

Modeling of Production/Reinjection Behavior of the Kizildere Geothermal Field by a Two-Layer Geothermal Reservoir Lumped-Parameter Model

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ABSTRACT

The main parts of a geothermal system are the reservoir and aquifer recharging and surrounding the reservoir. In this study, the reservoir is assumed to be composed of two parts: the upper (shallow) reservoir and the lower (deeper) reservoir which are hydraulically connected. This system can be viewed as similar to a two-layer reservoir system with crossflow.

This paper investigates the production/reinjection behavior of fields consisting of shallow and deeper zones in hydraulic communication. The fluid and rock properties in these zones can vary and the zones can be characterized by different temperatures. An example of such a geothermal system is the Kizildere geothermal field in Turkey. The shallow reservoir lies between 600-800 m depth and its temperature varies from 195 to 205 °C. A recently drilled well produces from a deeper reservoir about 1400-1500 m deep with a temperature of 240 °C. The water produced from the shallow zone has about 1.5 wt % dissolved CO₂ whereas the water produced from the deeper zone has nearly 3.0 wt % CO₂. Therefore, the distinctly different production and reservoir properties lead to the consideration of a two-layer model of the geothermal reservoir.

A new lumped-parameter model was used to study the production/reinjection behavior of the two-layer reservoir and to history match the long-term production data obtained from the Kizildere geothermal field. In the model, the reservoirs are assumed to be liquid-dominated and contain single-phase compressed water. The advantage of the two-layer geothermal reservoir model over the conventional one-tank model is that the upper and lower parts of the field can be treated separately. Several production and reinjection scenarios such as 1) production and reinjection for both zones, 2) production from the deeper one and reinjection into the shallow one, or vice versa, are investigated. Results of the modeling study for the Kizildere geothermal field indicate that the scenarios considering higher rate of production from the deeper reservoir result in lower pressure drop and thus increase the life of the reservoir. Modeling results discussed in the paper give important clues about the optimized and sustainable development of this type of field.

1. INTRODUCTION

The pressure/rate response of a geothermal reservoir to exploitation depends on the characteristics of the fluid recharge. The recharge in a reservoir, in particular, depends on differences in fluid pressure, permeability, temperature and geometry of the reservoir and surrounding formations. To understand the response, it is necessary to know the exploitation characteristics of the geothermal system, consisting of the reservoir and the surrounding recharge aquifers.

The response of a geothermal reservoir to exploitation can be analyzed by using lumped-parameter reservoir models. Lumped-parameter models provide estimates of the reservoir and aquifer parameters that fit data measured over an entire period of monitoring. Various lumped-parameter models have been proposed in the literature (Whiting and Ramey (1969), Grant (1977), Castanier et al. (1980), Brigham and Ramey (1981), Grant et al. (1982), Castanier and Brigham (1983), Grant (1983), Olsen (1984), Gudmundsson and Olsen (1987), Axelsson (1989), Alkan and Satman (1990), Axelsson and Dong (1998), Axelsson and Gunnlaugsson (2000), Satman and Ugur (2002)). Sarak et al. (2002a, 2002b) and Sarak (2004) improved the model developed by Axelsson (1989) and applied a regression approach considering weighted least square method and computed the statistics for the match (such as the 95% confidence intervals for parameters estimated). Such statistical indices are useful to evaluate uncertainty in the match and in the estimated parameters. One of the lumped-parameter models presented by Sarak et al. (2002a) is a model in which reservoir is considered to be composed of two parts: one upper (shallow) reservoir and one lower (deeper) reservoir. The two parts are connected hydraulically and both are also supported hydraulically by a surrounding aquifer or a recharge source. This paper discusses the application of these two-reservoir lumped-parameter models to production/reinjection data from the Kizildere geothermal field in Turkey.

2. THE KIZILDERE GEOTHERMAL FIELD

The Kizildere geothermal field is located in the easternmost part of the Buyuk Menderes graben, where it intersects the Gediz and Curuksu grabens. The field has a liquid-dominated reservoir system containing water with salinity of 4500 ppm and dissolved CO₂ (1-3% by weight) under reservoir temperatures between 195 and 240 °C, ranging in depth from 300 to 2300 m. The field was discovered in 1968, and 17 wells were drilled until the mid-1970s to assess the field potential and at the same time to develop the field. A 17.8 MWe power plant fed by six production wells (KD-6, 7, 13, 14, 15, 16) was installed in the field and power generation started in 1984. Three additional production wells (KD-20, 21, 22) were drilled two years later to produce more steam. The field has been generating approximately 7.5 MWe of energy. In 1997 a deep well (R-1) drilled to 2300 m for reinjection purposes found a temperature of 240 °C. Recently, reinjection through the R-2 well has been scheduled in the field for water disposal and reservoir pressure maintenance. Figure 1 shows the location of wells in the Kizildere field.

Two stratigraphically separate zones in the field were initially identified as the reservoir during the exploratory stage; a zone of limestone, with temperatures of 195-200 °C and moderate permeability, and a zone a few hundred meters further down of marbles, with temperatures of 200-205 °C and high permeability. The limestone is not

distributed homogenously and is not encountered in all the wells. The marbles are much more continuous and thicker, with a better permeability. Therefore, the marble zone was targeted for early exploitation (Serpen and Satman, 2000). The recent discovery of 240 °C temperature was made in another stratigraphically separate gneiss of the Paleozoic and increased the depth scale of the field.

As a summary, two-reservoirs have been identified in the Kizildere geothermal field: a shallow reservoir (at 600 m to 800 m depth), and a deeper one (about 1400-1500 m depth). Whether the deeper one extends throughout the entire field is yet to be determined by further deep drilling. However, the chemical analysis of the geothermal fluid has revealed the similarity of water produced from both reservoirs and supports the idea of a hydraulic communication between the shallow and deep reservoirs.

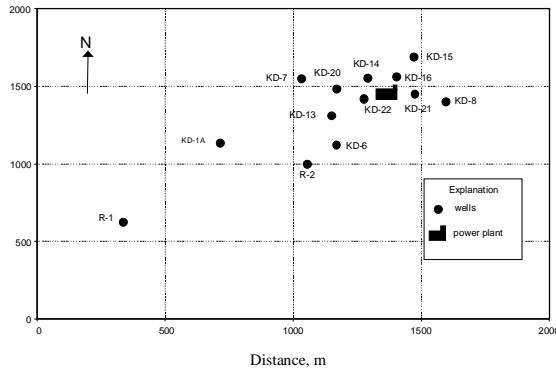


Fig. 1: Location of wells in the Kizildere geothermal field.

3. PRODUCTION HISTORY

The total production rate from the Kizildere geothermal field is presented in Fig. 2. The average fluid production rate has been about 1000 ton/hour since April 1988. Production is more or less constant throughout the year. The lowest production rate in most years occurs during the month of October due to water disposal problems to the nearby Buyuk Menderes river.

Monitoring of the production response of the Kizildere geothermal reservoir has been limited. However, some water level and wellbore pressure monitoring has been made and the most important data consist of a 15-year continuous record from one of the observation wells (KD-8) in the field. The KD-8 well has a depth of 576 m and is drilled to the shallow reservoir. Some of the daily monitoring data between April 1988 and August 2000 are also presented in Fig. 2.

The monthly water level record from the KD-8 well and the monthly production rate data are shown in Fig. 3. The contribution of the R-1 well on field production is also presented in the figure. The total production rates from the field with R-1 and without R-1 are also given to show the contribution of this well. As can be seen from Fig. 3, the production from the R-1 well helped to keep the monthly production from the reservoir at a “constant level” of about 7×10^5 ton.

As mentioned earlier, the R-1 well is the deepest and hottest well encountered in the field. The water produced through

R-1 contains a higher amount of dissolved CO₂ and has a higher CO₂ partial pressure. The produced fluid has higher steam quality at separator conditions. This improves the power production from the plant. Figure 4 presents the ratio of electricity production to water production in kWh/ton. Since February 2001 when the R-1 well was put on production the ratio increased by nearly 20%.

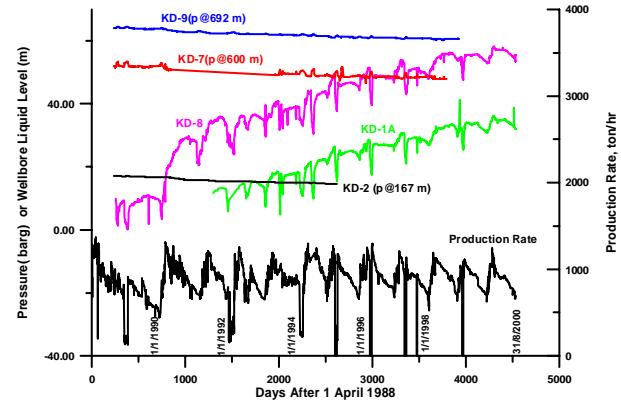


Figure 2: Daily production from all wells and water level changes and wellbore pressure record in observation wells.

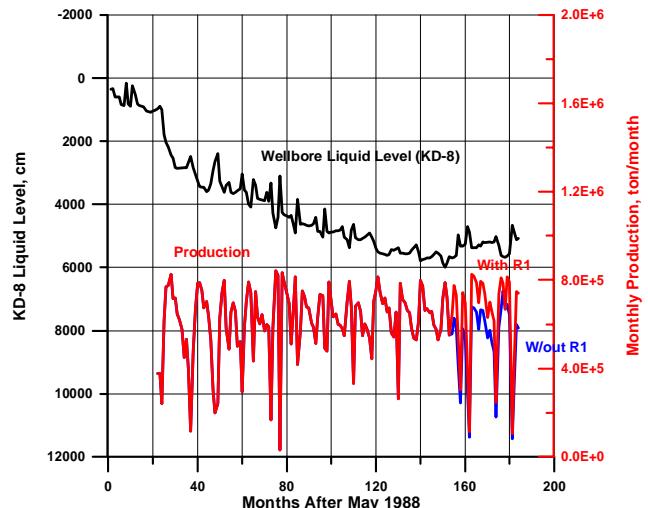


Figure 3: Monthly production rate-wellbore water level behavior.

Reinjection has been considered as an option in the Kizildere field to counteract the water level drawdown and to avoid the water disposal problem. A well, R-2, has been used for reinjection purposes since February 2002. The water was reinjected at an average rate of 225 ton/h, which is about 20% of the rate of production, and at a wellhead temperature of 135 °C.

Hot water production from the field has caused the water level in the geothermal system to drop considerably, and the level is now approaching about 55 m depth in the KD-8 well. The water level declined 55 m in the last 16 years, causing some concern to the utilizing company.

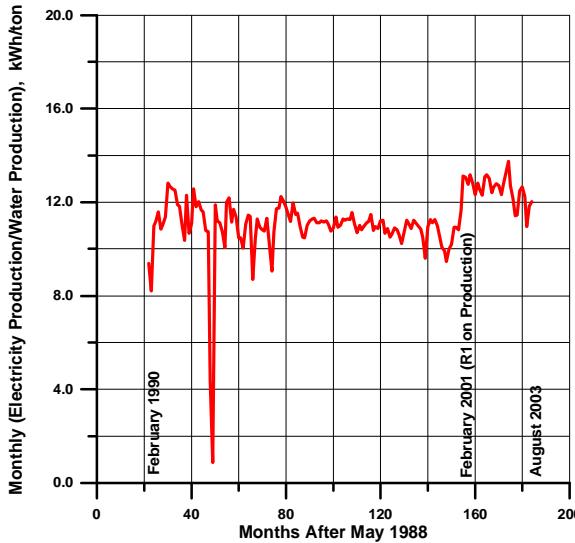


Figure 4: Monthly (electricity production/water production) from the field.

3. RESERVOIR MODELING

The main objective of the reservoir evaluation was to estimate the long term production potential of the Kizildere geothermal reservoir. The lumped-parameter models can be used to simulate the observed water level decline. The lumped-parameter models consider the total production from the field, and ignore the local effects of wells on the observed responses.

3.1. Lumped-parameter Models Used

Several variations of geothermal systems using the tank model approach are simulated by the lumped-parameter models. The systems simulated are: (A) one-reservoir with recharge source (One-Tank Model), (B) one-reservoir - one aquifer with/without recharge source (Two-Tank Open/Closed Model), (C) one-reservoir - two aquifers with/without recharge source (Three-Tank Open/Closed Model), (D) one shallow reservoir - one deep reservoir with recharge source (Two-reservoir Tank Model Without Aquifer), (E) one shallow reservoir - one deep reservoir - one aquifer with recharge source (Two-reservoir Tank Model With Aquifer). Figure 5 shows the schematics of all the models considered in this study. The general characteristics of the models are summarized below: (A) the one-tank model consists of a reservoir and a recharge source. (B) the two-tank model consists of two tanks. The first tank represents the reservoir where the production/reinjection occurs. The second tank, which is connected to the first tank, simulates the aquifer (outer part of the reservoir) recharging the reservoir. If the second tank (the aquifer) is connected to a constant pressure source (recharge source), then the system is described as an open system. If no recharge is allowed then the system is called as a closed system. (C) the three-tank model is similar to the two-tank model. The only difference is that it contains two aquifer tanks connected hydraulically to each other. The main purpose to model such a kind of system is to simulate the “unsteady-state” behavior of flow from the aquifer tanks to the reservoir tank. (D) the two-reservoir tank without aquifer model simulates one shallow reservoir and one deep reservoir. Both are interconnected and supplied by the same recharge source. Production/reinjection is allowed for both reservoirs. (E) the two-reservoir tank with aquifer model is similar to the

model described by D, with a difference that only one aquifer is included while the geothermal field itself contains one shallow and one deep reservoir. Both reservoirs are interconnected and supplied by the aquifer, which is connected to a constant pressure recharge source. Hot water is pumped out of or reinjected into the reservoir tanks, which causes the pressure and water level in the model to change. This in turn simulates the changes of pressure and water levels in the real geothermal system.

An open model leads to a final equilibrium between production and recharge during long term production with a stabilized water level drawdown. For a closed model, the water level declines steadily with time during long term production since no recharge is allowed for such a model. The general characteristics of models are discussed by (Sarak, 2004).

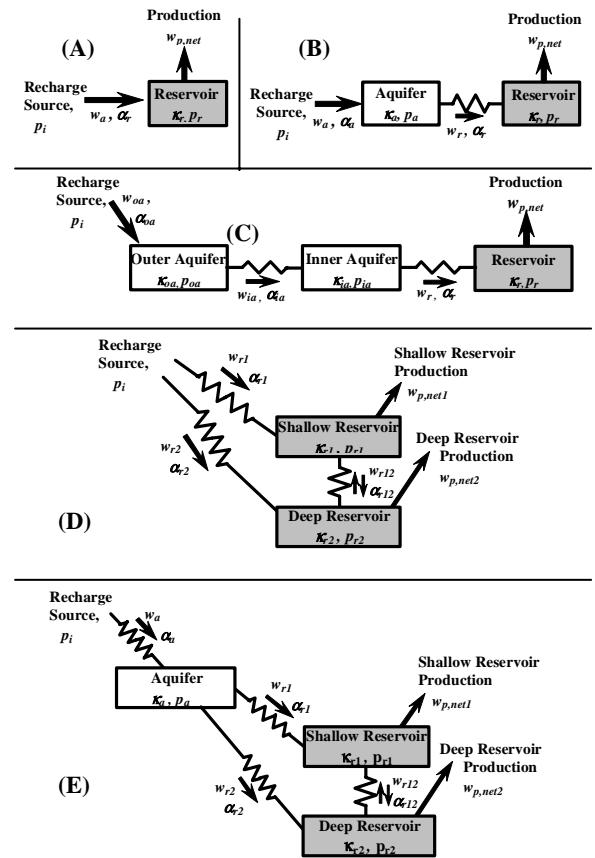


Figure 5: Schematics of tank models considered.

The definitions of the parameters, κ_i , α_i and $w_{p,net}$ used in models and given in Figure 7 are following:

$$\kappa_i = V_i \phi_i \rho_w c_{ti} \quad (1)$$

where κ_i , ϕ_i , c_{ti} are the storage capacity, the porosity and the total compressibility of tank i , respectively. ρ_w is the density of water in tank i . The parameter, α_i , represents the recharge constant, used to formulate the recharge which is proportional to the pressure difference between the tank i and the tank (or the recharge source) connected to it. The recharge is thus given by:

$$w_i = \alpha_i (p_{i-1} - p_i) \quad (2)$$

The net production term, $w_{p,net}$, is defined by

$$w_{p,net} = w_p - w_{inj} \quad (3)$$

where w_p and w_{inj} are the production and reinjection rates.

3.2. Discussion of Modeling Results

The models were used to match the long-term measured water level response to a given production history. For history matching purposes, the optimization algorithm based on the Levenberg-Marquardt method was used for estimating relevant aquifer/reservoir parameters. In addition, the parameters are constrained during nonlinear minimization process to keep them physically meaningful and compute statistics (e.g., standard 95% confidence intervals) to assess uncertainty in the estimated parameters. Moreover, the root mean square errors (RMS) are calculated for each data set to show the matching quality as quantitatively.

Figure 6 shows the match between the observed and simulated water level in the KD-8 well. The 1-tank, 2-tank open and 3-tank open models were used for simulation. The 1-tank model simulates the general trend of water level changes, however, it gives a rather poor match particularly with the cycles of the observed data. The stabilized water level drawdown indicates the equilibrium between production and recharge reached in the last three years. One may claim that this stabilization occurs due to reinjection of the R-2 well. However, we must consider the fact that the R-2 well has been used for reinjection purposes for only the last two years and that we observe stabilization for the last three years. Hence we can claim that this stabilization occurs due to a constant pressure recharge boundary which balances the net production from the reservoir with recharge from the aquifer, not due to reinjection of the R-2 well. Thus, this supports the validity of the open models representing the constant pressure outer boundary of the recharge sources shown in Fig. 5. The fit between the observed and simulated data is quite good for the 2-tank open and 3-tank open models. It should be noticed that all the models shown in Figure 6 assume that the reservoir is represented by one tank.

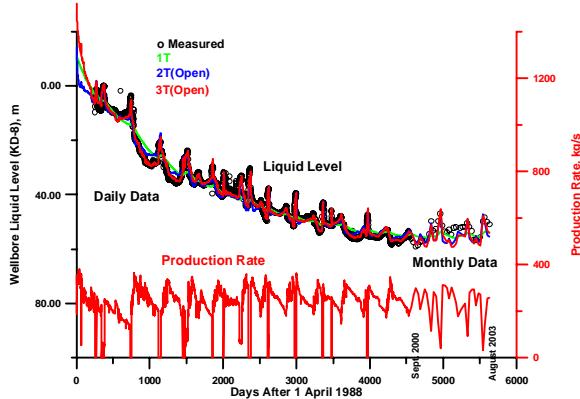


Figure 6: Simulation results of 1-tank, 2-tank open and 3-tank open models.

As a next step, the two-reservoir without aquifer model was used for simulation. Figure 7 shows the match between the observed and simulated water level in the KD-8 well. Since the water level record does not exist for the deeper reservoir, history matching was only conducted for the shallow reservoir. In order to treat the production rate data in history matching with the two-reservoir tank model, the production rate of the R-1 well was used to represent the production from the deeper reservoir whereas the rest of the total field production were allocated to the shallow reservoir.

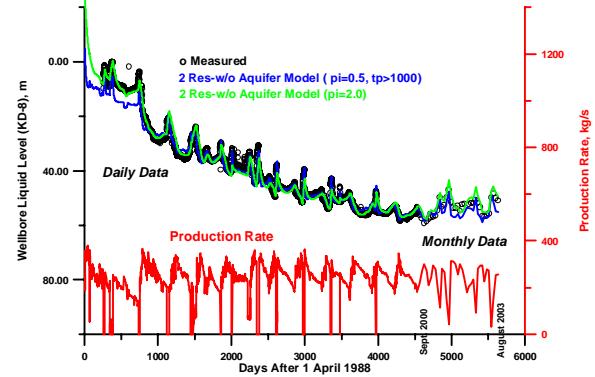


Figure 7: Simulation results of the two-reservoir tank without aquifer model.

As a final modeling study the two-reservoir with aquifer model was used for simulation. Figure 8 shows the match between the observed and simulated water level in the KD-8 well.

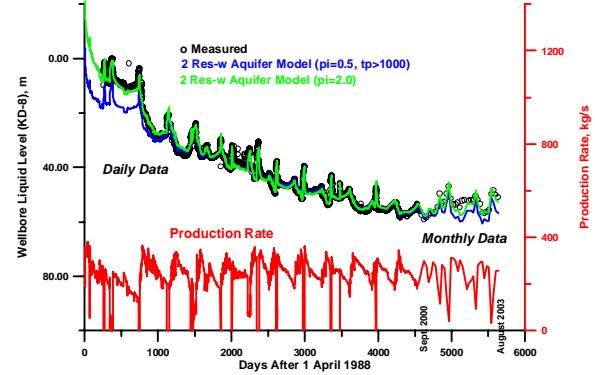


Figure 8: Simulation results of the two-reservoir tank with aquifer model.

Modeling results are given in Table 1 and 2. Table 1 and 2 summarize the estimated parameters obtained from the best fitting of the lumped-parameter models. The percentages given in parenthesis represent the 95% confidence intervals. As seen from Table 1, the confidence percentages computed for the parameters of the 1-tank, 2-tank open and 3-tank open models are acceptable. The confidence percentage of α_{r1} computed for the two-reservoir without aquifer model is much higher than for the two-reservoir

with aquifer model (Table 2). This indicates that the two-reservoir with aquifer model is more appropriate for the data.

Table 1: The parameters of the best fitting 1-tank, 2-tank open and 3-tank open models.

	1-Tank	2-Tank Open	3-Tank Open
α_{oa} , kg/bar·s	--	--	56.62 (%1.3)
κ_{oa} , kg/bar	--	--	1.1×10^{10} (%15.0)
α_{ia} (α_a for 2-T), kg/bar·s	--	45.38 (%0.47)	180.4 (%5.3)
κ_{ia} (κ_a for 2-T), kg/bar	--	5.77×10^9 (%1.33)	1.69×10^9 (%8.8)
α_r , kg/ bar·s	41.22 (%0.35)	315.1 (%3.15)	339.1 (%4.8)
κ_r , kg/bar	4.3×10^9 (%0.82)	2.15×10^8 (%7.36)	1.1×10^8 (%13.0)
RMS, bar	1.54	1.52	1.52

Table 2: The parameters of the best fitting two-reservoir with aquifer and without aquifer models.

Model Parameters	Two-reservoir Tank Model	
	With Aquifer	Without Aquifer
α_{r1} , kg/bar·s	46.2 (%161.4)	0.0105 (% 6.2×10^5)
κ_{r1} , kg/bar	1.17×10^8 (%11.3)	2.29×10^8 (%6.23)
α_{r2} , kg/bar·s	100.0 (%109.8)	49.3 (%177.9)
κ_{r2} , kg/bar	1.42×10^9 (%45.4)	7.57×10^9 (%46.8)
α_{r12} , kg/bar·s	328.2 (%23.4)	277.9 (%23.7)
α_a , kg/bar·s	55.93 (%2.06)	--
κ_a , kg/bar	1.14×10^{10} (%5.34)	--
RMS _{shallow} , bar	1.495	1.499
RMS _{deep} , bar

3.3. Water Level Predictions

The lumped-parameter models were then used to estimate the production potential of the Kizildere geothermal reservoir, by calculating water level forecasts for different future production scenarios, since the production response of the reservoir is mainly manifested as water level

drawdown. The 2-tank open, 3-tank open, two-reservoir with aquifer and two-reservoir without aquifer models all simulate the water level decline in the Kizildere reservoir quite accurately as discussed earlier.

The water level predictions were calculated for several different production scenarios. In using the 2-tank and 3-tank open models, the predictions were made for a scenario in which the October production is kept at a minimum level (50 kg/s) and the production for other months is maintained at 200, 250, 300, 400 and 500 kg/s for the next 20 years. The predictions for these scenarios are presented in Figure 9, which shows the water level in the KD-8 well. The 2-tank open and 3-tank open models yield identical prediction results. Figure 9 shows the prediction results obtained from the 2-tank open model. The water level in KD-8 well is expected to be about 65 m below the present level if the production rate is increased from 250 kg/s to 500 kg/s.

Then the two-reservoir with and without aquifer models were used for prediction purposes. Since the water level record does not exist for the deeper reservoir, predictions were only computed for the shallow reservoir. The water level predictions were calculated for constant production, valid for the whole year, and for the next 20 years. For all prediction runs, a constant production rate from the field consisting of one shallow reservoir and one deep reservoir was maintained. Although the net production, which is defined as the difference between production rate and reinjection rate, from the field was kept the same, 300 kg/s, the shallow and deep reservoirs were assigned different production and reinjection rates.

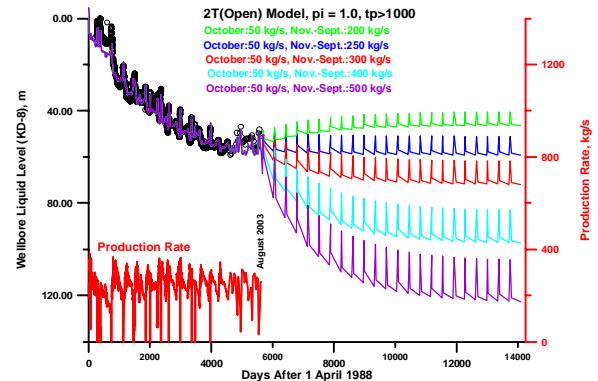


Figure 9: Water level changes predicted by 2-tank open model.

The production and reinjection scenarios such as 1) production and reinjection for both reservoirs, 2) production from the deeper reservoir and reinjection into the shallow one, or vice versa, were investigated.

Figure 10 shows the water level changes predicted by the two-reservoir without aquifer model. By keeping the net production from the total system at a constant value of 300 kg/s, the following prediction scenarios were modeled: a) reinjection into shallow reservoir at 200 kg/s and production from the deeper one at 500 kg/s, b) production from the deeper reservoir at 300 kg/s, c) production from the shallow one at 100 kg/s and production from the deeper one at 200 kg/s, d) production from the shallow one at 300 kg/s, e) production from the shallow one at 400 kg/s and reinjection into the deeper one at 100 kg/s, and finally f) production from the shallow one at 500 kg/s and reinjection

into the deeper one at 200 kg/s. The minus (-) sign for production rate in Figure 10 indicates reinjection. The prediction result for the 2-tank open model for $q=300$ kg/s is also given for comparison purposes. The prediction behavior of the two-reservoir model is completely different than the behavior of the 2-tank model. As mentioned earlier, the advantage of the two-reservoir model over the conventional one-reservoir tank model is that the shallow and deeper reservoir parts of the system can be treated separately. The most conclusive result of the prediction approach is that the scenarios considering higher rate of production from the deeper reservoir result in lower water level (or pressure) drop and thus increase the life or sustainability of the field. The prediction results of the 2-tank open model coincide with the prediction results of the two-reservoir without aquifer model when the production is from the shallow reservoir, as expectedly.

Figure 11 shows the water level changes predicted by the two-reservoir with aquifer model. For comparison purposes, the same prediction scenarios valid for the two-reservoir without aquifer model were applied. The prediction result for the 2-tank open model for $q=300$ kg/s is also given for comparison purposes. The water level drops predicted by the two-reservoir with aquifer model are slightly higher than the drops predicted by the two-reservoir without aquifer model. This is due to the unsteady state recharge behavior of the model with aquifer. The recharge response of the aquifer takes longer and is lower in magnitude.

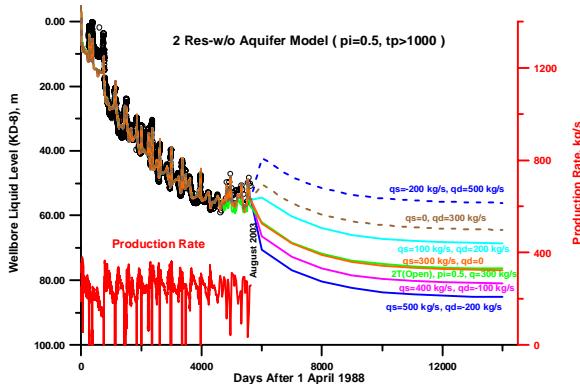


Figure 10: Water level changes predicted by the two-reservoir without aquifer model.

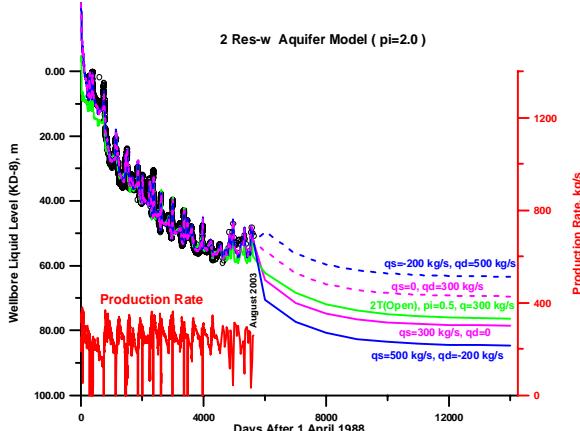


Figure 11: Water level changes predicted by the two-reservoir with aquifer model.

Figure 12 shows a comparison of water level drop predictions obtained from the two-reservoir without aquifer, the two-reservoir with aquifer and the 2-tank open models.

The results given in Figures 10-12 indicate the advantages of the two-reservoir models over the conventional type one-reservoir models. The two-reservoir models simulate the responses of the shallow and deeper reservoirs individually. For the Kizildere geothermal field, in the long term, our modeling results imply that new production wells should be drilled into the deep thermal reservoir, and the shallow hot water reservoir should be targeted for reinjection.

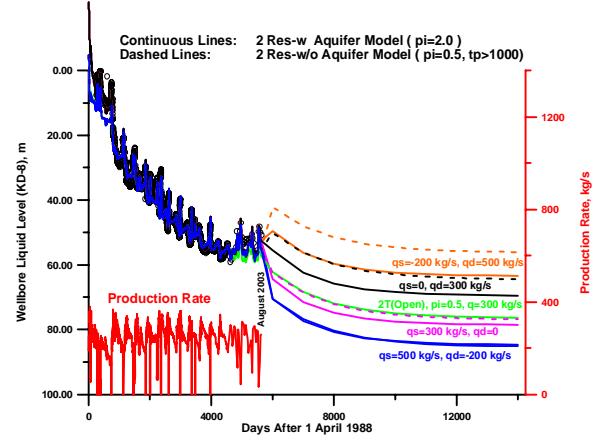


Figure 12: Comparison of water level changes predicted by the two-reservoir with aquifer, the two-reservoir without aquifer and the 2-tank open models.

4. CONCLUSIONS AND RECOMMENDATIONS

The main objective of this study was to model the water level response and to predict the behavior of the Kizildere geothermal field for different production scenarios. To achieve this, the conventional type one-reservoir tank models as well as newly developed two-reservoir tank models were used. All models simulate the water level decline quite accurately.

The advantage of the two-reservoir model over the conventional type one-reservoir model is that the shallow and deeper reservoirs of the field can be treated separately. Using the two-reservoir model various production and reinjection scenarios for the reservoirs can be handled. Predictions based on these scenarios can lead to optimized and sustainable development of this type of fields.

This study also led to a number of recommendations with regard to the modeling approach of the Kizildere field and to the future management of the field:

1. The two-reservoir models seem to simulate production performance of the Kizildere geothermal field properly. Given the fact that the field consists of one shallow reservoir and one deeper reservoir, such a conclusion seems reasonable
2. Modeling results discussed in the paper indicate that the scenarios considering higher rate of production from the deeper reservoir result in lower pressure drop. This should be an important guide for the reservoir management. The shallow reservoir should be targeted for the reinjection and the deeper reservoir for the production.

3. Since the simple two-reservoir lumped-parameter models used in the field evaluation simulate the geothermal system fairly accurately, they should suffice as management tools for the Kizildere geothermal reservoir in coming years. As time passes, however, these models should be revised on a regular basis by updating with new production data.

4. Monitoring is an essential part of reservoir management. This aspect requires significant improvement in Kizildere, particularly in view of foreseeable increase in production during the coming years. All the results discussed in this paper are based on the production data obtained from only one well, R-1, drilled to the deeper reservoir. Water level measurements for the deeper reservoir were not available and thus such data could not be incorporated into the modeling study. Production data as well as the water level observations from the further wells to be drilled in the deeper reservoir should be employed and evaluated in order to increase the reliability of the two-reservoir models discussed in this paper.

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REFERENCES

Alkan, H., Satman, A.: A new lumped-parameter model for geothermal reservoirs in the presence of carbon dioxide. *Geothermics* 19, 469-479, 1990.

Axelsson, G. and Gunnlaugsson, E.: Long-Term Monitoring of High-and Low-Enthalpy Fields Under Exploitation, International Geothermal Association, WGC2000 Short Courses, Kokonoe, Kyushu District, Japan, 28-30 May (2000).

Axelsson, G., Dong, Z.: The Tanggu Geothermal Reservoir (Tianjin, China). *Geothermics* 27, 271-294, 1998.

Axelsson, G.: Simulation of pressure response data from geothermal reservoirs by lumped-parameter models. *Proceedings*, 14th Workshop on Geothermal Reservoir Engineering, Stanford University, Palo Alto, CA, USA, pp. 257-263 (1989).

Brigham, W.E. and Ramey, H.J.Jr.: Material and energy balance in geothermal reservoirs. In: Ramey, H.J.Jr. (Editor), *Reservoir Engineering Assessment of Geothermal Systems*. Petroleum Engineering Department, Stanford University, Palo Alto, CA, USA (1981).

Castanier, L.M., Sanyal, S.K. and Brigham, W.E.: A practical analytical model for geothermal reservoir simulation. *Proceedings*, the 50th Annual California Regional Meeting of SPE. Los Angeles, CA, USA April 9-11, SPE 8887 (1980).

Castanier, L.M. and Brigham, W.E.: Use of lumped-parameter modeling for geothermal engineering. In: *Proceedings of SPE California Regional Meeting*, Ventura, CA, USA, March 23-25, SPE 11730 (1983).

Grant, M.A.: Approximate calculations based on a simple one phase model of a geothermal reservoir. *New Zealand Journal of Science*, Vol. 20, 19 (1977).

Grant, M.A., Donaldson, I.G., Bixley, P.F.: Geothermal reservoir engineering. Academic Press, New York, pp. 55-57 (1982).

Grant, M.A.: Geothermal reservoir modeling. *Geothermics* 12, 251-263 (1983).

Gudmundsson, J.S., Olsen, G.: Water-influx modeling of the Svartsengi Geothermal Field, Iceland. *SPE Reservoir Engineering*, February, 77-84 (1987).

Olsen, G.: Depletion modeling of liquid dominated geothermal reservoirs. Technical Report SGP-TR-80, Stanford Geothermal Program, Stanford University, USA (1984).

Sarak, H., Onur, M., Satman, A.: New lumped-parameter models for simulation of low-temperature geothermal reservoirs. *Proceedings*, 28th Stanford Workshop on Geothermal Reservoir Engineering. Stanford University, USA, 27-29 January (2003a).

Sarak, H., Onur, M., Satman, A.: Applications of lumped-parameter models for simulation of low-temperature geothermal reservoirs. *Proceedings*, 28th Stanford Workshop on Geothermal Reservoir Engineering, Stanford University, USA, 27-29 January (2003b).

Sarak, H.: Lumped-parameter reservoir models for low-temperature geothermal reservoirs. PhD Thesis, Istanbul Technical University, Petroleum and Natural Gas Engineering Department (2004).

Satman, A., Ugur, Z.: Flashing point compressibility of geothermal fluids with low CO₂ content and its use in estimating reservoir volume. *Geothermics*, 31, 29-44 (2002).

Serpen, U., Satman, A.: Reassessment of the Kizildere geothermal reservoir, *Proceedings*, World Geothermal Congress 2000, Kyushu-Tohoku, Japan, May 28-June 10 (2000).

Whiting, R.L. and Ramey, H.J.Jr.: Application of material and energy balances to geothermal steam production, *Journal of Petroleum Technology*, July, 893-900 (1969).