Table 4.

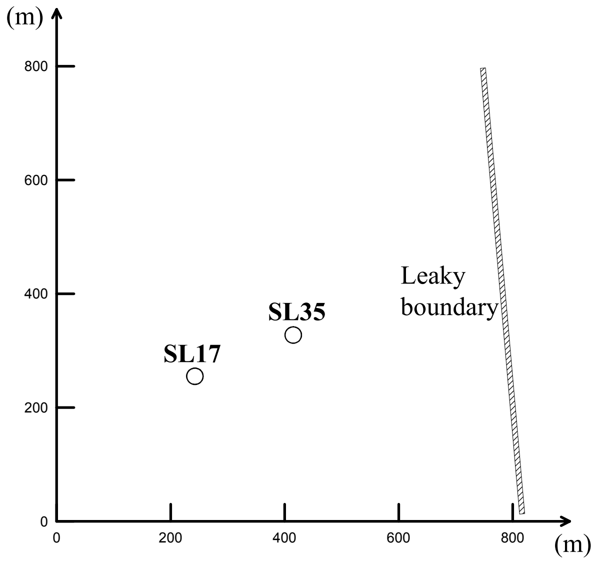


FIGURE 6: Sketch map of wells and boundary

Figure 6 is a sketch map of the position of the wells and the boundary. Heated fluids in a deep sedimentary reservoir rise along a fault until a highly permeable aquifer is intersected. The fluid then enters the aquifer and with time, replaces the existing fluid with hot water. Just like in Figure 6, hot water from the leaky boundary moves toward the wells and is then drawn up to the surface.

TABLE 3: Parameters used in the VARFLOW model

Well no.		SL17	SL35
Flow rate (l/s)		3.72 5.122 6.84	3.522 5.002 6.279
Transmissivity ($10^{-7}m^3$ /Pa/s)	**X-axis**	1.536	1.536
	Y-axis	0.864	0.864
Storage coefficient (10^{-7}m/Pa)		0.22	0.22
Kind of boundary		Leaky	Leaky
Angle of boundary		85	85
Distance to the boundary (m)		800	800

TABLE 4: Results of simulating the well test data with variable sized lumped models

Well no.	**Type of model**	**A(1)**	**L(1)**	**B**	**K_1 (m s^2)**	**K_2 (m s^2)**	**σ_1 (10^{-6}ms)**	**Coeff. of determ.(%)**
SL17	1-open	1.3307	0.4769		0.46×10^{-2}		0.37×10^{-4}	99.425
	2-closed	1.3475	0.4869	0.1829×10^{-4}		0.45×10^{-2}	0.37×10^{-4}	99.457
SL35	1-open	0.2963	0.2325		0.60×10^{-1}		0.53×10^{-4}	97.413

The calculated water levels compared with the observed water level from the well tests are given in Figures 7 and 8. The figures show that the results from the simulations match well the observed data.

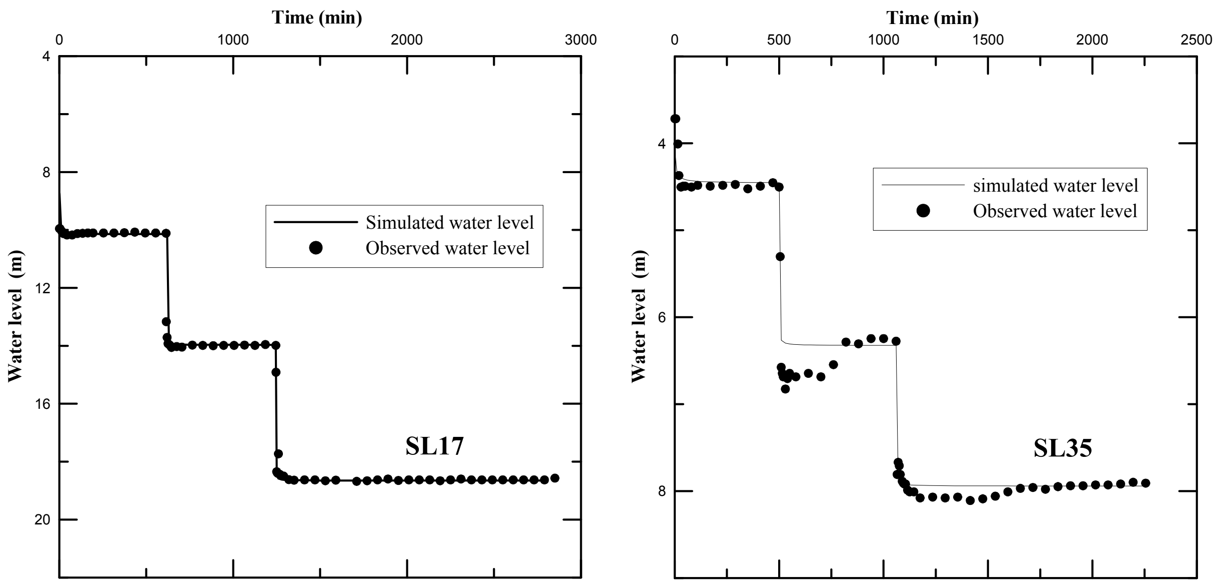


FIGURE 7: Simulated well test results of wells SL17 and SL35 using VARFLOW

4. FUTURE PREDICTIONS FOR THE SILAPU GEOTHERMAL FIELD

4.1 Predicted water level

There is no long term production data available for the Silapu geothermal field, but the well test data is used here to predict the future water level changes in the Silapu geothermal field. Both the VARFLOW and the LUMPFIT models are used.

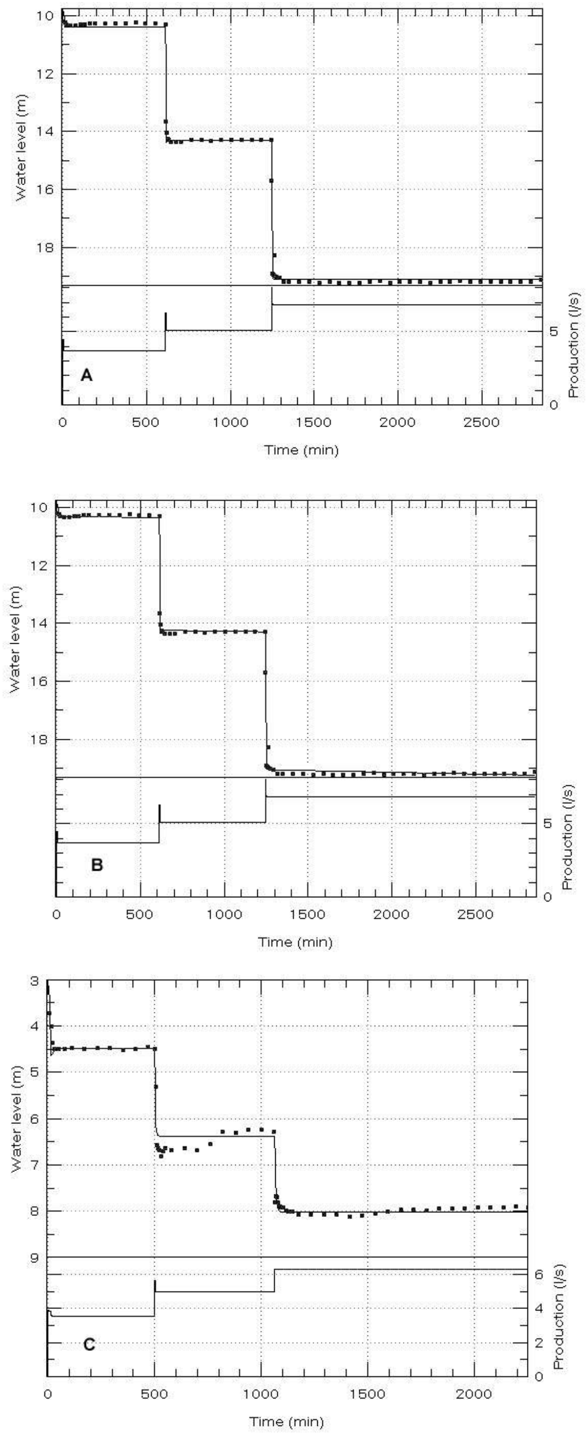


FIGURE 8: Simulated well test results using LUMPFIT, a) One-tank open model SL17; b) Two-tank closed model SL17; c) One-tank open model for SL35

Figure 9 shows the predicted water level of wells SL17 and SL35 over a one month period. The future flow rate is assumed to be 10 l/s, and the other parameters used are the same as in Table 3. Water levels in both wells quickly stabilized, which may reflect the nature of the reservoir. But it should be noted that the well testing time is very short.

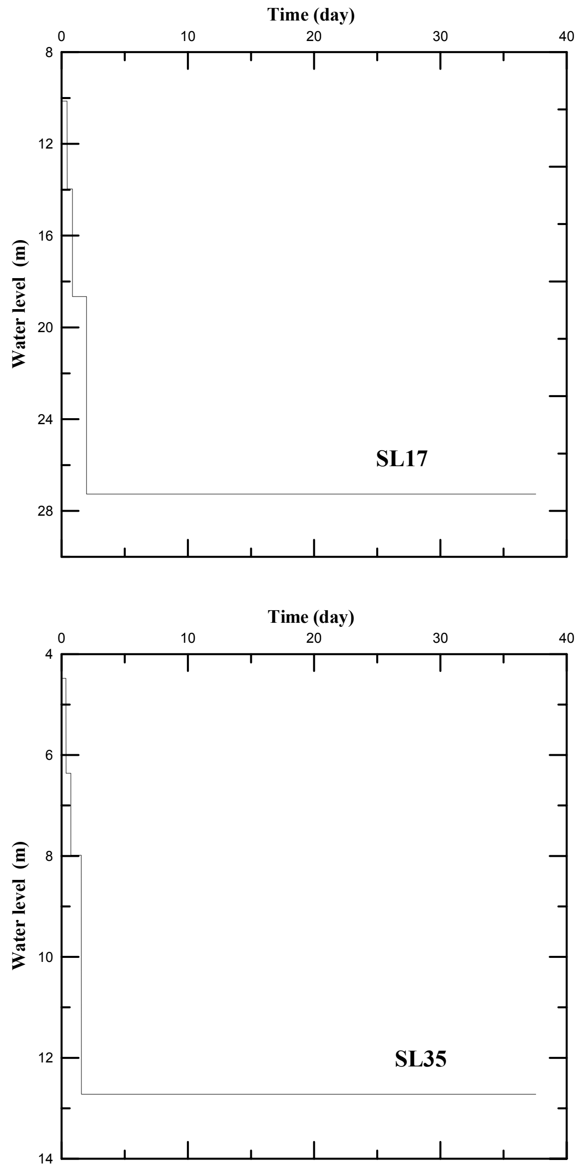
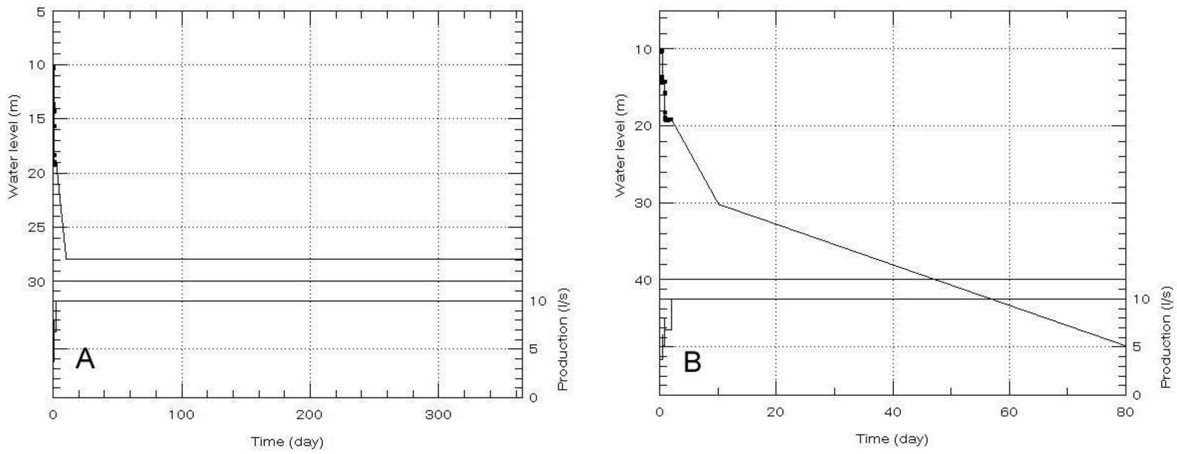


FIGURE 9: Predicted water level of wells SL17 and SL35 over one month's period using VARFLOW

A future flow rate of 10 l/s is also used in LUMPFIT to predicted water level changes (Figure 10). Since an equilibrium between production and recharge is eventually reached during long-term production, the water level predicted by the one-tank open model stabilizes after about 10 days. In contrast, because of no recharge, the water level predicted by the two-tank closed model declines steadily. The final water level could be between the estimates from the two models.



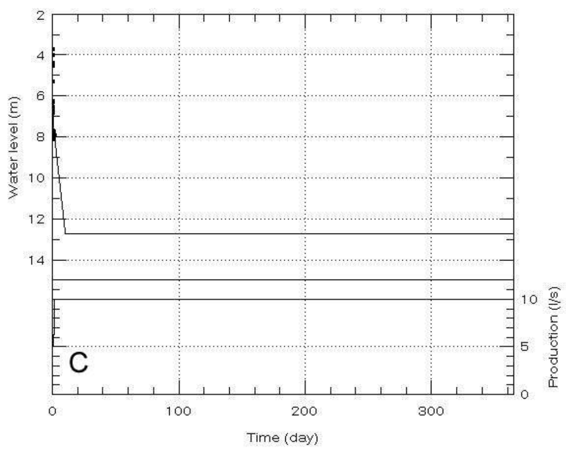


FIGURE 10: Predicted water level using LUMPFIT, a) one-tank open model SL17; b) two-tank closed model SL17; c) one-tank open model SL35

Another prediction of the water level in the Silapu geothermal field was carried out using VARFLOW. In this case, four production wells (SL3, SL13, SL17, SL35) and 2 observation wells (SL8, SL11) are used together. The water level is simulated for the next 30 years, but it appears to become stable after only 8-10 hours. Figure 11 shows the results of the predictions with future flow rates of 10 l/s and 15 l/s as water level contour maps.

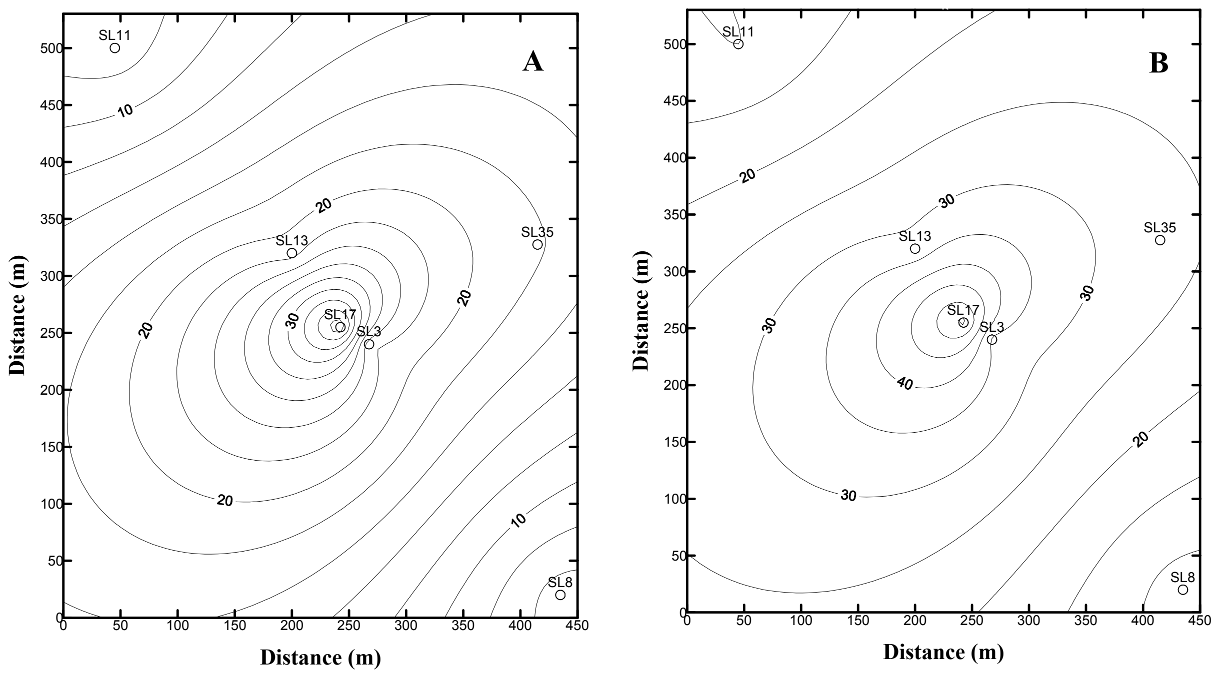


FIGURE 11: Water level contour maps after 30 years of production from four wells, as predicted by the VARFLOW model, a) flow rate is 10 l/s for each production well; b) flow rate is 15 l/s for each production well

4.2 Future predictions including reinjection

4.2.1 Thermal breakthrough time

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

First, the condition of only one reinjection well without nearby production is considered. Porous media heat transport by intergranular fluid flow is considered. Furthermore, a liquid reservoir system is assumed and the gravity effects of variable water temperatures are neglected. The differential equation which approximately describes this process is

$$\frac{\partial T}{\partial t} + \frac{c_w}{<\rho c>} q \times \nabla T = 0 \tag{12}$$

where T = Temperature [°C];
$c_{w,r}$ = Heat capacity of water or rock matrix [J/kg °C];
$<\rho c>$ = $\phi\, c_w\, \rho_w + (1\text{-}\phi)\, c_r\, \rho_r$ = Volumetric heat capacity of the reservoir [J/m^3 °C];
$\boldsymbol{q}$ = (q_x, q_y, q_z) = Mass flux vector [kg/m^2 s];
∇T = $(dT/dx, dT/dy, dT/dz)$ = Temperature gradient [°C/m].

An infinite horizontal reservoir of constant thickness h, is considered. It is assumed that Q kg/s of cold water (T = 15°C) are injected since time t = 0. The cold front consequently moves away from the well, with the radial distance from the well to the thermal front given by:

$$r_T = \left[\frac{c_w Q t}{\pi h <\rho c>}\right]^{\frac{1}{2}} \tag{13}$$

It is assumed that the reinjected water diffuses evenly through the reservoir, with an adopted average thickness of 64 m. Using Q = 2.5 kg/s, it takes 357 years for the thermal front to move 500 m from the injection well. However, most of the reinjected water may travel through more limited flow channels associated with feed-zones. Assuming the thickness to be 6.4 m (10% of the total effective thickness), it takes the front only 36 years to travel the same distance.

Another case considered is a reservoir with initial temperature T_0 surrounded by fluid of temperature T = 15°C, initially at a radial distance r_o. Fluid is withdrawn from a line-sink at rate Q kg/s. In this case, the cold-front reaches the well when

$$t = \frac{r_o^2 \pi h <\rho c>}{c_w Q} \tag{14}$$

Assuming again Q = 10 kg/s and r_0 = 500 m, the cold front reaches the production well in 90 years and 9 years when the thickness is 64 m and 6.4 m, respectively.

The final case considered involves production and reinjection wells with a spacing of 500 m. The average reinjection rates are assumed as 2 kg/s and 4 kg/s, and the average production rate is 15 kg/s. Thermal breakthrough is calculated by a one-dimensional flow channel model. The program TRCOOL in the ICEBOX program package (Arason and Björnsson, 1994) is utilized for this purpose.

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

$$T(x,t) = \begin{cases} T_i + (T_o - T_i)\, erf\left[\dfrac{Kxh}{c_w q \sqrt{D(t-x/\alpha)}}\right] & for\ t>x/\alpha \\ T_o & for\ t<x/\alpha \end{cases} \quad (15)$$

with α defined by $\alpha = q\, \rho_w / < \rho c > h\, b$

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

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

$$T_p = T_o - \frac{q}{Q}[T_o - T(L,t)] \quad (16)$$

where $T(L, t)$ is given by Equation 15.

The result of using this method to predict the thermal breakthrough and temperature decline in the production wells for 50 years is presented in Figure 12. Based on the results, it is recommended that it would be better to locate the reinjection well about 800 m from the production wells. If they are too close, reinjection may cause rapid cooling of the production wells. But the pressure support from reinjection will diminish if the reinjection wells are much further away.

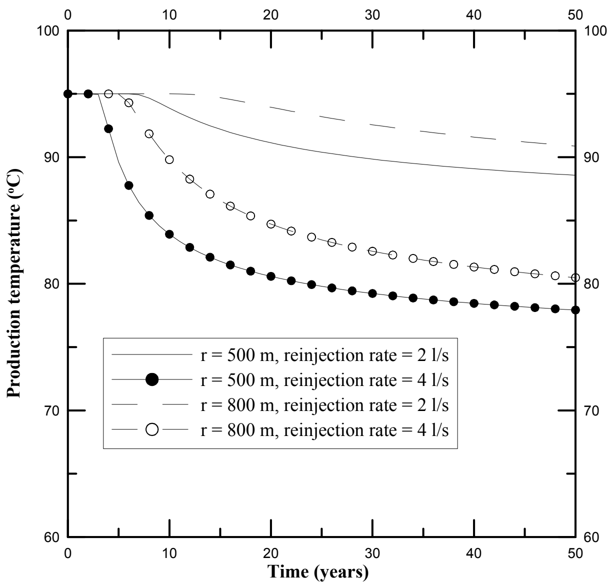


FIGURE 12: Calculated temperature changes in a production well located at some distances from a reinjection well during reinjection for 50 years

4.2.2 Future predictions including reinjection

The WARFLOW model is used here to simulate the water level recovery with one reinjection well INJ01. Two cases are considered with an injection rate assumed as 3.0 l/s, and flow rates of the production wells as 10 l/s for the first case and 15 l/s for the second case. Figure 13 shows the results. Comparison between Figures 11 and 13 indicates that the water level recovery for both cases would be about 0.6 m. When two reinjection wells (INJ01 and INJ02) are used, with 3 l/s injection rate each, but other circumstances the same as in the above cases, the water level recovery would be about 1 m (Figure 14).

It should be noticed that the injection rate assumed here is only a small portion of the production rate. If the injection rates are increased, the water level recovery in Silapu geothermal field will be greater.

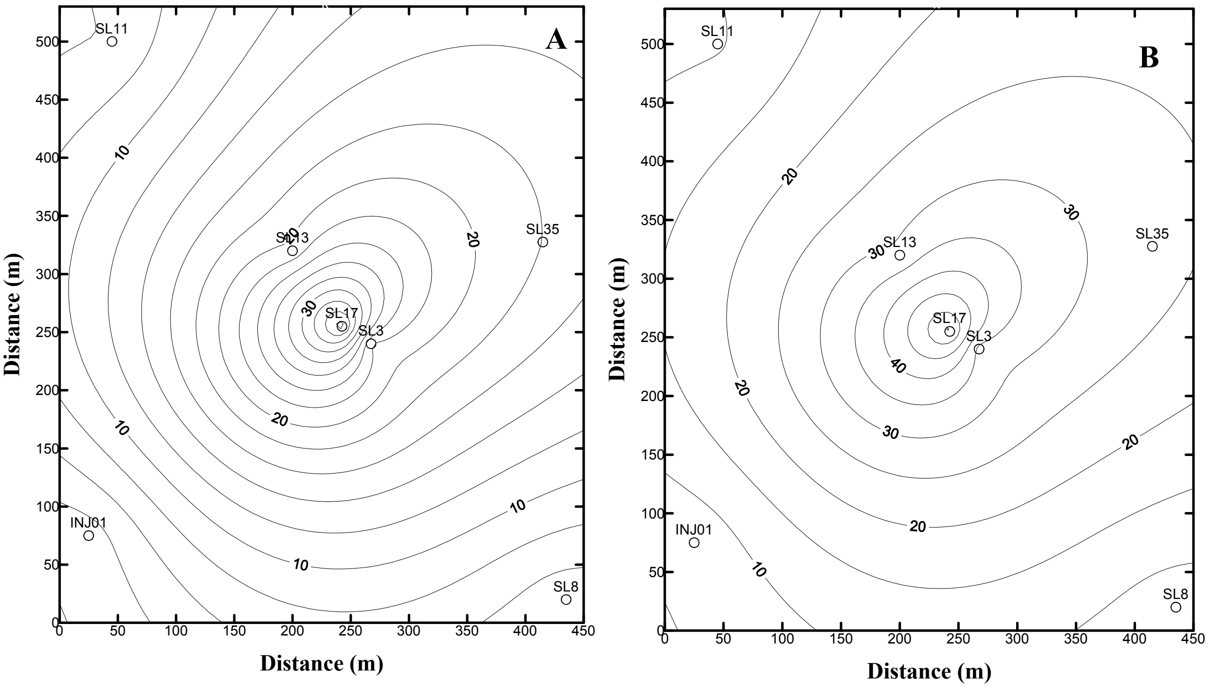


FIGURE 13: Predicted water level changes for 30 years with one reinjection well,
a) flow rate is 10 l/s for each production well; b) flow rate is 15 l/s for each production well

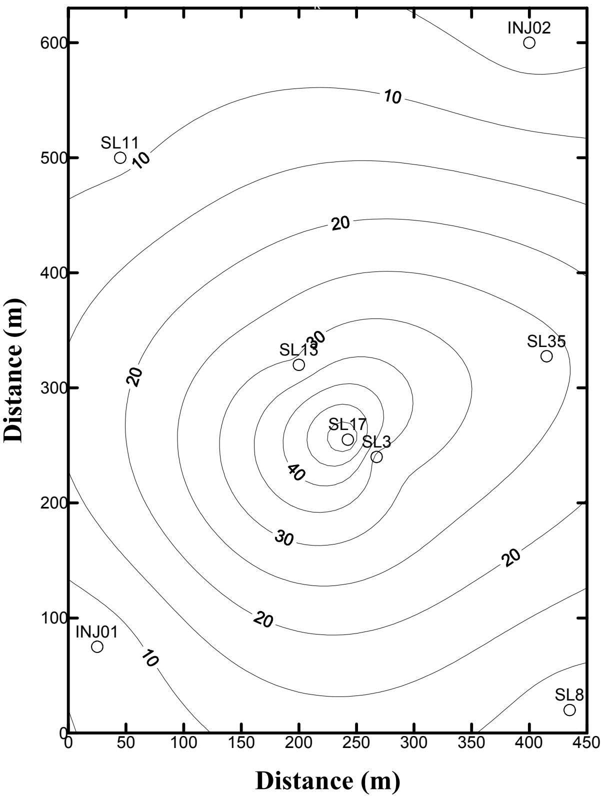


FIGURE 14: Predicted water level changes after 30 years with two reinjection wells, total production rate = 60 l/s

4.3 Geothermal field potential

The maximum allowable drawdown determines the production potential. Such a limit was not easy to define, but was based on a number of criteria, the first being the setting depths of the well pumps. It must be kept in mind, that the operational costs of pumps increases rapidly with increasing depth, which may set an economic limit to the maximum drawdown. The second criterion is the design of the production wells. The width and depth of casings in production wells can also limit the maximum drawdown. The third criterion is the risk of colder water inflow, and hence cooling of the reservoir. Although considered minimal, this risk increases rapidly with increasing drawdown.

Based on the above considerations, the maximum allowable drawdown of the Silapu geothermal field is here set at about 75 m. The total production rate could, therefore, be 80 l/s with injection rates of 3.0 l/s for each reinjection well (see Figure 15). The production potential of the geothermal field is, therefore, estimated to be about 2.5 Mm^3/year.

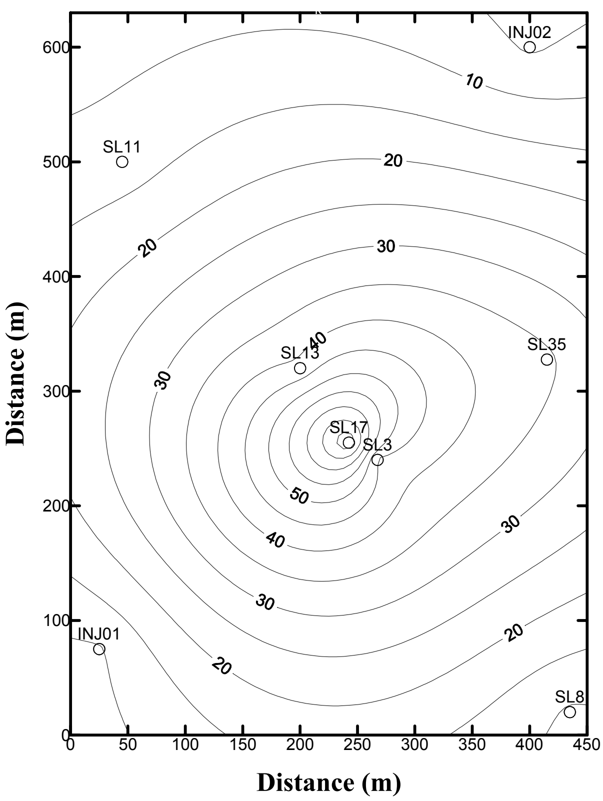


FIGURE 15: Predicted water level contours for a case of maximum water level drawdown of 75 m

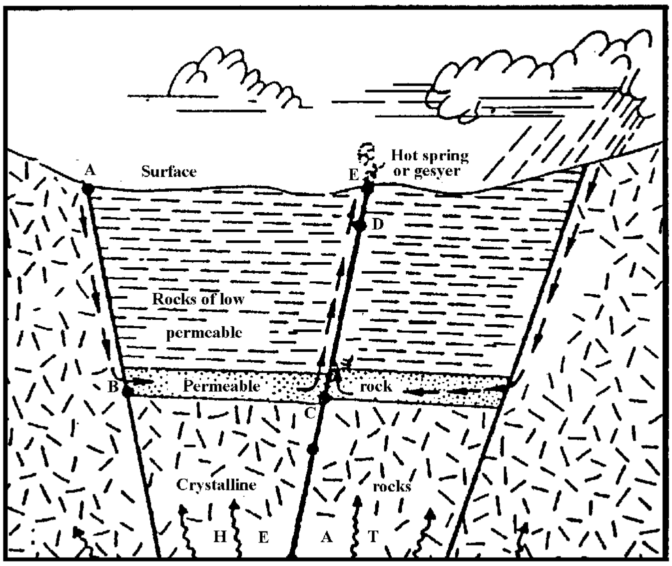


FIGURE 16: Schematic model of a hydrothermal convection system

4.4 Temperature prediction for the deeper reservoir

It is well known that hot intrusions or, in general, the hot crust is the heat resource of geothermal reservoirs in the Silapu area. It heats the cold water recharged into the proposed sedimentary reservoir, and by convection the hot water rises and often flows through fractures to the surface. This is the typical cyclic hydrothermal system (Figure 16). When the hot water flows up, some of the heat energy is transferred to the rock and the water temperature decreases.

Drilling a well directly into the geothermal reservoir is, of course, the best way to get hot water with high temperature. But in some cases, wells are not drilled deep enough to reach the sedimentary reservoir, such as the wells drilled in Silapu area.

Most of the production wells drilled in the Silapu geothermal field are between depths of 200 to 250 meters. Only well SL35 is about 500 m, but does not reach the depth of the sedimentary reservoir. Two methods are discussed here to estimate water temperature in the sedimentary reservoir.

A geochemical method is used to estimate the reservoir temperature. Concentrations of SiO_2 in the hot water can be used for this purpose, i.e. using the so-called silica geothermal thermometer as given by Equation 17 (Fournier, 1981):

$$T = \frac{1309}{5.19 - \log c} - 273.15 \qquad (17)$$

where
T = Temperature [°C];
c = Concentration of SiO_2 in the water [mg/l].

Table 5 shows the estimated temperature using a concentration of SiO_2 in the five production wells. The average temperature for the five wells is, therefore, about 140°C.

TABLE 5: Estimated temperature in the deep sedimentary reservoir using concentration of SiO_2

Well no.	Concentration of SiO_2 (mg/l)	Estimated temperature (°C)
SL3	135.2	154.6
SL17	68.4	117.1
SL11	100	137.2
SL13	122.4	148.7
SL35	115.6	145.4

The temperature gradient method may also be used. Figure 17 shows the temperature-depth curves of wells SL3 and SL17. The temperature gradient for the deep part of the wells is then estimated and extrapolated to greater depth.

Assuming the depth to the geothermal reservoir to be 2000 meters, the temperature estimated for SL3 is 134°C, and for SL17, 137°C, which is in an agreement with Table 5.

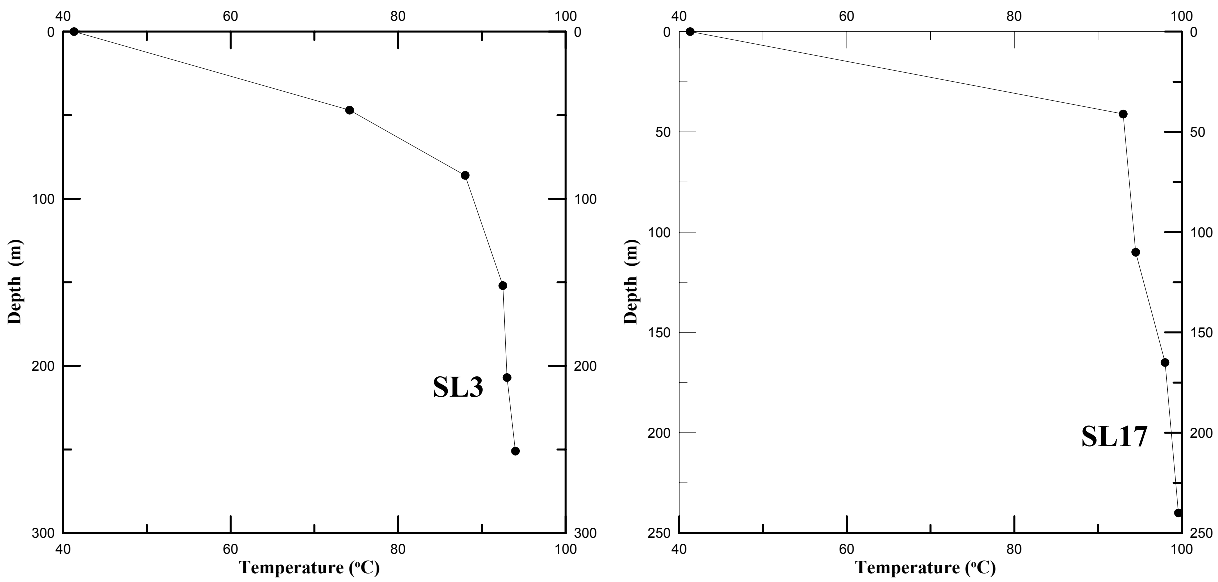


FIGURE 17: Temperature profiles used to predict reservoir temperature

5. CONCLUSIONS AND RECOMMENDATIONS

Based on the reservoir evaluation for the Silapu geothermal field presented here, the main conclusions and recommendations may be summarized as follows:

1. According to results of the volumetric resource assessment, the usable total energy potential of the Silapu geothermal field is about 3.1×10^{16} J. Heat energy which can be used by space-heating is 2.68×10^{16} J. This gives a space-heating power potential estimate for the Silapu geothermal field as 32.7 MW_t. Based on an average requirement of 40 W/m^2 for space-heating, this should be sufficient power to heat more than 800,000 m^2 of living space, or about 10,000 average-sized apartments (assuming 80 m^2 for each apartment).

2. The results of well test analysis and reservoir modelling indicate that the transmissivity of the geothermal field is anisotropic. The transmissivity in an east-west direction is about 1.5×10^{-7} m^3/Pas and in a north-south direction 0.86×10^{-7} m^3/Pa s. The average transmissivity is 1.2×10^{-7} m^3/Pa s.

3. Predictions indicate that for total production rate of 40 l/s (4 wells), the lowest water level in the geothermal field will be -37.8 m. The lowest water level will be -56.7 m when the total production rate is 60 l/s. When one reinjection well is utilized with an injection rate of 2 l/s, the water level recovery is predicted to be 1%. If two reinjection wells are utilized, the predicted water level recovery is about 1.8%.

4. The maximum allowable drawdown of the water level is determined at 75 m. For that case and using two reinjection wells with 3 l/s injection each, the maximum total production rate can be as high as 80 l/s. The production potential of the field, is thus, estimated to be 2.52 Mm^3/year, corresponding to a space-heating power potential of about 22 MW_t.

5. Further exploration and drilling is necessary to obtain more water with higher temperature. Assuming the depth to an underlying sedimentary reservoir to be at 2000 m, the temperature is estimated to be as high as 140°C.

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

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