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Implications of Temporal Changes in Solute Concentrations for the Mass Balance of the Berlin Geothermal Reservoir

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ABSTRACT

Berlin Geothermal Field is located in eastern El Salvador, Central America. The exploitation of this field started in February 1992 with a 5 MW unit, the addition of a similar unit in 1995, and large scale exploitation in December 1999 with the operation of two turbogenerating condensation units of 28 MW each. In December 2006, a third unit was installed that provides additional 40 MW. Since the beginning of exploitation, all the residual waters generated during the generation of electricity have been reinjected back to the reservoir. Records of the mass extracted and mass reinjected to the different wells, as well as the results of frequent chemical analysis of the extracted and reinjected waters and gases have been kept. The exploited area measures around 4.4 E6 m^2. The thickness of the reservoir is around 200 m and the porosity around 0.1 (Castro et al., 2006). The concentrations of the different solutes throughout time were used to generate best fitting equations that describe the average variation of concentration with time. These equations were used to calculate the expected concentration of the solutes at each production or reinjection well each day. Multiplication of the volume of water produced or reinjected times the expected concentration produces the expected mass of solute extracted or reinjected each day. The volume of water within the reservoir seems to have decreased with time, as it is evident from the increase in concentrations of ions in the extracted waters. Only SiO_2 and alkalinity show a decreasing trend. Comparison of the net extracted water mass and the decrease in reservoir water predicted by the change in chloride concentration have allowed the calculation of the water mass supplied to the reservoir by the net natural recharge (natural inputs-natural outputs). For the last year of the study period (July 2004 to June 2005) the total net mass extracted from the reservoir is 3.8E9 kg, with 2.4E9 (around 64%) coming from the reservoir storage and 1.4E9 kg coming from natural water recharge to the reservoir.
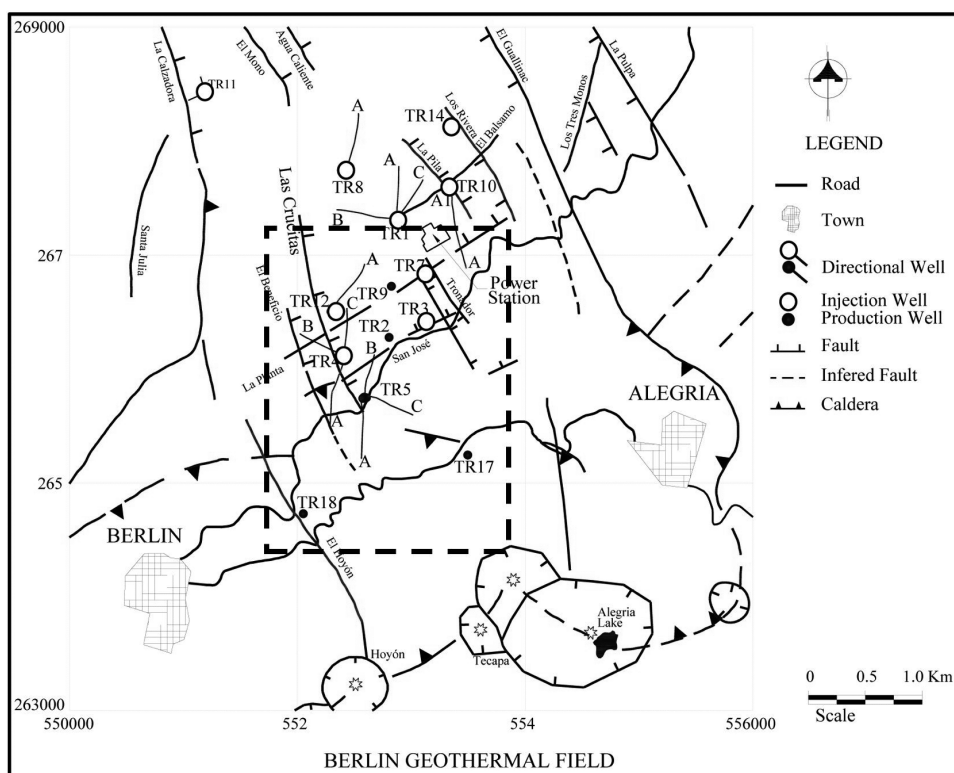

Figure 1. Structural features of the Berlin Geothermal Field, production and exploitation wells. Dashed rectangle illustrates area of production wells (after López et al., 2006).

Introduction

The exploitation of the Berlin Geothermal Field started in February 1992 with a 5 MW unit. Later, in 1995, another similar unit was incorporated. In December 1999, exploitation at a large scale started with the operation of two turbogenerating condensation units of 28 MW each, a third unit was installed that provides additional 40 MW. Since the beginning of exploitation to today, all the waste waters generated during the generation of electricity are reinjected back to the reservoir (Castro et al., 2006). The company that exploits the field (LaGeo) has kept good records of the mass extracted and mass reinjected to the different wells, as well as the results of frequent chemical analysis of the extracted and reinjected waters and gases. Variations in chemical composition of the discharged waters and gases have been observed with time. Some ions show trends that seem to increase with time (e.g. chloride, Na, sulfate) and other species present a decreasing trend (e.g. dissolved carbon dioxide, silica). Changes in fluid chemistry with exploitation have been reported for many other geothermal fields (e.g Seltjarnarnes and Bakki in Iceland, Kristmannsdottir and Armannsson, 1996; Broadlands in New Zealand, Ellis and Mahon, 1977; Los Humeros in Mexico, Prol-Ledesma, 1998). In this paper, these variations in concentration and the exploitation history of the field (masses extracted and reinjected) are used to gain an insight into the natural recharge processes of this geothermal field.

The wells that provide the fluids for production are located towards the center and South of the exploited area and the reinjection wells towards the center and the North. Figure 1 shows the location of those wells. The dashed rectangle illustrates the area where the production wells are preferentially located and the most likely to suffer depletion in the water levels due to mass withdrawal as it is evidenced in the pressures drop measured in the wells. This area measures around 4.4 E6 m^2. The thickness of the reservoir is around 200 m and the porosity around 10% (Castro et al., 2006). Using this information, the volume of the reservoir in the vicinity of the production wells is around 8.8 E8 m^3. Considering these parameters, the initial mass of water stored in the reservoir before the start of exploitation in 1992 was around 8.061 E10 kg. This value was calculated assuming a salinity of 10,000 ppm and an average reservoir temperature of 240° C (water density equal to 916 kg/m^3). At 25°C and a salinity of 10,000 ppm (water density is 1004.6 kg/m^3), the same mass of water corresponds to 8.02 E7 m^3 (mass/density) contained in the fractures and pores of the reservoir.

Evidence of mixing of reinjected and production waters in Berlin Geothermal reservoir have been provided by several radiotracers tests carried out with variable success. Two of these test provided important information about the travel times between several wells (Matus, 2000; Matus 2003). The first of this tracer tests was carried out on May 16, 2000 with the injection of I-131 (1.96 Ci) in well TR-12A. The radiotracer was recovered at different collection times in wells TR-4C, TR-5B, TR-9, and TR-5A. For well TR-5B, the fastest molecules arrived around 3 days after the injection of the tracer, the slowest molecules arrived at 93 days, and the majority of the molecules (maximum fraction of tracer recovered per liter) arrived about 28 days later. Montalvo et al. (2000) modeled the results of this tracer test for the couple

TR-12A –TR-4c and found groundwater velocities ranging from 1.0E-4 to 7.0E-4 m/s with an average value of 3.6E-4 m/s.

Methodology

The following steps were followed for this work:

1) The information on fluid extraction and reinjection and their chemical compositions that LaGeo has monitored during the exploitation history of the reservoir is used in this paper to calculate the net mass extracted from the reservoir. For each day, the total kg/s of fluids (gases plus separated water) extracted at each exploitation well are added for all the production wells, and the total kg/s of water reinjected at each reinjection well are added to get the reinjected mass per second. As the data is reported for every day, the totals are converted to kg/day. The accumulated masses extracted and reinjected are added from 1992 to June 30, 2005. The difference between the daily accumulated extracted and reinjected water masses is the accumulated net extraction.

2) The concentrations of the different solutes for the waters extracted and reinjected throughout time were used to generate best fitting equations that describe the average variation of concentration with time. The test of significance of the correlation coefficient (Swan and Sandilands, 1995) was done to determine if the observed trends have statistical significance. The best-fitting equations were used to calculate the concentration of the solutes at each production or reinjection well each day. Multiplication of the volume of water extracted or reinjected times the concentration produces the mass of solute extracted or reinjected each day. For the period 1992 to June 30, 2005, the reinjected total masses and the extracted masses of solutes were compared to determine if they balance or not, and what is the fate of the different chemical species.

3) The variations in concentrations for conservative ions like chloride can give important information about the net natural recharge to the reservoir (natural inputs - natural outputs). If we consider a simplified model of the reservoir (Figure 2), the mass balance equation for water in the reservoir is:
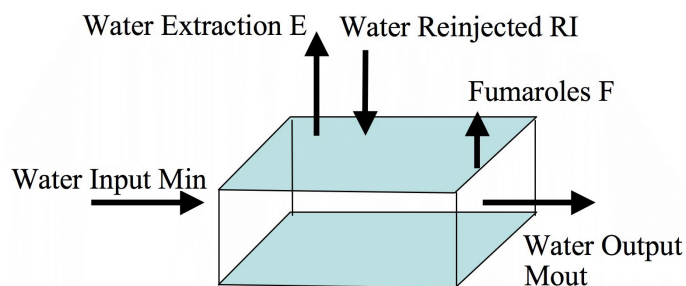
Figure 2. Water inputs and outputs to the Berlin Geothermal reservoir. Water Inputs are the reinjected water RI, the natural recharge to the aquifer from the South and probably from overlying layers, Min. Water Outputs are the extracted waters from the production wells, the fluids rising thru the faults to the fumaroles F, and the natural discharge of the aquifer towards the North of the system. Mout represents the discharge to the north and the fumaroles.

$$M_{in} + RI - E - M_{out} = \Delta M_w \qquad \text{Eq. 1}$$

Where M_{in} represents the natural inputs of water to the reservoir, *RI* represents the hot reinjected water (cold reinjection

occurs in a shallower aquifer), E represents the extraction of the production wells, M_{out} represents all the natural outputs of water including the discharges throughout faults or fumaroles, and ΔM_w is the change in water storage in the reservoir. If the net extraction (E-RI) is represented by NE, the change in storage is:

$$\Delta M_w = M_{in} - M_{out} - NE \qquad \text{Eq. 2}$$

As all the residual waters produced in Berlin Geothermal Field are reinjected back to the reservoir, the chemical species that do not evaporate are reinjected back to the reservoir. The mass of solute extracted by the production wells should be equal to the mass of solute reinjected by the reinjection wells. For a given time interval, the mass balance equation for conservative chemical species such as chloride is given by:

$$C_{Cl_{in}} M_{in} - C_{Cl_{out}} M_{out} = C_{Cl_f} M_{wf} - C_{Cl_o} M_{wo} \qquad \text{Eq. 3}$$

Where $C_{Cl_{in}}$ and M_{in} are the average chloride concentration and mass inflow of the water recharging the system naturally, $C_{Cl_{out}}$ and M_{out} are the average concentration and mass outflow of the water discharged from the system naturally, C_{Cl_o} and M_{wo} are the average concentration and mass of the water stored in the system at the beginning of the time interval, and C_{Cl_f} and M_{wf} are the average concentration and mass of the water stored in the system at the end of the time interval.

From Equation 3:

$$M_{wf} = \left[\frac{\left(C_{Cl_{in}} M_{in} - C_{Cl_{out}} M_{out}\right)}{C_{Cl_f}} \right] + \frac{C_{Cl_o}}{C_{Cl_f}} M_{wo} \qquad \text{Eq. 4}$$

The second term of the right hand side of Equation 4, $\frac{C_{Cl_o}}{C_{Cl_f}} M_{wo}$, corresponds to the mass of water left in the aquifer if the change in concentration is only due to the extraction of water and reinjection of a brine more concentrated in chloride (water vapor lost). If the natural fluxes of chloride entering and leaving the system naturally have not changed considerably with time, the final mass of water in the reservoir is:

$$M_{wf}^* = \frac{C_{Cl_o}}{C_{Cl_f}} M_{wo} \qquad \text{Eq. 5}$$

From Equation 2, 3 and 4:

$$M_{in} - M_{out} = \Delta M_w + NE = NE - (M_{wo} - M_{wf})$$

$$M_{in} - M_{out} = (NE - (M_{wo} - M_{wf}^*)) + \left[\frac{\left(C_{Cl_{in}} M_{in} - C_{Cl_{out}} M_{out}\right)}{C_{Cl_f}} \right] \qquad \text{Eq. 6}$$

Then the net natural recharge to the reservoir is given by the difference between the net extraction NE and the change in mass predicted by the variation in concentration of chloride $(M_{wo} - M_{wf}^*)$, plus a term $\left[\frac{\left(C_{Cl_{in}} M_{in} - C_{Cl_{out}} M_{out}\right)}{C_{Cl_f}} \right]$. This term has null value when the natural fluxes of the chloride entering and leaving the system are equal, as it was the case before exploitation. It could have a maximum value if the total mass of water in the reservoir does not change because the net natural recharge is

supplying enough water to maintain the mass of water unchanged, and if the concentration of the water entering the system is increasing with time producing an increase in concentration in the aquifer. This is unlikely to occur because the reservoir pressure decreases during exploitation suggesting a decrease in water stor-
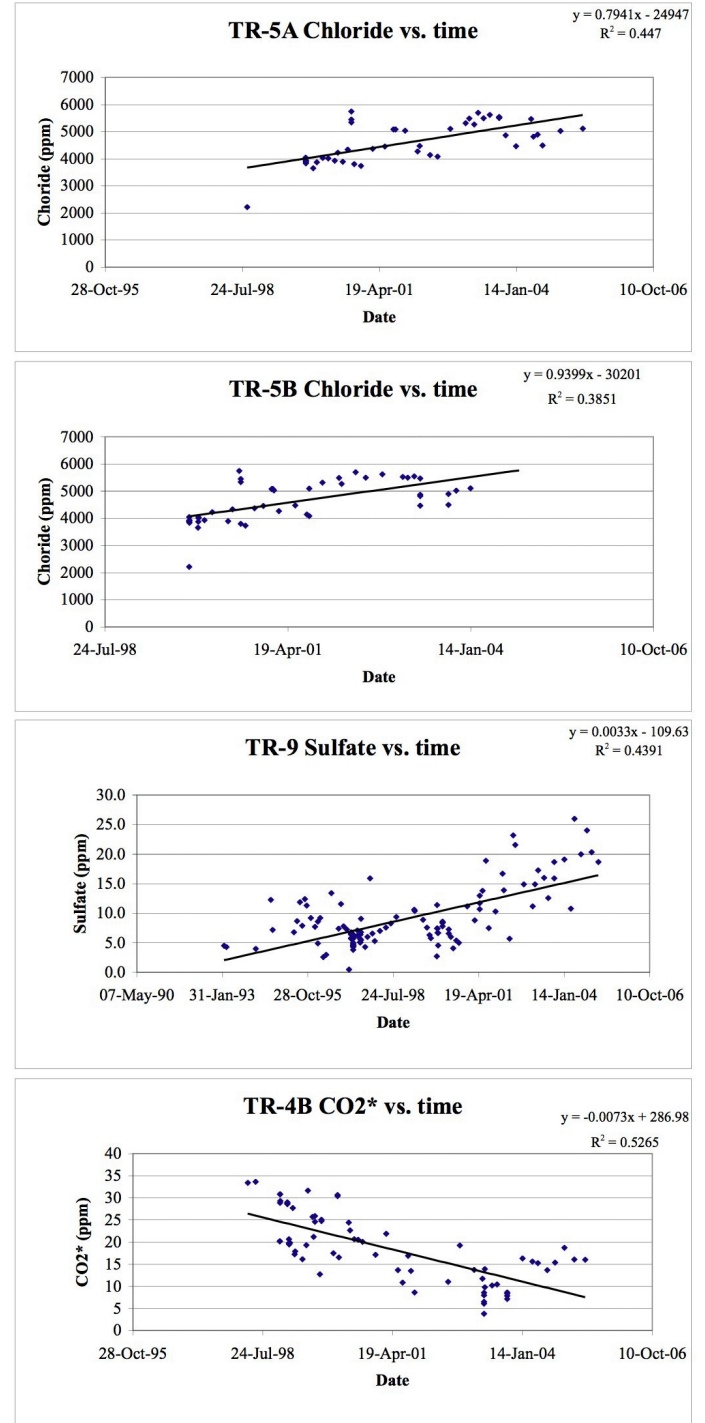

Figure 3. Examples of graphs of concentration versus time for production wells of the Berlin Geothermal Field. Chloride, sulfate and the metals show increasing trends with time. Dissolved carbon dioxide and silica present decreasing trends with time due to the separation of CO_2 during the production process and the precipitation of silica in the pipes and reservoir.

Table 1. Statistical significance of correlation coefficient between concentration and times for different chemical species and production wells at Berlin Geothermal Field. The test of significance of the correlation coefficient (Swan and Sandilands, 199x) has been applied. The calculated t value is compared with the critical t value for p = 0.05.

Well	Number points	Correlation Coefficient	t calculated	t critical	Trend Type	Conclusion
Chloride						
TR2	181	0.03	0.42	1.65	Increasing	Correlation is not sign.
TR4B	83	0.33	3.12	1.66	**Increasing**	**Significant correlation**
TR4C	84	0.71	9.17	1.66	**Increasing**	**Significant correlation**
TR5	72	0.24	2.05	1.67	**Increasing**	**Significant correlation**
TR5A	46	0.76	7.80	1.68	**Increasing**	**Significant correlation**
TR5B	50	0.76	8.01	1.68	**Increasing**	**Significant correlation**
TR5C	53	0.25	1.86	1.68	**Increasing**	**Significant correlation**
TR9	114	0.02	0.21	1.66	Decreasing	Correlation is not signif.
Sulfate						
TR2	181	0.23	3.15	1.65	**Increasing**	**Significant correlation**
TR4B	83	0.07	0.67	1.66	Decreasing	Correlation is not signif.
TR4C	84	0.01	0.09	1.66	Decreasing	Correlation is not signif.
TR5	72	0.33	2.90	1.67	**Increasing**	**Significant correlation**
TR5A	46	0.11	0.71	1.68	Decreasing	Correlation is not signif.
TR5B	50	0.47	3.71	1.68	**Increasing**	**Significant correlation**
TR5C	53	0.03	0.20	1.68	Decreasing	Correlation is not signif.
TR9	114	0.55	6.93	1.66	**Increasing**	**Significant correlation**
Carbon Dioxide						
TR2	181	0.43	6.37	1.65	**Decreasing**	**Significant correlation**
TR4B	83	0.73	9.49	1.66	**Decreasing**	**Significant correlation**
TR4C	84	0.23	2.14	1.66	**Decreasing**	**Significant correlation**
TR5	72	0.60	6.25	1.67	**Decreasing**	**Significant correlation**
TR5A	46	0.47	3.54	1.68	**Decreasing**	**Significant correlation**
TR5B	50	0.63	5.56	1.68	**Decreasing**	**Significant correlation**
TR5C	53	0.61	5.51	1.68	**Decreasing**	**Significant correlation**
TR9	114	0.55	6.88	1.66	**Decreasing**	**Significant correlation**

age. In this study, we assume that the natural fluxes of chloride entering and leaving the system are balanced and that the increase in concentration with time is due to the reduction of water storage.

Results and Discussion

The volume of water within the reservoir seems to have decreased with time, as it is evident from the increase in concentrations of the ions with time in the extracted waters. Figure 3 illustrates the increase in concentration for chloride for wells TR-5A and TR-5B, increase in concentration for sulfate in well TR-9, and decrease in concentration of dissolved CO_2 in well TR-4B, similar graphs are observed for other ions and different wells. Only SiO_2 and dissolved CO_2 show a decreasing trend. However, dispersion is observed in these graphs. To determine if the observed correlations are statistically significant, the test of significance of the correlation coefficient (Swans and Sandilands, 1995) was done. Results for this test for selected species are presented in Table 1. The increasing trend for chloride concentration with time is statistically significant at the 95% confidence level or better in 6 of the 8 producing wells. Fitting equations were deduced for the different ions, Table 2 shows the fitting equations for chloride as an example.

Table 2. Best fitting equations for the increase of Cl concentrations in the Berlin Geothermal Reservoir. All the concentrations in ppm.

Well	Equation
TR4B	0.2688x - 5794.8
TR4C	1.1573x - 37214
TR5	0.1902x - 2205.6
TR5A	1.1608x - 38454
TR5B	1.7692x - 59751
TR5C	0.4658x - 10563

The fitting equations for the different wells were used to obtain the interpolated concentrations for every day for the different chemical species in water. These concentrations multiplied by the mass extracted or reinjected each day in each well allow the calculation of the total solute mass extracted and reinjected in the reservoir from Jan 1992 to June 30, 2005. Table 3 shows values for selected species. The ratio between total mass reinjected/mass extracted for the different species in Table 3 is 1.0 for SiO2, 1.04 for Cl, 1.03 for B, 1.08 for Na, and 1.15 for sulfate. The fact that these ratios are close to 1.0 even considering the multiple sources of errors (e.g. analytical errors, the use of fitting equation instead of actual values of concentration, etc.) suggest that for the non-volatile species close to 100% of the extracted chemicals are returned to the aquifer with the reinjected waters. The concentration in the aquifer increases with

Table 3. Total mass extracted and reinjected for selected chemical species at Berlin Geothermal Field from 1992 to 2005.

Total mass reinjected 1-jan-92 to 30-jun-2005				
Cl (Kg)	B(Kg)	Na (Kg)	SO4 (Kg)	SiO2 (Kg)
4.41E+08	8.66E+06	2.54E+08	8.51E+05	5.41E+07
Total mass extracted 1-jan-92 to 30-jun-2005				
Cl (Kg)	B (Kg)	Na (Kg)	SO4 (Kg)	SiO2
4.26E+08	8.38E+06	2.34E+08	7.37E+05	5.40E+07
Mass reinjected/mass extracted ratio				
Cl	B	Na	SO4	SiO2
1.04	1.03	1.08	1.15	1.00

time due to the net extraction of water and conservation of the mass of solutes in the aquifer. At Los Humeros geothermal field in Mexico, an increase in chloride concentrations in the reservoir has been interpreted assuming that the recharge of the reservoir is not enough to balance the output for production, and proposing that drying of the reservoir could been taking place (Prol-Ledesma, R.M, 1998).

For silica, a ratio of 1.0 for the mass reinjected/mass extracted is unexpected because of the observed precipitation of silica in pipes. However, these results show that the mass of silica deposited in the pipes is negligible compared with the silica that must be precipitating inside the reservoir. The decreasing trends in concentration of silica and alkalinity can be explained if we consider that the temperature of the reservoir decreases due to the cold reinjected waters. The temperature of the producing wells is around 290 ° C and 305 ° C and the reinjection temperature is around 179°C. The drop in temperature produces the precipitation of silica (Castro et al., 2006). The volume of water in the reservoir is decreasing but as silica precipitates the dissolved silica in the reservoir also decreases. Our previous studies (Castro et al., 2006; López et al., 2006) have shown that the travel time of the residual waters within the external pipes of Berlin Geothermal Field is lower than the induction time for precipitation of silica, and that precipitation of silica is happening within the reservoir clogging the pores and reducing the absorption capacity of the reinjection wells. We have modeled (López et al., 2006) and evaluated the precipitation of silica around the reinjection wells. Precipitation of silica seems to occur within 10 m of the well, and after 10 years a great proportion of the well should be clogged (43 to 50% decrease in porosity).

With respect to alkalinity, its decrease is due to the reduction of concentration of dissolved carbonate species in the residual water. As exploitation happens, gases are separated from the water during the generation of electricity decreasing the mass of carbonate species in the reinjected waters. If the replenishment of CO_2 to the reservoir from natural recharge is low, the reservoir becomes poorer in dissolved CO_2 with time. It should be noted that a second degree polynomial curve fitting for alkalinity in Figure 3 is not significant and does not represent steady state condition at the end of the time interval. None of the wells presents steady state conditions for alkalinity at the end of the studied exploitation period.

The daily concentrations of chloride in each well predicted with the fitting equations were used to determine the average con-

centration of chloride in the aquifer (Table 4). These calculations were done from January 1999 to June 2005. During the period of time between 1992 and 1999 the number of wells was too low to produce a reliable average of the concentration. The average concentration of chloride in the aquifer prior to exploitation is not known. The concentration of chloride in well TR-2 in 1992 cannot be taken as the average concentration of the reservoir at that time because this well always presents a concentration considerable higher than most of the other wells, as it is observed in collected data. This behavior suggests that the fault intercepted by this well (Figure 1) is transferring deep saline fluids to the reservoir. Before 1999 the exploitation of the reservoir was not intensive because only two wells were exploited and 10 MW were produced. For that reason the first concentration measured at each well after it was drilled and completely stabilized was taken as the concentration at the point prior to exploitation. In that way, an average concentration of chloride equal to 4628 ppm was estimated for the reservoir prior to exploitation.

The average concentration of chloride in the reservoir every six months was determined. This concentration and the estimated initial mass of water in the reservoir was used to determine the final mass of water in the reservoir as predicted by Eq. 5 (Table 4, overleaf). The accumulated masses extracted and reinjected are also presented in Table 4, as well as the accumulated net extracted mass in the reservoir and the change in net mass extracted during the six months period. The apparent net water drop is the difference between the mass in the reservoir predicted by the chloride concentration at the end and beginning of the six months period. Note that in most cases the apparent net water drop is lower than the change in net mass extracted, the difference between these two values is the water supplied by the net natural recharge (natural inputs -natural outputs). The pressure in the reservoir has also changed with time (Table 4), from 40 bars in 1992 to 27 bars in June 2005. If we consider the percent change in pressure and in water mass storage in the reservoir predicted by the change in chloride concentrations, we get the following values:

1992-2005 –   % change of pressure= 33%,
         % apparent change of water mass= 29%

1999-2005 –   % change of pressure= 21%,
         % apparent change of water mass= 26%

We have different sources of errors in our calculations (e.g. use of average concentrations, determination of initial average concentration in the reservoir, etc.). However, these values suggest that the increases in chloride concentration observed at Berlin Geothermal Reservoir are due mainly to the change in water storage within the reservoir, which is also producing the decline in reservoir pressure.

Figure 4, overleaf, shows the variation in reservoir pressure and the water supplied by the net natural recharge (Table 4) versus time. The net natural recharge seems to increase as the pressure in the reservoir decreases and it stabilizes as the pressure in the reservoir stabilizes. This behavior can be explained by the hydrodynamics of the system. As the pressure in the reservoir decreases, the pressure gradient between the recharge zone and the reservoir increases producing a higher water flow or suctioning water from the recharge zone. On the other hand the pressure gradient between the discharge zone and the reservoir should de-

López, *et al.*

Table 4. Average chloride concentrations for the aquifer, net mass extracted, change in water storage as given by chloride concentrations, and probably natural net recharge (natural input- natural output) for Berlin Geothermal Field from 1999 to 2005.

Date	Reservoir Pressure, well TR 4	Av. Cl reservoir concentration	Accumulated Mass Production	Accumulated Mass Reinjected Cold	Accumulated Mass Reinjected Hot	Accumulated Net Mass Extracted Reservoir	Change Net Mass Water Extracted 6 months	Mass of water in reservoir as given by Cl concentration	Net mass water drop in 6 months	Water supplied by net natural recharge
	bars	(ppm)	Kg	Kg	Kg	Kg	Kg	Kg	Kg	Kg
1-Jan-99	33.9	4812	1.99E+10	0.00E+00	1.49E+10	4.99E+09		7.75E+10		
30-Jun-99	32.6	4941	2.21E+10	0.00E+00	1.65E+10	5.59E+09	6.01E+08	7.55E+10	2.01E+09	-1.41E+09
1-Jan-00	27.2	5075	2.60E+10	0.00E+00	1.91E+10	6.89E+09	1.30E+09	7.35E+10	2.00E+09	-7.04E+08
30-Jun-00	28.7	5204	3.20E+10	0.00E+00	2.32E+10	8.88E+09	1.99E+09	7.17E+10	1.82E+09	1.71E+08
1-Jan-01	28.4	5338	3.72E+10	1.91E+08	2.66E+10	1.06E+10	1.72E+09	6.99E+10	1.80E+09	-8.80E+07
30-Jun-01	28.2	5467	4.27E+10	1.24E+09	3.03E+10	1.24E+10	1.82E+09	6.82E+10	1.64E+09	1.82E+08
1-Jan-02	27.8	5601	4.91E+10	2.38E+09	3.43E+10	1.48E+10	2.38E+09	6.66E+10	1.64E+09	7.43E+08
30-Jun-02	27.8	5729	5.57E+10	3.58E+09	3.88E+10	1.69E+10	2.09E+09	6.51E+10	1.49E+09	6.00E+08
1-Jan-03	28.6	5864	6.23E+10	4.80E+09	4.34E+10	1.88E+10	1.96E+09	6.36E+10	1.50E+09	4.61E+08
30-Jun-03	28.5	5992	6.91E+10	6.05E+09	4.83E+10	2.08E+10	1.94E+09	6.23E+10	1.35E+09	5.90E+08
1-Jan-04	27.9	6127	7.60E+10	7.32E+09	5.33E+10	2.27E+10	1.92E+09	6.09E+10	1.38E+09	5.45E+08
30-Jun-04	25.8	6255	8.31E+10	8.62E+09	5.84E+10	2.47E+10	1.97E+09	5.96E+10	1.25E+09	7.23E+08
1-Jan-05	27.4	6390	9.00E+10	9.90E+09	6.34E+10	2.66E+10	1.91E+09	5.84E+10	1.26E+09	6.54E+08
30-Jun-05	27.1	6518	9.67E+10	1.11E+10	6.83E+10	2.85E+10	1.85E+09	5.72E+10	1.14E+09	7.11E+08
Initial Water in reservoir 1992=	8.06E10 Kg									

June 2004 – July 2005

Net mass extracted (Kg)=	3.8E+09	**Apparent net mass water drop (Kg)=**	2.4E+09	**Water probably supplied by net natural recharge (Kg)=**	1.4E+09

Reservoir Pressure and natural net water recharge versus time
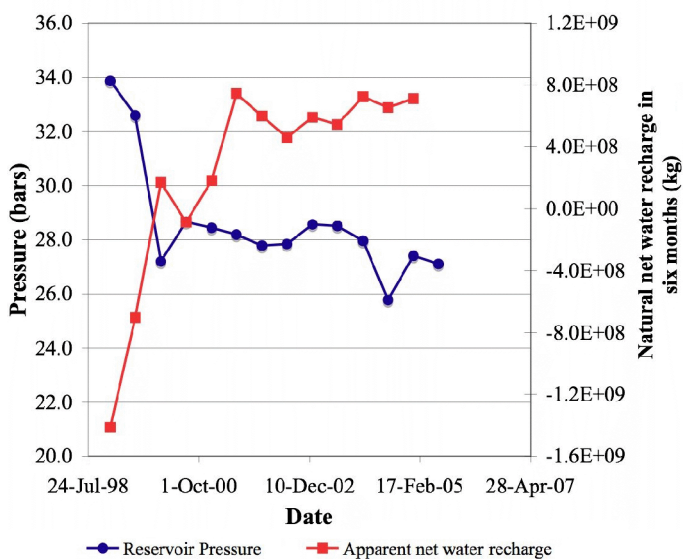

Figure 4. Reservoir pressure and water supplied by net natural recharge (natural inputs- natural outputs) versus time for the period January 1999 to June 2005. Note that the decline in reservoir pressure promotes an increase in net water recharge to the reservoir.

crease as the pressure in the reservoir declines reducing the water output, both processes should increase the net natural recharge to the reservoir. However, the net natural water supply is negative at the beginning of the study period and only becomes positive as the rate of pressure change decreases in early 2000 when the exploitation increased but also the reinjection of residual water. This behavior can have two possible explanations: 1) It is possible that the reinjected water before 2000 was overestimated leading to a underestimation of the net water extracted from the reservoir. An underestimation of the net water extraction would produce a higher "natural output" than the real output. If we look at Table 3, all the ratios of mass reinjected/mass extracted are slightly higher than 1.0 for the different chemical species. If different study periods are consider, we get the similar results. This bias to values slightly higher than 1.0 can only be explained if the masses of the reinjected waters have a systematic error towards higher values. That overestimation of the reinjection discharge probably produced more problems in the water balance at the beginning of the exploitation when only a few wells were involved. 2) It is also possible that the large perturbation of the system produced by the fast decline in reservoir pressure observed between 1992 and 1999 produced other processes in the aquifer, such as sudden development of a gas phase that is more effective in transferring mass and energy out of the system.

Changes in fumarolic fields due to exploitation have been reported in other geothermal fields (e.g. Ellis and Mahon, 1977; Prol-Ledesma, 1998). Of these two possible reasons for the initial negative values of net natural water recharge, the second one is probably more likely. The reason is that even if the reinjection masses are overestimated, it should be usually less than 10% as suggested by the values of mass reinjected/mass extracted ratios in Table 3. If hot reinjection is 10% lower than the reported values, the negative initial value for the net natural water recharge is still 88% of the value found in Figure 4. These results support the increased natural output mechanism as an explanation for the initial behavior of the net natural water recharge. At Wairakei geothermal field in New Zeland, Glover and Stewart (1996) report that during the first 10 years of exploitation, an enlarged steam zone produced a temporary increase in steam flow and heat ouput at the Karapiti thermal area.

The data in Table 4 shows that the mass of water supplied by the net natural recharge stabilizes during the last 18 months. For the last year of the study period (July 2004 to June 2005) the total net mass extracted from the reservoir is 3.8E9 Kg, with 2.4E9 coming from the reservoir storage and 1.4E9 coming from natural water recharge to the reservoir. This means that around 64% of the water extracted is coming from storage.

Conclusions

The analysis of the transient data sets for mass of water extracted and reinjected, as well as the chemical composition of the discharge can give important insight into the processes that affect the mass balance of the reservoir. A balance between the non-volatile extracted and reinjected chemical species suggest that the salinity of the reservoir water is increasing with time due to the vapor extracted for the production of electricity. The net result of these operations is the extraction of water and volatile species such as carbon dioxide increasing the salinity of the reservoir water. As exploitation continues the salinity will continue increasing. The increased salinity could lead to the precipitation of other minerals in addition to silica and clog the pores reducing the productivity of the field. Modeling work is needed to predict what is going to happen as the volume of water reduces and the salinity of the reservoir as a whole increases.

The initial high pressure drop rate in the reservoir seems to have promoted an increased natural output of water from the reservoir probably due to the production of a vapor phase and increased heat and mass transfer to fumaroles, other aquifers and soils. Stabilization of the reservoir pressure seems to have helped to reduce the natural ouput or increased the natural input to produce a net positive recharge to the system. The results of this study show the importance of keeping good records of the mass extracted and reinjected as well as the frequent chemical sampling of the extracted and reinjected waters. It also shows the need to monitor the natural outputs of the reservoir such as hotsprings and fumaroles. Changes in the areal extension and heat and mass discharge at these sites could be correlated with changes within the reservoir. Future monitoring of geothermal fields in exploitation should consider the need to monitor frequently the surficial features as well as the reservoir.

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