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NUMERICAL MODELING OF THE CERRO PRIETO GEOTHERMAL FIELD, MEXICO

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ABSTRACT

A completely new, detailed three-dimensional numerical simulation model of the Cerro Prieto geothermal field has been developed to optimize field management and the plant capacity expansion. A conceptual model was developed from all available exploration data, drilling records, well logs, chemical and well test data. A three-dimensional simulation model was then constructed and calibrated against the initial state of the system, which confirmed the conceptual model and helped refine boundary conditions. The model was further calibrated by trial-and-error matching of the production history, which involved over 200 wells and a 26-year exploitation history. Observed and calculated production histories were matched satisfactorily. Using the calibrated reservoir model and wellbore simulation, well behavior was forecast under various possible production and injection scenarios and proposed capacity expansion schemes. These forecasts were the basis of optimization of field management and capacity expansion.

1. INTRODUCTION

Cerro Prieto (figure 1) is the largest liquid-dominated geothermal field in the world, with an installed plant capacity of 620 MW soon to be expanded to 720 MW. With continuous power generation since 1973, it is the second oldest geothermal development in North America. A new, detailed three-dimensional numerical simulation model of the field has been developed to optimize field management and the plant capacity expansion.

This study started with the refinement of an existing conceptual geohydrological model of the field from all available exploration data, drilling records, well logs, fluids chemistry and well test data; that work is not described herein.

2. METHODOLOGY

The numerical model of the reservoir was developed in two stages. The first stage consisted of developing an initial state model, based on the conceptual geohydrological model and utilizing the TETRAD simulator. The second stage consisted of production history matching and parameter adjustment.

After a thorough review of the conceptual model, a simulation grid was generated to represent a three-dimensional discrete model of the geothermal system. All relevant parameters were then estimated for each grid element, from observed or inferred data. When sufficient data were not available to estimate a parameter, adequate values were assumed based on our studies of similar systems.

During initial state modeling the main objective is to verify the temperature distribution and the heat and mass discharge of the model. As a result, the most important properties of the rocks are x, y and z permeability and thermal conductivity, which must be specified with some detail. The storage parameters, as well as porosity, density, and rock specific heat, are not as important for the initial state, and it is sufficient to utilize mean values for these parameters until the production history match.

System discharge and recharge flows were identified and specified for the appropriate grid elements. For elements located at the grid boundaries, the following hydraulic boundary conditions were considered: defined recharge (or discharge) flow; open boundary with constant pressure and temperature; recharge flow as a function of pressure and closed boundary (without flow) at a constant temperature.

3. DESCRIPTION OF THE NUMERICAL MODEL

The model encompasses 110 km^2, with dimensions of 11 km NE to SW and 10 km NW to SE (figures 2 and 3). The NW-SE direction is parallel to the NE-dipping Cerro Prieto Fault.

Vertically, the model has a thickness of 3,600 m divided into seven layers. The first layer is 800 m thick and represents the cap rock above the top of the reservoir. The second layer extends from 800 m to 1,200 m depth and represents the uppermost portion of the geothermal reservoir. The next four layers are each 400 m thick and represent the main body of the reservoir, in which most of the current production and injection take place. The seventh is 800 m thick and represents the deepest portion of the reservoir. The bottom of the seventh layer (and of the model) is at 3,600 m depth.

The reservoir is represented by a double-porosity model, with 9,072 grid blocks: 4,536 blocks devoted to matrix and 4,536 overlapping blocks devoted to fractures. Each one of the seven layers contains 648 grid blocks of each type, and in plan view, each block is a square, with side lengths of 250 m to 2,000 m.

To thermally couple the model to the surrounding rock, constant temperature boundaries were added to the top of layer 1, bottom of layer 7 and to the sides of layers 2 to 6. The temperature at the top of layer 1 was set at 40ºC and the temperatures at the sides of layers 2 to 6 were set to match the regional temperature gradient. There is a lack of temperature data from below 3,200 m, the node level of layer 7, but it was reasonable to assume that the rock temperature at 3,600 m (lower surface of layer 7) is somewhat higher than the node temperature at 3,200 m. This assumption is included by setting the temperature at the lower limit of each block of layer 7 to approximately 10ºC above the observed temperature in the same block at 3,200 m. This causes heat flow to be conducted into the model, but the magnitude of this flow is small relative to the convected heat that enters with hot fluid recharge at the bottom of the Eastern sector of the CP-II and CP-III production areas (figure 3).

Data from Cerro Prieto and the knowledge of other geothermal reservoirs in the adjoining Salton Trough geologic district of California were used to set the initial properties of the rocks in the model. It was initially assumed that matrix porosity decreases with depth from a value of 17.6% in layer 1 to 1% in the layer 7, and that fracture porosity was 2%. Horizontal permeabilities were assumed to be a logarithmic function of porosity and ranged from 4.64 millidarcy (md) at 17.6% porosity to 0.0215 md at 1% porosity. The horizontal permeabilities of the fractures were two orders of magnitude (100 times) larger than the matrix permeabilities.

These matrix and fracture permeability values were then increased within the high temperature zones in each layer and later modified during the calibration of the initial state and the adjustment to production history. Vertical permeabilities were also adjusted during the calibration of the initial state.

4. CALIBRATION OF THE INITIAL STATE.

4.1 Methodology

The initial state model was allowed to run for a simulated period of several thousand years, which was increased as necessary until the system evolved to a quasi-steady state. If a quasi-steady state was not achieved, it was considered that the model did not represent reality, and the model parameters were modified accordingly.

Final calculated temperature distributions and mass and heat discharges were then compared with the corresponding observed distributions. If these comparisons resulted in differences of less than ±10ºC between the calculated and observed temperatures, and differences of less than ±5 bars between the calculated and observed pressures, it was concluded that the model was an adequate quantitative representation of the system initial state. If these tolerances were exceeded, additional parameter modifications were made, and the trial-and-error process was followed until a satisfactory match was reached between the calculated and the observed data.

4.2 Results

The primary heat source that is required to simulate the initial temperature distribution is hot brine that enters the system at depth and moves upward, driven by buoyancy. This deep upflow was modeled by injecting brine at high temperature into the bottom layer of the model, at locations indicated by the conceptual hydrogeological model.

Through a trial-and-error process, the upflow and temperature ratio, the location of the upflow areas and the permeability of the blocks in the model grid were varied until an adequate matching temperature distribution was observed. The best matching was obtained with a recharge of approximately 1,250 tonnes per hour that enters the grid from underneath the eastern end of areas CP-II and -III (figure 3).

The model was then allowed to run for a simulated 500,000 years, to test stability, which was confirmed by monitoring temperature and pressure versus time in selected grid blocks. An excellent match to the observed temperature distribution was finally obtained (e.g. figure 4), and the first stage of calibration was successfully completed.

5. CALIBRATION WITH PRODUCTION HISTORY

5.1 Methodology

The second stage of model development consisted of calibration to represent as closely as possible the effects of production and waste fluid injection, although it is not always possible in practice to obtain a close match to all data.

Many geothermal wells have multiple feed zones at different depths and sometimes different enthalpies, yet usually the rates and enthalpies of the individual zones are not well known. It is therefore assumed in a simulation that production to a given well comes from a single level of the model grid. For this reason the model reflects an average condition over the depth range that is represented by the assumed level.

In observation wells the permeable interval can be contained in more than one level of the model grid. Therefore, it is possible for observation wells to react to production and/or injection occurring in multiple levels, and the pressure reaction can reflect an average signal.

There are some wells that are affected by broken casings or by leaks at the liner overlap, and fluid entries at defective zones cause the measured wellhead enthalpy to be lower than the real enthalpy at the reservoir production zone.

As mentioned above, thermal conductivity and permeabilities are the most important parameters for matching the initial reservoir temperature distribution. If production history matching requires changing the permeability over a large area, it is necessary to again run the initial state model, to verify that the calculated temperature and pressure distributions still match the observed data within the allowed tolerance. If tolerance is not met, the process continues until a model is found that reproduces both the initial temperature distribution and the production history.

5.2 Results

The model that was used for the history matching phase consisted of the initial state model with additional data files to describe the locations of production, injection and observation wells and the production and injection rates. The description of each well was based on location, casing depth and total depth. The flow rates were based on monthly measurements.

The observed response to exploitation indicates that peripheral aquifers are providing a large amount of reservoir pressure support, except for some support from injection primarily in the south of the CP-I area.. In the upper layers of the model these peripheral aquifers provide recharge of cool water to the CP-1 area. In the deeper layers, peripheral aquifers provide hot recharge to the CP-II and CP-III areas.

To model peripheral recharge, aquifers were added to the sides of the seven layers, essentially coupling the model to the hydrology of the Mexicali Valley. The match to observed reservoir pressure response was obtained by adjusting permeability in these aquifers and in blocks within the model.

Furthermore, upflow beneath the eastern part of the CP-II and CP-III areas was allowed to increase from 1,250 tonnes per hour at initial state to 2,306 tonnes per hour at the end of the field history matching period, in response to the pressure decrease in the reservoir.

The history matching of a typical well is represented by figure 5, which includes measured flow rates, calculated bottomhole pressures and measured and calculated enthalpies.

A notable characteristic of the field history has been the develop-ment and subsequent partial collapse of excess enthalpy (reservoir steam production) in the central area. In order to improve the enthalpy history match and in particular this retrograde behavior, a 10% fraction of reservoir rock was set to be in intimate thermal contact with the fracture system. Conversely, 90% of the heat in the reservoir rocks can interchange with the fracture system only by the heat-conduction through the matrix system to the fracture system.

Even with this setting, the numerical model can calculate the general shape of the observed total production enthalpy history, but the enthalpy increase calculated from 1986 and its subsequent decrease are both smaller than the changes observed. Part of this difference is due to the transient reservoir steam production, principally at some CP-II wells, which has not been exactly calculated by the model. A calculated match could be facilitated by using smaller grid blocks in the CP-II area. However, such an improvement of the model will not produce any significant improvement of the long-term enthalpy projection, because the majority of the wells affected by this change in enthalpy are presently producing only liquid. The basic model (existing production) forecasts a decrease in mean enthalpy at CP-I, II and III, which is similar to the decrease observed since 1992.

To achieve the observation well matches it was necessary to significantly adjust the horizontal and vertical permeabilities; figure 6 represents a typical result. Figure 7 shows the combined flow rates from the recharge aquifers versus time.

6. EXPLOITATION SCENARIOS

6.1 Exploitation models

The calibrated model of the reservoir was then used to forecast the behavior of wells and the reservoir for a 30 year exploitation period.

The Comisión Federal de Electricidad, the field owner, requested the evaluation of three simulation scenarios, each of which represents 80 MW of new production (unit CP-IV) starting in year 2000, supplied by 1,000 tonnes/hr of steam from 17 specified wells that produce from depths of 2,400 to 3,000 m in the CP-IV area (that is, the 'Hidalgo polygon'), a rectangle east of CP-III (figure 1). In each case, the existing production of steam from CP-I, -II, and -III is maintained at 5,400 tonnes/hr throughout the 30-year period of forecast. The other characteristics of the scenarios are as follows.

- Scenario 1: 40% of the separated water from CP-IV is assumed to be injected into the existing CP-I, -II, and -III wells.
- Scenario 2: 100 % of the separated water from CP-IV is assumed to be injected into shallow wells located in the northern part of the Hidalgo polygon.
- Scenario 3: production for CP-I, -II, and -III is maintained by adding production fluids from deeper levels in the reservoir that is currently being exploited.

For comparison, a base case scenario was also run, in which the new CP-IV production is ignored.

6.2 Exploitation results

Under Scenario 1, pressure declines of up to 25 bars after 30 years are anticipated in certain areas. As temperature and enthalpy decline, more mass withdrawal is required to maintain the necessary steam rate. In the CP-I, II, and III areas, a 63% increase of mass flow is needed after 30 years. In the CP-IV area, a 47% increase in mass flow is needed.

Under Scenario 2, shallow injection of CP-IV water in the northern part of the polygon reduces the amount of reservoir enthalpy decline. To maintain the steam rate in the CP-I, -II, and -III areas, a 60% increase in mass flow is needed. In the CP-IV area, a 45% increase in mass flow is needed.

Under Scenario 3, the system receives the benefit of both shallow injection of CP-IV water in the northern part of the polygon and deep make-up wells in CP-I, -II and -III, further reducing the amount of reservoir enthalpy decline. To maintain the needed steam rate, a 19% increase in mass flow is needed in CP-I, a 6.7% increase is needed in CP-II, a 13% increase is needed in CP-III, and a 9% decrease is needed in CP-IV (due to the increase of steam production).

The two fundamental parameters for the future of the system are reservoir pressure and production enthalpy. The numerical model forecasts a continuing decrease of the observation pressure, and predicts that the additional development (CP-IV) will produce a limited increase of this decline.

With the new production from the Hidalgo polygon for unit CP-IV, the model forecasts a small increase of average enthalpy in the CP-I, -II, and -III regions. This is due mainly to a growing reservoir steam saturation, that is in-turn caused by the increase of reservoir pressure decline. In Scenario 3 there is an additional mean production enthalpy increase due to the drilling of wells deeper than the present wells in areas CP-I, -II, and -III.

The inferred enthalpy for the CP-IV area is about 1,600 kJ/kg. Since this area is located quite far from the majority of the production and injection in sectors CP-I through –III, there is not much difference between Scenarios 1 and 3.

Generally, the model indicates that the expected pressure and enthalpy decreases lie within a manageable range and, therefore, the reservoir can sustain additional development. In order to further understand the effect of development on the production of steam and electric power, it is advisable to use models to calculate flow of individual wells, flow and pressure in the steam collection network, and production at the generation plants. Such calculations were outside the scope of this study.

The Cerro Prieto reservoir has responded to production with a reduction in pressure and enthalpy. Although additional declines are anticipated in some areas as a result of the additional production required for CP-IV, the numerical model suggests that the impact of CP-IV can be minimized by directing some injection to shallower levels on the periphery of the reservoir and by drilling relatively deep make-up production wells in the central production areas.

The CP-IV area appears to have sufficient capacity to provide 1,000 tonnes/hr of separated steam for 30 years.

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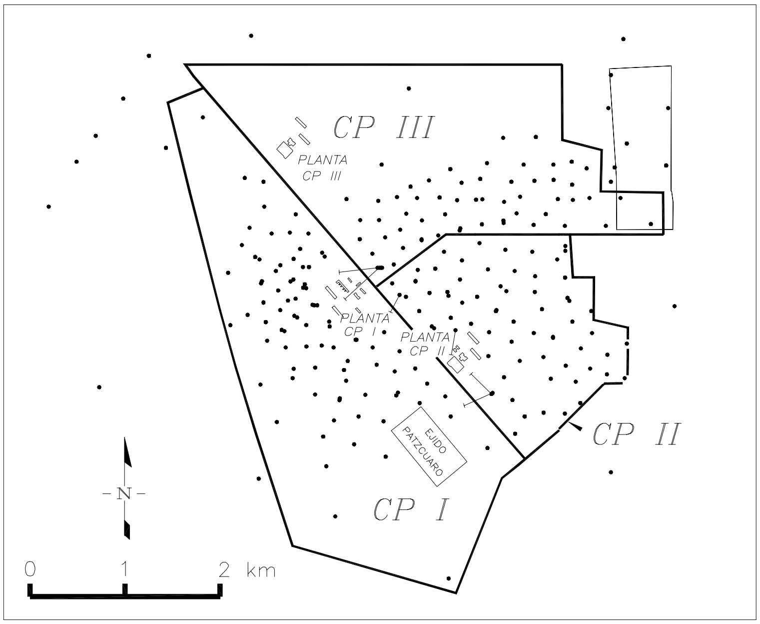

Figure 1. Map of the Cerro Prieto field with well locations

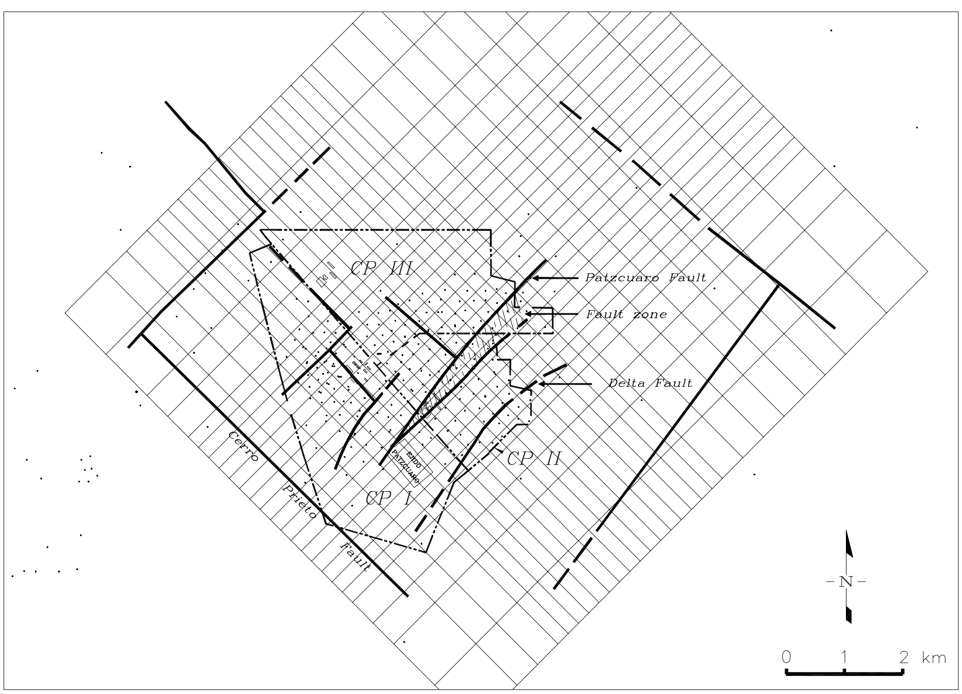

Figure 2. Simulation grid overlaying a map of the field

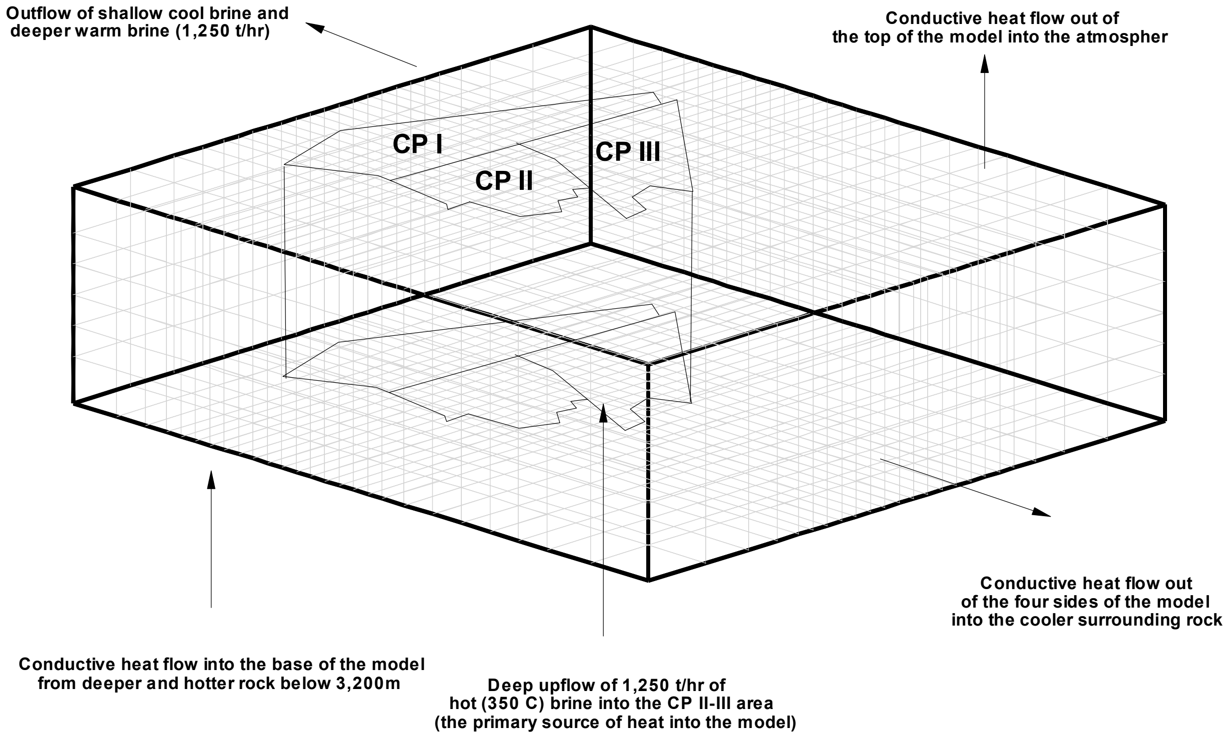

Figure 3. Heat and mass balance diagram for initial state model

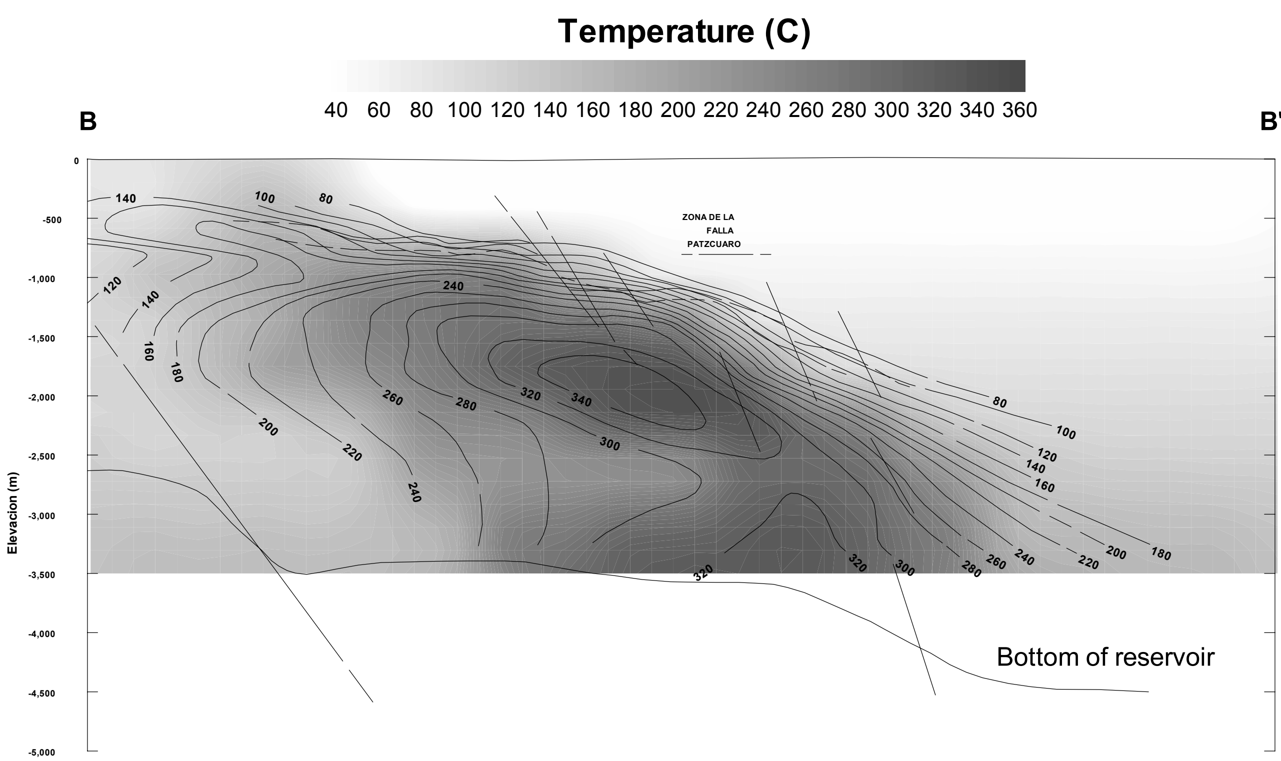

Figure 4. NW-SE cross section of observed and initial state model temperatures

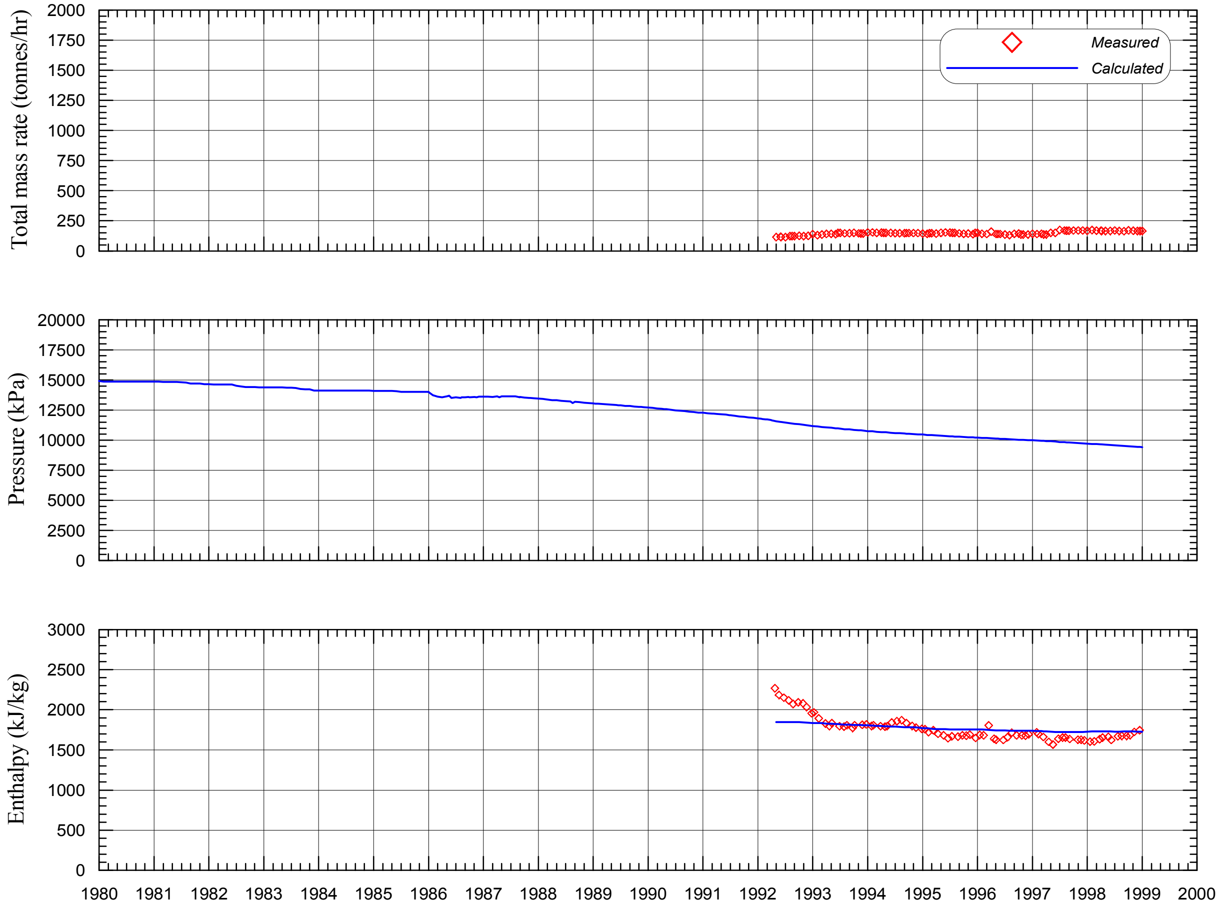

Figure 5. History match of enthalpy, well 610

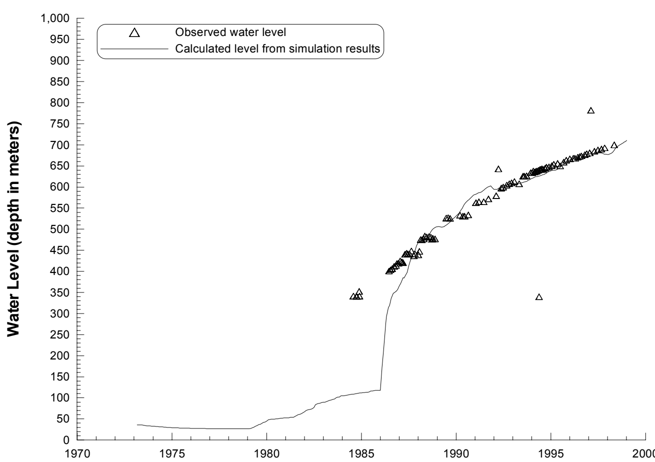

Figure 6. History match of water level in observation well M-203

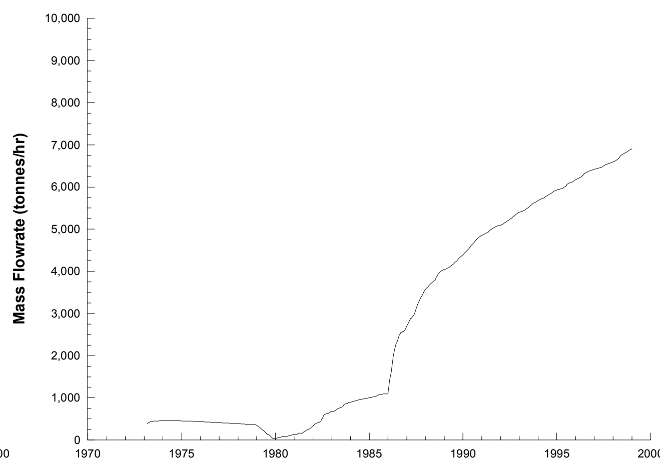

Figure 7. Total rate of mass recharge into reservoir as calculated by the model