Updated Numerical Simulation of the Miravalles Geothermal Field, Costa Rica

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ABSTRACT

The Instituto Costarricense de Electricidad (ICE) carried out an update of the numerical simulation model of the Miravalles geothermal field in 2001, to understand the evolution of the geothermal system and develop forecasts of field behavior under different operational scenarios.

Since the last previous numerical modeling effort, the installed generation capacity at the field had increased from 60 MW to 142.5 MW, expanding significantly the base of operational data, and increasing the need to optimize management of the geothermal reservoir.

The updated three-dimensional model was developed using the TOUGH2 simulation program and included a "double porosity" formulation. Production enthalpies, production chloride concentrations and downhole pressures from observation wells were available for calibrating the model by history matching. A second water component was incorporated in the model to represent chloride concentrations, which proved to be valuable for calibration because of the high quality of the chloride data and the reliability of chloride as a tracer of injected water. Good matches to pressure and chloride histories were achieved in most cases during the calibration stage. Detailed matching of the production enthalpies was not attempted, because the relatively low accuracy of the measurements obscured subtle changes in enthalpy, but a reasonable agreement between calculated and measured enthalpies was reached.

Many Miravalles wells are producing fluid that has been previously injected. Production enthalpies have so far not declined significantly, because the returning fluid has been adequately heated by the reservoir rock, but the model has shown that, under the current scheme of production and injection, reservoir temperatures will decline in the production wells located closest to the injection areas. There will also be additional pressure declines during the next 25 years. A series of forecasts was made with the updated model, using a trial-and-error process, to investigate the best means of mitigating predicted enthalpy and pressure declines. It was found that, by shifting a portion of the injection from wells located in the southern part of the field to wells in the western sector, the pressure and temperature declines rates could be greatly reduced. ICE is already taking action to implement this scheme for improving field management.

Introduction and Methodology

Significant changes have occurred at the Miravalles field since the last previous numerical modeling effort was undertaken in 1998 (Pham *et al.*, 2000). The 55 MW Unit II came on line in August 1998, and the 27.5 MW Unit III started operation May 2000. These two units increased the installed generation capacity at Miravalles by more than 135% (from 60 MW to 142.5 MW). Consequently, the rate of extraction of geothermal fluid from the reservoir has more than doubled. New wells drilled in the field have provided new information about subsurface temperatures and pressures, and the natural pattern of fluid movement in the geothermal system. These changes, and the availability of three more years of production and injection data, required that the model be updated in order to serve as an effective tool for reservoir management.

Three major modifications were made to the existing model in this study: (1) the grid-block layout was refined in all layers of the model, (2) the double-porosity option of the modeling software was implemented; and (3) multiple fluid components were modeled to track fluid flow paths in the reservoir.

Previous simulation work utilized the single-porosity method to calculate heat and mass flow in the reservoir. This approach was sufficient to provide an overall long-term forecast of the reservoir's behavior under various assumed configurations of production and injection. For the new simulation effort we transformed the single-porosity model into a double-porosity model, using the MINC method of the simulator TOUGH2. With this method, the reservoir can be discretized into fractures and matrix blocks. The fractures are interconnected while each rock matrix block connects only to an adjacent fracture. Under this arrangement, the geothermal fluid moves mainly through the fracture network, while the matrix blocks act as storage units. This type of model provides a more accurate representation of the real behavior of a volcanic reservoir such as Miravalles.

Chloride concentrations in produced fluids have been monitored at Miravalles since the Unit I plant began operation. However, fully-processed chloride data were not available when the 1998 model was developed. Subsequent processing of the data has allowed the chloride trends to be defined clearly, allowing their incorporation into the model to provide additional insight into the behavior of injected fluid in the reservoir. Chloride concentrations may vary substantially from well to well, even for production wells located close to one another. To model these variations effectively, the gridblock size was further refined, particularly in the central part of the field, and the double-porosity method was used.

In the model, one water type is used to represent injected and produced fluids, while the second water type represents the chloride component. The simulator keeps track of the mass movement of the two types of water separately, thus allowing quantitative tracking of chloride concentrations within the reservoir.

Description of the Updated Model

The model covers 9 km in the east-west direction, and 12 km in the north-south direction (Figure 1). It contains 6 layers, covering a total vertical interval of 1,600 meters. Layer 1 extends from +100 m to -200 m elevation, layer 2 from -200 m to –400 m, layer 3 from -400 m to -600 m, layer 4 from -600 m to -800 m, layer 5 from -800 m to -1,100 m, and layer 6 from -1,100 m to -1,500 m. All elevations are referenced to mean sea level (msl).

To model chloride trends more accurately, the gridlock configuration of the model was refined in layers 1, 5, and 6, increasing the number of blocks from 283 to 365. Further partitioning of the gridblocks using the double-porosity method raised the number of gridblocks in each of these three layers to 730.

A similar refinement of the grid was made for the production layers (2, 3 and 4) of the model. In the central part of the field, the gridblocks were sub-divided, increasing their number from 365 to 477. Applying the double-porosity method increased the total gridblock number in each of these three layers to 954. Therefore, the total number of gridblocks in the model was increased from 1,944 to 5,052.

Permeability patterns remained relatively unchanged with respect to the previous model. Areas in the central part of the field, where well density and productivity are the highest, were assigned the highest permeability. Peripheral areas in the western and northern parts of the field were assigned the lowest permeability, as indicated by well data and subsurface temperatures.

Initial-State Simulation

Overall, the initial-state model duplicates the subsurface distribution of measured temperature, typically to within ±5°C. As an example, Figures 2 and 3 show the measured and calcu-

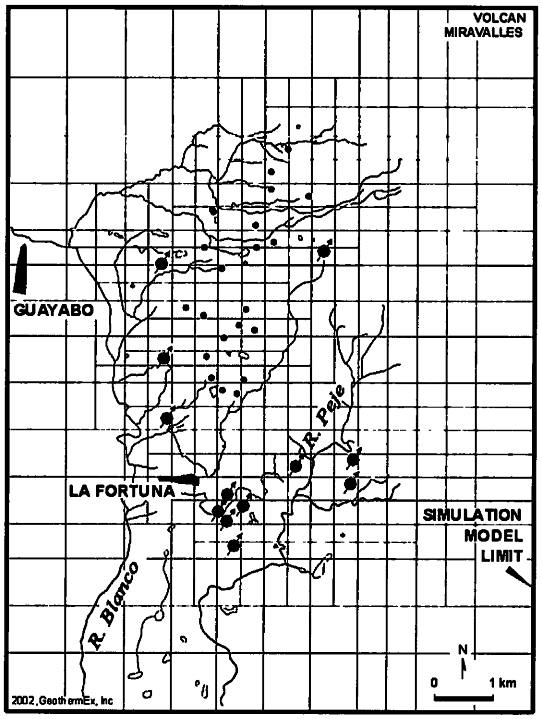


Figure 1. Well location map showing simulation model limit.

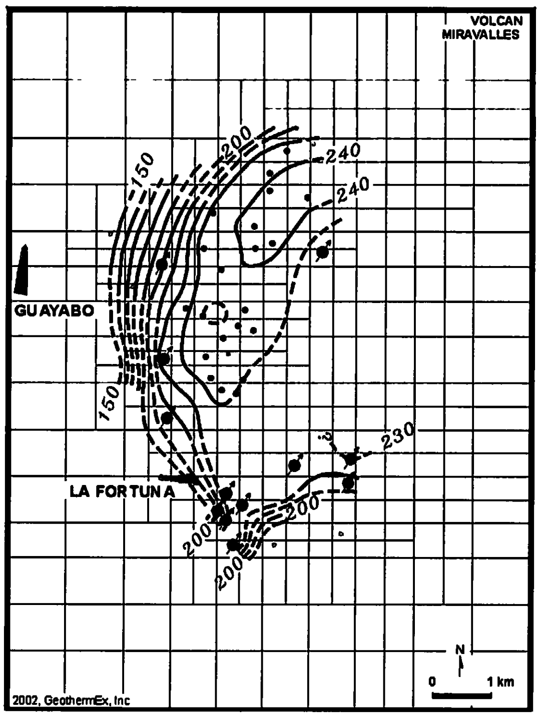
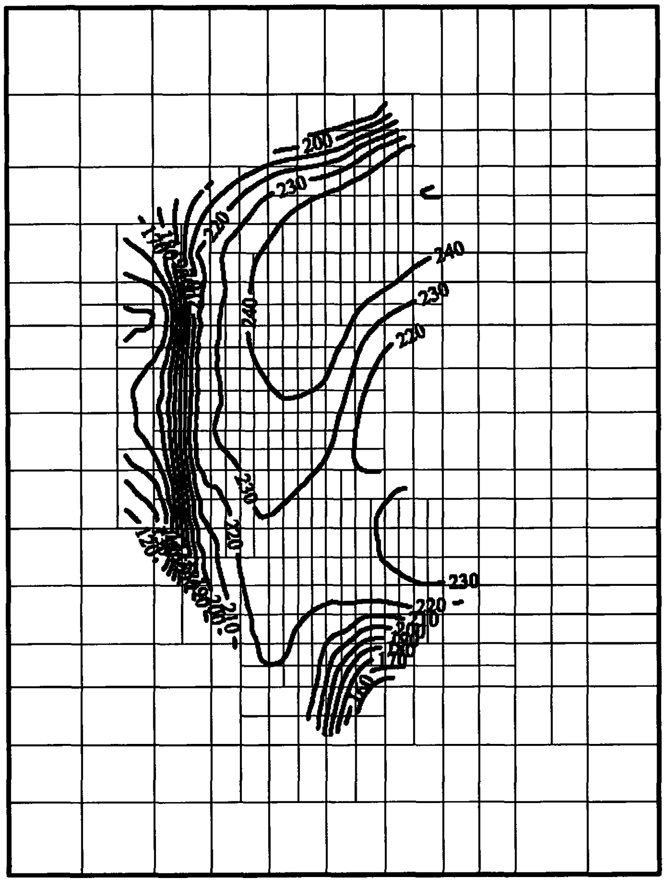


Figure 2. Measured temperature distribution (°C) at -500m (msl), layer 3.



2002, GeothermEx, Inc.

Figure 3. Calculated temperature - layer 3, at -500 m, msl.

lated temperature distributions in one of the main production zones, layer 3. These figures indicate an excellent match, considering the uncertainty associated with measurement and interpretation of pre-exploitation formation temperatures. A similarly good match was obtained for the other model layers.

After numerous trial-and-error iterations, the double-porosity model was successfully calibrated against observed subsurface temperatures and static temperature and pressure profiles. Once the updated initial-state model was fully calibrated, it was used to match the dynamic historical production data.

Historical Data Matching

Of the available historical data, water levels and downhole pressures in observation wells, and chloride trends from the production wells, were used to calibrate the model. Detailed production and injection data were input into the model, as were chloride concentrations in the injected water, and the observed pressure and chloride trends were matched.

The locations of production and injection zones in the model were selected primarily on the basis of data obtained from flowing downhole surveys. For wells without flowing survey data, the production/injection zones were assigned based on surveys from nearby wells.

Water-level measurements were translated into pressures at a common data of -300 m msl by calculating the weight of the overlying water column, taking into account density variations occurring as a function of temperature changes with depth. Downhole pressure data were adjusted by the calculated pressure difference between the pressure probe level and the reference datum.

Chloride does not participate in water-rock reactions in most volcanic environments, so it a good tracer for determining the pathways between injection and production zones. The initial distribution of chloride concentrations in the reservoir is known reasonably well (with concentrations falling in the range of 2,800 to 2,950 parts per million). Reliable chloride trends at the production wells are available from detailed data collection and processing carried out by ICE. Therefore, it was possible to understand the return behavior of injected water by matching the available chloride data using the double-porosity method and employing the two-water feature in TOUGH2.

Reservoir chloride concentrations were determined from chemical analyses of samples taken from the weir box at atmospheric pressure during production tests, back-calculating to reservoir conditions based on flowing pressures and temperatures. These values were used to calculate the amount of chloride in the separated brine at the satellite separator, which was injected back into the reservoir. The chloride concentration calculated by the model for each of the production wells was then compared to the measured value. The model was modified if a large difference between the measured and calculated chloride values was observed. This process continued until a suitable match between calculated and measured concentrations was achieved.

Matching Results

The pressure-decline trends of the observation wells constituted one of the most reliable sources of data for matching the reservoir response to production and injection. An example of pressure matching for wells in the central area is shown in Figure 4,overleaf, (well PGM-09). Both downhole pressure measurements (broken line) and water levels (solid circles) were available for this well. The solid line in Figure 4 denotes the pressure trend calculated by the model. An excellent agreement was attained throughout the time interval covered by the data, suggesting that the petrophysical parameters in this area of the model have been accurately assigned. Similarly good matches were obtained for the wells in the main production area of the field.

It would have been very difficult to use the measured enthalpy data to obtain a clear picture of the effect of injection on the production wells, due to the lack of definable enthalpy trends. Fortunately, the results obtained by matching the trends of measured chlorides provided a much clearer picture of the effect of injection on production well enthalpies. To better analyze the effect of injection into the western and southern injectors on the production wells, the production area was divided into 5 separate sections (north-central, west-central, south-central, southern and eastern), as shown in Figure 5, overleaf.

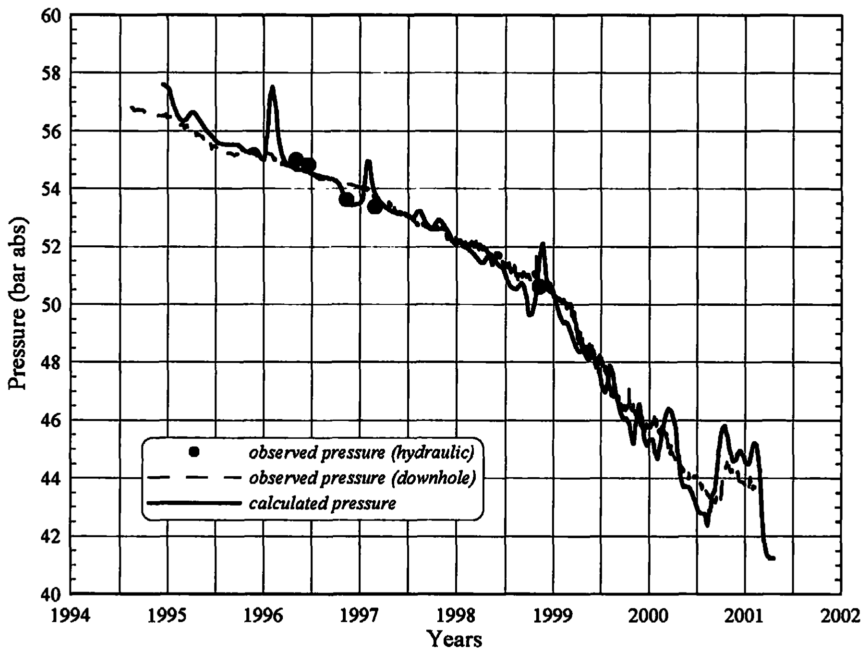


Figure 4. Matching of observation pressure, well PGM-09, Miravalles.

Figure 6 shows the chloride concentration matches obtained for wells PGM-05, PGM-42, and PGM-43 in the west-central part of the field. Excellent matches were obtained for all three wells, and the effect of injection into PGM-22 on the nearby production wells is clearly illustrated. From March 1994 to May 1998, while only Unit 1 was on line, the rate of injection into PGM-22 was about 210 kg/s. When Unit 2 came on line in May 1998, and Unit 3 in June 2000, some of the production wells that were supplying satellites 1 and 2 were shifted to other satellites for the new units. With less production, Satellite 1 generated less separated liquid, reducing the rate of injection into PGM-22 to around 110 kg/s after May 1998. Figure 6 shows that, prior to May 1998, the chloride concentration measured in PGM-05 increased from about 2,800 to 3,200 ppm, whereas after May 1998 the concentration stabilized or declined slightly as a smaller amount of the water returned from PGM-22 to PGM-05. A similar pattern was also observed in well PGM-42, which is located less than 1 km south of PGM-05. The effect on PGM-43 is less clear than it is for PGM-22, as this production well is located between PGM-22 and PGM-24.

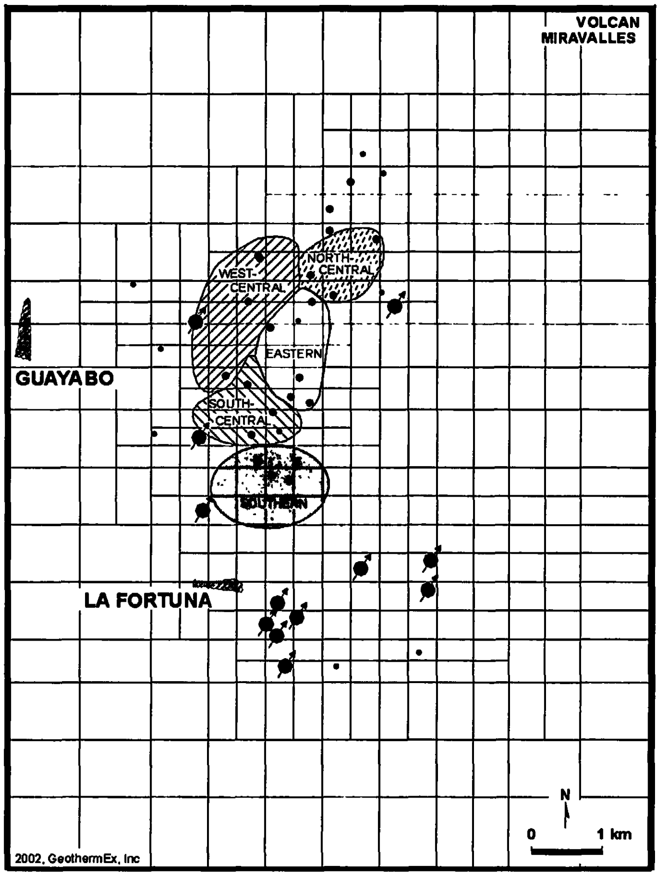


Figure 5. Regions of distinctive chloride production.

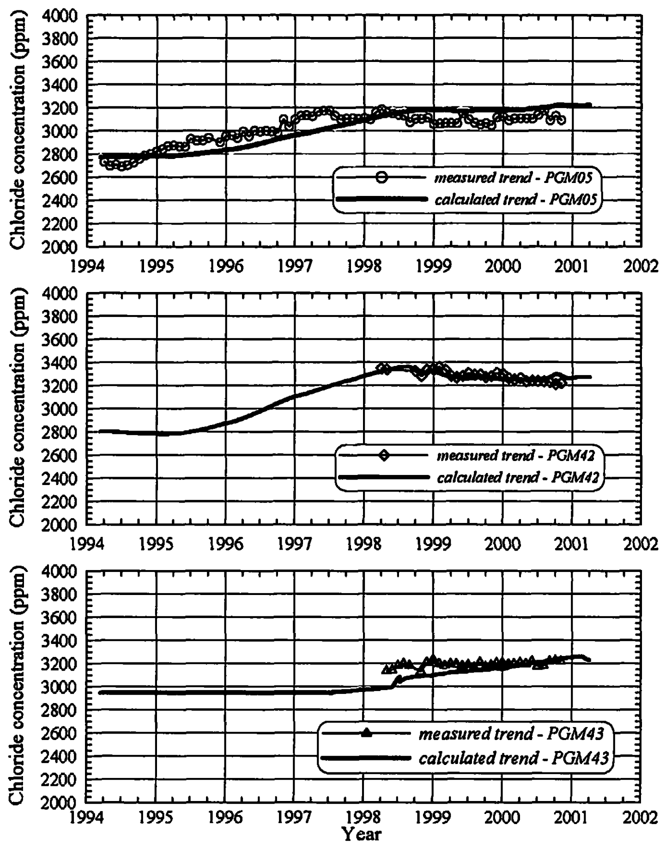


Figure 6. Matching of chloride trand, west-central wells.

The most dramatic increase in chloride concentration is observed in the southern production wells, as shown in Figure 7. Prior to May 1998, the higher-chloride injected water from PGM-24 and the southern injectors migrated back to PGM-12 and PGM-20, causing the measured chloride concentration to rise from about 2,800 to 3,200 ppm. During the same period, the chloride concentration measured at PGM-21 did not increase significantly, as this well is further from PGM-24. When Unit 2 came on line, a large amount of waste fluid was injected into the southern injectors. This fluid quickly came back to the southern production wells, causing their chloride concentrations to rise quickly; the model was able to replicate this change very well. The difference between measured and calculated concentrations is typically less than 300 ppm, or less than 10% of the measured value.

The chloride-concentration match obtained for wells in the north-central area is shown in Figure 8, which shows the calculated and measured chloride trends of PGM-01, PGM-10, and PGM-11. Overall, calculated and measured chloride concentrations remained constant throughout the time period considered. Minor variations in the measured chloride concentration in wells PGM-01 and PGM-10 could be due to uncertainties in the metering instrumentation, or to local phase changes in the geothermal fluid within the reservoir. When the geothermal fluid changes from single-phase to two-phase, more chloride is concentrated into the liquid phase; conversely, as the steam condenses into liquid, dilution of the chloride occurs. However, the variations observed in the measured data are very small, and the overall trends are fairly constant. This indicates that the injected fluid has not reached this part of the reservoir.

Good matches to the trends of the measured chloride concentration were also achieved for the other wells in the field.

The chloride data have shown that many of the wells at Miravalles are producing fluid that has been previously injected. So far, the returning injection fluid has been adequately heated by the reservoir rock, so it has not caused a significant decline in the production enthalpy. However, the amount of heat available in the rock formations is limited, so it is likely that cooling will accelerate in the future as the heat supply from the rock is diminished. Under the current production and injection scheme, production wells in the south (PGM-12, PGM-20, and PGM-21), and south-central (PGM-45, PGM-46, PGM-47, and PGM-49) areas will be affected by injection return, with the greatest effect seen in the southern production wells.

The results of the history matching show that the model successfully simulates the behavior of the reservoir under the historical conditions of production and injection. Pressures derived from water levels and downhole measurements have been well matched. Excellent matches to measured chloride data have been achieved for the majority of the production wells. Thus, the model is adequately calibrated for use in forecasting future reservoir behavior under various production and injection scenarios.

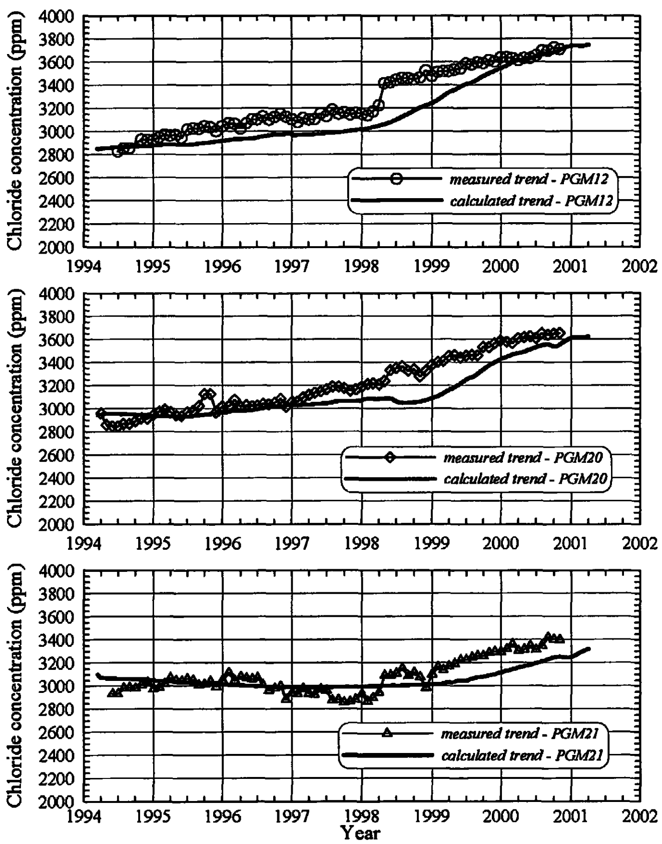


Figure 7. Matching of chloride trand, southern wells.

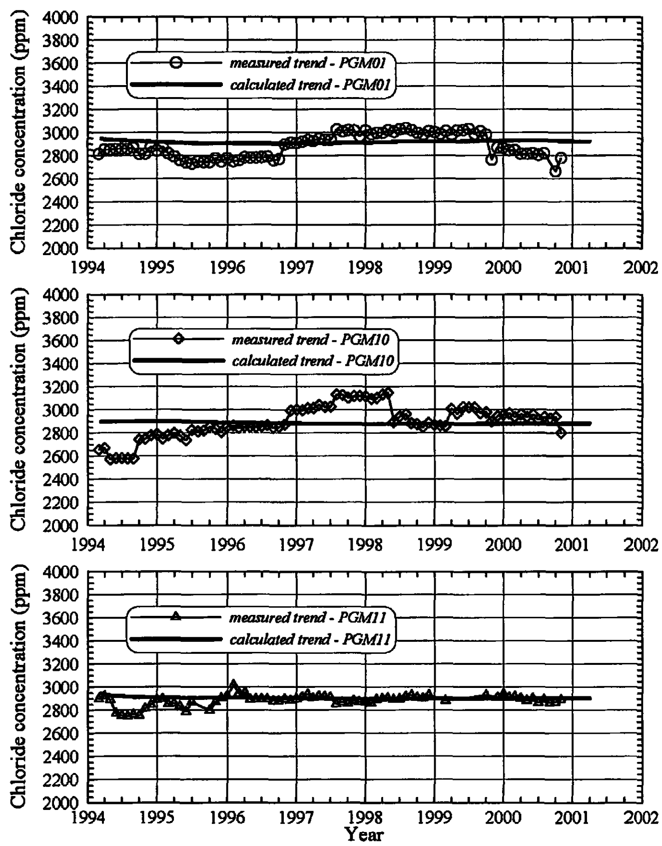


Figure 8. Matching of chloride trand, north-central wells.

Forecasting of Reservoir Behavior

Forecasts made using the model showed that, under the current scheme of production and injection, reservoir temperatures will decline as much as 20°C (at the southern production wells) during the next 25 years, and additional pressure declines of up to 10 bars will occur. Additional forecasts were made under a variety of production/injection scenarios, to determine the optimum distribution of injection and production for prolonging the life of the field under the current condition of mass extraction from the reservoir.

The rate of pressure decline currently being experienced by most wells in the field will eventually be reduced in response to stabilized production and injection rates. The model forecasts a lessening of the pressure decline rate as recharge and peripheral water re-equilibrate with the geothermal fluid in the main reservoir zone. The total pressure decline will range from 7.5 bars for wells close to injection wells to 10 bars for wells further from injectors.

Furthermore, the model suggests that shifting a portion (up to 300 kg/s) of the injected fluid from the southern injectors to the western injectors will provide additional pressure support to all the production wells in the field, with the most significant pressure support experienced by the wells of Satellites 1, 4, and 5. Under this scenario, an observable but small increase in the cooling trend is expected at all satellites except Satellite 3.

Based on this result, ICE is considering shifting up to 300 kg/s injection fluid from the southern injectors (PGM-16, PGM-26, and PGM-28) to the western injectors (PGM-22 and PGM-24), and, if economically feasible, to the currently idle wells PGM-15, PGM-25, and PGM-38. The shift in injection would probably be carried out in increments of 100 kg/s at time intervals of 6 months, so that ICE can effectively monitor the effects of the changes in injection on reservoir pressure and enthalpy.

Conclusion

The numerical simulation model, once properly calibrated, constitutes an effective tool for managing the geothermal field at Miravalles. ICE plans to make various other operational changes based on the results obtained from the numerical model.

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