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Problems in the Use of Lumped-Parameter Reservoir Models for Low-Temperature Geothermal Fields

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ABSTRACT

Lumped-parameter modeling is commonly used at the beginning of the life of a field, when field data are scarce. Generally, in lumped-parameter models, the reservoir is described as a single homogeneous block with the production/reinjection rates and recharge flow specified. Pressure (and/or water level) changes in the reservoir are modeled by using mass and energy balances and therefore, the potential of the field can be predicted under various production/reinjection scenarios.

The main objective of this paper is to discuss the problems involved in modeling the low-temperature liquid-dominated geothermal reservoirs by using lumped-parameter models. In the lumped models considered in this work, the geothermal system is assumed consist of reservoir, aquifer and recharge source, which are represented as different tanks having different properties. Model solutions for constant production/reinjection flow rates are given in the form of analytical expressions. The variable flow rate case is modeled by Duhamel's Principle. The models are used to match the long-term observed water level or pressure response of a field to a given production history. For history matching purposes, an optimization algorithm based on the Levenberg-Marquardt method is used to minimize an objective function based on weighted least-squares, to estimate relevant aquifer/reservoir parameters. In addition, we constrain the parameters during the nonlinear minimization process to keep them within physically meaningful limits and compute statistics (e.g., standard 95% confidence intervals) to assess uncertainty in the estimated parameters. Moreover, root mean square errors (RMS) are also computed for each observed data set matched.

Three field examples (Laugarnes and Glerardalur geothermal fields located in Iceland and Balcova-Narlidere geothermal field located in Turkey) and a hypothetical field case are considered to show the use of the models and the optimization algorithm. The observed and simulated water level changes obtained from the models are discussed. The modeling results indicate that the accuracy, continuity, and duration of the input data such as the production/reinjection flow rates and the water level measurements greatly affect the confidence intervals and RMS values computed from the matching analysis of the model. They cause major problems in choosing the appropriate model. Our results also suggest that the additional data, such as geological, geophysical, and hydrological, are required to identify the proper lumped-parameter model.

1. INTRODUCTION

As a result of the growing need throughout the world to increase utilization of geothermal energy in different sectors such as generating electricity and district heating, reservoir management has become a significant step. Some important questions of reservoir management, such as the production capacity of the geothermal field, the rate of the reservoir pressure decline, and the effect of recharge and reinjection on the field performance, are primary objectives of geothermal reservoir modeling.

Three main methods are currently available in the literature for modeling the behavior of geothermal reservoirs. They are decline curve analysis, lumped-parameter models (zero-dimensional models), and numerical models.

In this study, lumped-parameter modeling is considered. The reservoir is described as a single homogeneous block in all lumped-parameter models. The changes of reservoir pressure, temperature, and production are monitored and the pressure changes in the reservoir are modeled by using mass and energy balances. Therefore, the potential of the field can be predicted under various production/injection scenarios.

Many lumped-parameter models have been reported in the literature (Whiting and Ramey, 1969; Grant, 1977, Brigham and Neri, 1980; Castanier, Sanyal, and Brigham, 1980; Brigham and Ramey, 1981; Grant, 1983; Olsen, 1984; Gudmundsson and Olsen, 1987; Axelsson, 1989; Alkan and Satman, 1990; Axelsson and Dong, 1998; Axelsson and Gunnlaugsson, 2000; Sarak et al., 2003a and 2003b, Sarak, 2004).

In this paper, the lumped-parameter models presented by Sarak et al. (2003a and 2004) are considered. The effects of the accuracy, continuity, and duration of the input data such as the production/reinjection flow rates and the water level measurements on the modeling are emphasized by three field applications.

2. LUMPED-PARAMETER MODELS FOR LOW-TEMPERATURE GEOTHERMAL RESERVOIRS

The geothermal system is considered mainly of three parts: (1) the reservoir, (2) the aquifer, and (3) the recharge source. In this study, the first two are treated as homogeneous tanks with average properties. The recharge source connected to the aquifer or directly to the reservoir is treated as a point source supplying recharge into the system. These three parts can be considered from the center to the periphery as described by Castanier et al. (1980 and 1983) (Figure 1). It is also possible to consider these parts as a series of connected tanks (Figure 2).

The reservoir in which the production/injection occurs represents the innermost part of the geothermal system. The changes in pressure are monitored and production/injection rates are recorded. The aquifer, in which neither production nor injection occurs, recharges the reservoir. The production causes the pressure in the reservoir to decline, which results in water influx from the aquifer to the reservoir. The recharge source represents the outermost part of the geothermal system. It recharges the aquifer.

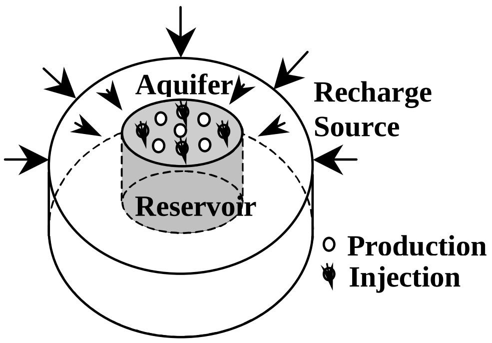

Figure 1: Parts of a geothermal system from the center to the periphery.

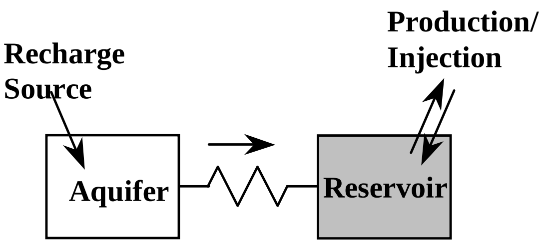

Figure 2: Parts of a geothermal system considered in tanks.

The water influx between aquifer and reservoir, and recharge source and aquifer, and recharge source and reservoir can be modeled by various methods given in the petroleum literature (Schilthuis, 1936; van Everdingen and Hurst, 1949; Fetkovich, 1971).

Several variations of geothermal systems using the tank model approach were studied and explicit analytical solutions were presented by using mass balance equations to describe the reservoir pressure behavior (Figure 3). The systems studied are;

(a) One reservoir with recharge source (1-Tank Model),

(b) One reservoir, one aquifer with/without recharge source (2-Tank Open/Closed Model),

(c) One reservoir, two aquifers with/without recharge source (3-Tank Open/Closed Model),

(d) One shallow reservoir, one deep reservoir with recharge source (2 Reservoir Tanks Without Aquifer Model),

(e) One shallow reservoir, one deep reservoir, one aquifer with recharge source (2 Reservoir Tanks With Aquifer Model).

The detailed analytical solutions for these systems are given by Sarak et al. (2003a) and Sarak (2004). There are two main parameters for each tank used in models. The parameter α represents the recharge constant and is described by Schilthuis type steady-state water recharge equation :

$$w = \alpha \Delta p \quad (1)$$

where Δp is the pressure change and w is the recharge rate.

The parameter κ is the storage capacity and is given by

$$\kappa = V \phi \rho c_t \quad (2)$$

where V is the bulk volume of the tank, ϕ the porosity, ρ the fluid density and c_t the total compressibility.

The parameters α and κ can be defined for all tanks and formed based on properties of each tank (Sarak et al., 2003a; Sarak, 2004).

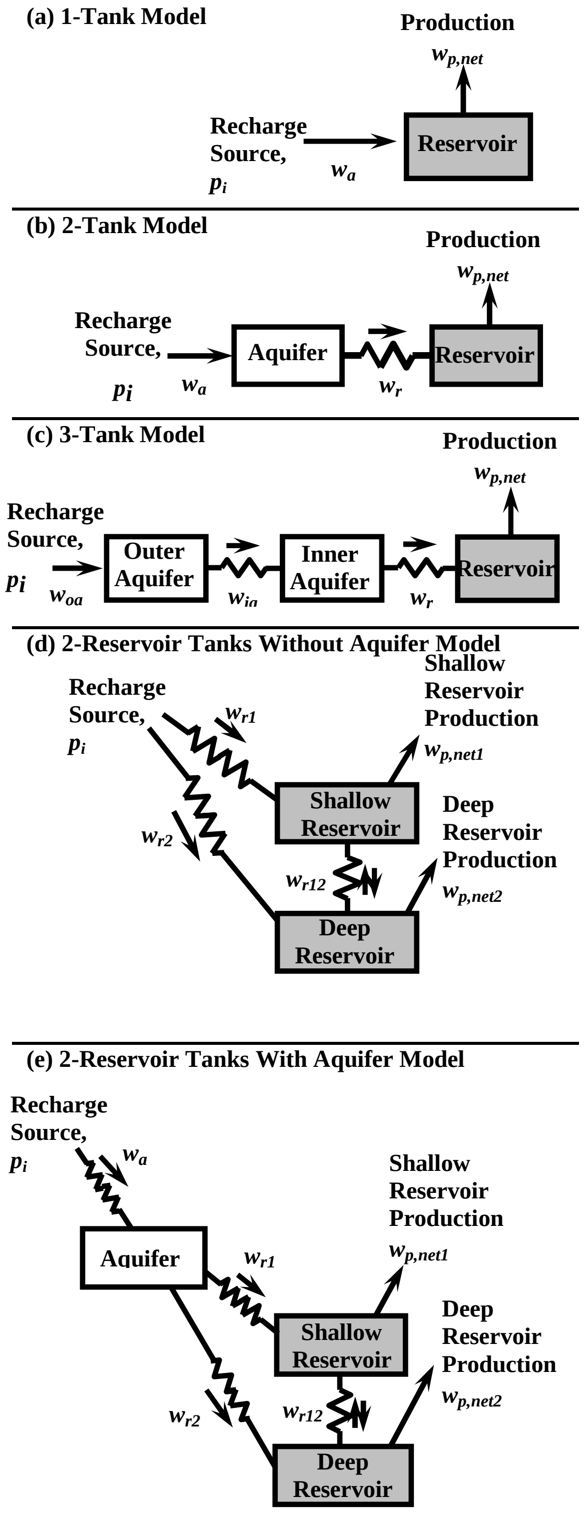

Figure 3: Schematics of tank models.

3. PROBLEMS INVOLVED IN FIELD APPLICATIONS

This section deals with the applications of the lumped-parameter models to field cases and discusses the problems involved in applications. The models are used to match the long-term measured water level or pressure response to a given production history.

For history matching purposes, an optimization algorithm based on the Levenberg-Marquardt method is used to minimize an objective function based on weighted least-squares to estimate the relevant aquifer/reservoir parameters. In addition, the parameters are constrained during the nonlinear minimization process to keep them physically meaningful. Statistics (e.g., standard 95% confidence intervals) are computed to assess uncertainty in the estimated parameters. Wider confidence intervals imply that the relevant parameter can not be well determined.

Moreover, the root mean square errors (RMS) are calculated for each data set to show the matching quality as quantitatively. Higher RMS value for the models indicates a larger deviation between the model results and measured water levels.

Three field examples (two fields are located in Iceland and one in Turkey) and one hypothetical field case are studied to validate the use of the models and the optimization algorithm. For the field applications discussed here, all observed data were given in terms of water levels. All the measured water level data were first converted to pressure equivalence by $p(t) = \rho g h(t)$ and then used in the regression algorithm. Thus, all parameter estimates are given in pressure units. However, all graphical results are presented in terms of water levels to be consistent with the field data.

The field applications of the models indicate some problems, which can be summarized as;

(a) the accuracy of the data,

(b) choosing the right model,

(c) choosing the representative well of the geothermal reservoir,

(d) the duration and continuity of the data,

(e) the effect of the initial guesses,

(f) the periodicity of the data.

3.1 The Accuracy of the Data

The importance of the accuracy of the measured data is studied using the 2-reservoir tanks with aquifer model for a hypothetical field case. For this purpose, the pressure change, Δp, data is generated for the deep and the shallow reservoirs for 10 years of production/reinjection. In constructing the production/reinjection history, the flow rate history for the Balcova-Narlidere field for the period of 15.12.2002 and 15.12.2003 were taken for the first year and the same data were assumed to be valid for the next 9 years. Thus, this represents the constant yearly production/ reinjection case. The flow rate history and the model parameters used to generate pressure change data of the deep and the shallow reservoirs are presented in Figure 4 and in the forward run column in Table 1, respectively.

The pressure change data generated by the forward run are shown in Figure 5.

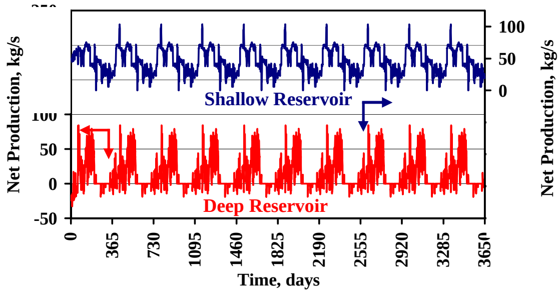

Figure 4: Production/reinjection history of both deep and shallow reservoirs.

Table 1: Model parameters of the 2-reservoir tanks with aquifer model.

Model Parameters	Forward Run (True Values)	Initial Guesses
α_{r1}, kg/bar-s	30	3.0
κ_{r1}, kg/bar	2.0x10^{7}	2.0x10^{6}
α_{r2}, kg/bar-s	50.0	70.0
κ_{r2}, kg/bar	4.0x10^{7}	4.0x10^{8}
α_{r12}, kg/bar-s	5.0	20.0
α_{a}, kg/bar-s	10.0	50.0
κ_{a}, kg/bar	2.0x10^{8}	2.0x10^{7}

As the next step, assuming that the true pressure change data are the data generated by forward run, i.e., pressure data do not contain any errors, the regression is applied (called regression-I) using the initial guesses given in Table 1. A comparison of forward run (true pressure change data) and regression-I results is shown in Figure 6. An excellent match was obtained. The model parameters from the regression have narrow confidence intervals and low RMS values (Table 2). Here and throughout, the numbers given in parenthesis in tables represent the 95% absolute confidence interval for the relevant model parameter.

To investigate the effects of data errors in regression, the true pressure change data were corrupted by adding random normally-distributed errors with mean zero and standard deviation of 1 bar. The pressure change data with error and the true pressure change data without any error are plotted in Figure 7. Then the regression (called regression-II) was performed on this pressure data using the same production/reinjection history used in regression-I. The regression-II results are presented in Table 2 and a comparison of pressure data with error and regression-II results is shown in Figure 8.

Finally, both true pressure data and true production/ reinjection data were corrupted by adding random normally-distributed errors with mean zero and standard deviation of 1 bar and 1 kg/s, respectively. Then the regression (called regression-III) was performed with these data sets. The regression-III results are presented in Table 2 and a comparison of pressure data with error and regression-III results is shown in Figure 9.

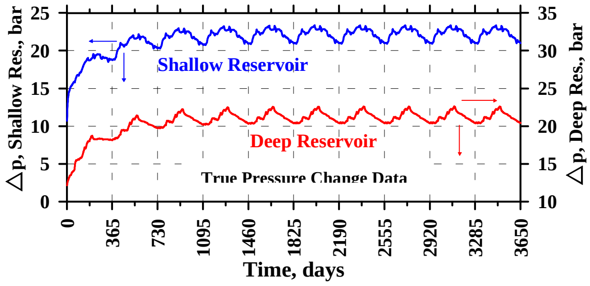

Figure 5: Forward run results

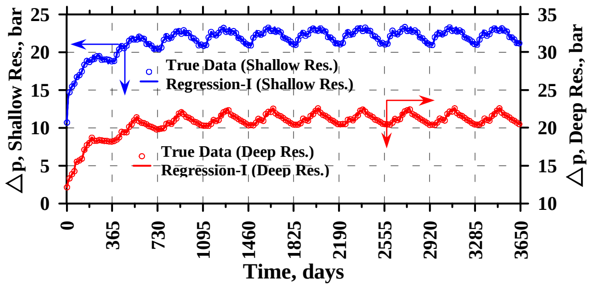

Figure 6: A comparison of true pressure change data and regression-I results.

Table 2: Regression results.

Model Parameters	Regression -I	Regression -II	Regression -III
α_{r1}, kg/bar-s	30.0 ($\pm 1.6 \times 10^{-8}$)	32.19 ($\pm$4.91)	36.29 ($\pm$4.85)
κ_{r1}, kg/bar	2.0×10^{7} ($\pm$0.014)	1.74×10^{7} ($\pm 4.0 \times 10^{6}$)	1.28×10^{7} ($\pm 3.1 \times 10^{6}$)
α_{r2}, kg/bar-s	50.0 ($\pm 3.3 \times 10^{-8}$)	52.21 ($\pm$10.10)	59.21 ($\pm$10.20)
κ_{r2}, kg/bar	4.0×10^{7} ($\pm$0.036)	3.23×10^{7} ($\pm 1.0 \times 10^{7}$)	2.39×10^{7} ($\pm 8.3 \times 10^{6}$)
α_{r12}, kg/bar-s	5.0 ($\pm 1.2 \times 10^{-8}$)	2.54 ($\pm$3.60)	0.037 ($\pm$3.42)
α_{a}, kg/bar-s	10.0 ($\pm 1.9 \times 10^{-9}$)	9.90 ($\pm$0.62)	9.67 ($\pm$0.57)
κ_{a}, kg/bar	2.0×10^{8} ($\pm$0.046)	2.09×10^{8} ($\pm 1.4 \times 10^{7}$)	2.15×10^{8} ($\pm 1.3 \times 10^{7}$)
$RMS_{shall.}$,bar	2.91×10^{-9}	1.00	0.998
RMS_{deep},bar	3.38×10^{-4}	0.99	0.988

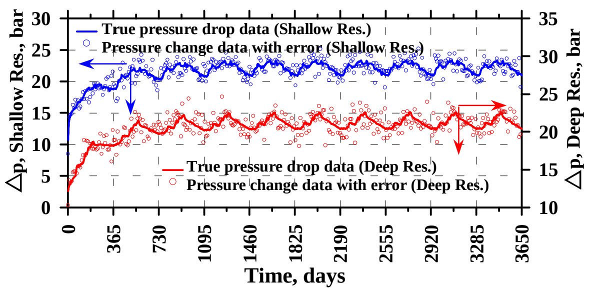

Figure 7: A comparison of true pressure change data and pressure change data with error.

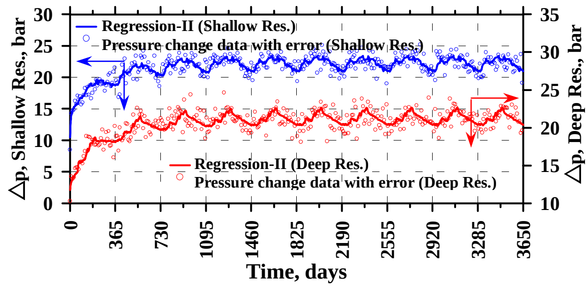

Figure 8: A comparison of pressure change data with error and regression-II results.

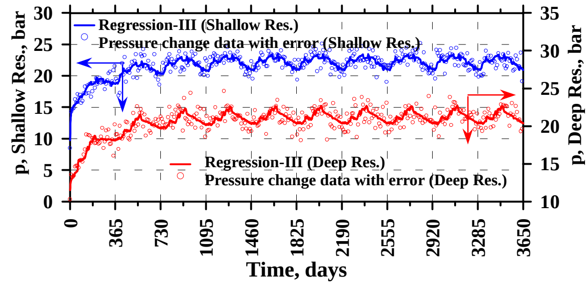

Figure 9: A comparison of pressure change data with error and regression-III results.

The results given in Table 2 indicate that the confidence intervals of the model parameters are higher in the case of pressure data including error (regression-II) as compared to the case of pressure data with no errors (regression-I). Similar comments are valid for regression-III case in which both the pressure and production/reinjection data contain errors. Although reasonable matches are still obtained from regression-II and regression-III (Figures 8 and 9, respectively), the parameters estimated from both regressions clearly deviate from the true values.

Extremely narrow confidence intervals and low RMS values obtained from the regression-I reflect the importance of accuracy of the field case pressure (or water level) data and production/reinjection history on modeling.

3.2 Choosing the Right Model

As the next step, we investigated whether the true data obtained from the hypothetical 2-reservoir tanks with aquifer model could be matched with the other models (1-tank, 2-tank, 3-tank and 2-reservoir tanks without aquifer models).

The pressure change data generated by forward run of the 2-reservoir tanks with aquifer model (model parameters given in the first column in Table 3) were assumed to be the input data. Both shallow and deep reservoir pressure change data were utilized in matching with 2-reservoir tanks without aquifer model whereas only the deep reservoir pressure change data were assumed to represent the whole reservoir and used in matching with 1-, 2-, and 3-tank models.

The production data of whole field (shallow+deep) were used for 1-, 2- and 3- tank models. Then 1-tank, 2-tank (open/closed), 3-tank (open/closed), and 2-reservoir tanks without aquifer models were all tried separately to match the input data.

The results of the model applications were evaluated and compared based on confidence intervals and RMS values obtained for each model. Except for the 2-tank (closed) and 3-tank model (open/closed) models, the other models yielded matches with acceptable confidence intervals and RMS values. The highest RMS value was obtained for the 2-tank (closed) model as shown in Table 4. The 3-tank (both open and closed) models yielded relatively high confidence intervals and RMS values. Hence we will not discuss them here any further. The regression results of the matches obtained with other models are given in Tables 3 and 4 for comparison purposes.

This part of study demonstrates one major problem in modeling. No unique solution exists if the type of model is not known *a priori*. Except for the 2-tank (closed) and 3-tank models, the other models tried yielded excellent matches. For example the match with the 1-tank model is shown in Figure 10.

Table 3: Comparison of the model parameters used in hypothetical true data and obtained by 2-reservoir tanks without aquifer model.

Model Parameters	2-Reservoir Tanks With Aquifer Model (True Data)	2-Reservoir Tanks Without Aquifer Model
α_{r1}, kg/bar-s	30.0	1.37 (±0.082)
κ_{r1}, kg/bar	$2.0x10^7$	$1.59x10^7$ ($\pm 5.7x10^5$)
α_{r2}, kg/bar-s	50.0	7.58 (±0.109)
κ_{r2}, kg/bar	$4.0x10^7$	$2.1x10^8$ ($\pm 1.4x10^6$)
α_{r12}, kg/bar-s	5.0	35.91 (±0.514)
α_a, kg/bar-s	10.0	--
κ_a, kg/bar	$2.0x10^8$	--
RMS $_{shallow}$,bar	--	0.048
RMS $_{deep}$, bar	--	0.192

Table 4: Comparison of the 1- and 2- tank model results.

Model Parameters	2-Tank (Open) Model	2-Tank (Closed) Model	1-Tank Model
κ_{r2}, kg/bar	$6.45x10^7$ ($\pm 7.8x10^6$)	$6.72x10^8$ ($\pm 1.6x10^8$)	$2.02x10^8$ ($\pm 1.6x10^6$)
α_{r12}, kg/bar-s	117.27 (±13.36)	28.87 (±6.28)	7.51 (±0.031)
α_a, kg/bar-s	7.86 (±0.068)	--	--
κ_a, kg/bar	$1.53x10^8$ ($\pm 6.4x10^6$)	$2.24x10^9$ ($\pm 1.8x10^8$)	--
RMS $_{deep}$, bar	0.148	1.474	0.191

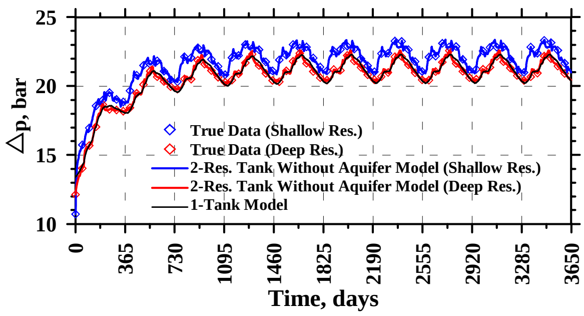

Figure 10: A comparison of 2-reservoir tanks without aquifer and 1-tank models.

The excellent match in Figure 10 and the results of regression in Tables 3 and 4 indicate that the different models may exhibit a very similar reservoir pressure response. Therefore one should be very careful in specifying the type of the model.

Additional data obtained from other sources such as geological, geophysical and hydrological studies should be coupled with the regression results to identify the right model of the geothermal system. The additional data could be the reservoir area estimated from the geophysical resistivity measurements, the volumetric extent of the reservoir estimated from the wells drilled in the geothermal field, the directional movements of the recharge water obtained from the hydrological studies, the limiting boundaries of the field determined from the well tests and temperature surveys, or the extension of the aquifer surrounding the reservoir determined from the basin geological analysis (see Axelsson and Dong, 1998; Olsen, 1984).

3.3 Choosing a Representative Well of the Geothermal Reservoir

The Balcova-Narlidere Geothermal Field, which is situated 10 km west of Izmir, is considered to demonstrate the importance of choosing a representative well. The geothermal water with temperature ranging from 80 to 140°C is produced from the wells from depths between 48.5 m and 1100 m. There are about 50 wells drilled to date and they are classified as gradient, shallow and deep wells. In general, the deep wells were produced in winter and the shallow wells were produced in summer months.

The water level measurements of the deep wells BD-1 and BD-5 are considered to model the Balcova-Narlidere geothermal system (Figure 11). The water level in the well is measured positive downward from the wellhead.

The BD-1 well with a moderate depth is located near the center of the field and has been used as an observation well. Satman et al. (2002) stated that the water level of the BD-1 well is strongly affected by the production from and the reinjection into the shallow wells and also affected by the production from the deep wells.

The BD-5 well is situated in the northwestern area of the field. The water level of the BD-5 well shows a similar behavior to the BD-1 well. However, the BD-5 well exhibits greater water level changes than the BD-1 well (Figure 11). The reasons for such differences in behavior are thought to be; (1) the direction of the natural recharge is from east to south-west in the field thus the natural recharge support is weaker at BD-5, (2) BD-5 is further away from the reinjection region so that the reinjection into the shallow wells causes stronger support to BD-1.

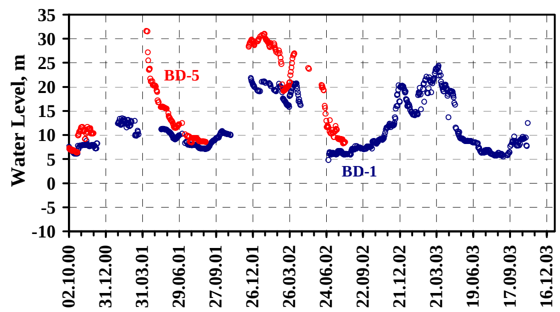

Figure 11: Water level changes of well BD-1 and BD-5.

The 1-tank model was applied by using water level measurements of BD-1 and BD-5, and the production data of the whole field. The regression results are given in Table 5 and the matches obtained are shown in Figure 12.

Comparing the confidence intervals and RMS values given in Table 5, and the matches obtained in Figure 12, the modeling of BD-1 gives more reliable results than the modeling of BD-5.

Table 5: 1-tank model results for BD-1 and BD-5.

Model Parameters	1-Tank Model	
	BD-1	BD-5
α_r, kg/bar-s	58.78 (±1.74)	81.66 (±6.71)
κ_r, kg/bar	5.0×10^7 ($\pm4.88\times10^6$)	2.96×10^7 ($\pm1.22\times10^7$)
RMS, bar	0.307	0.501

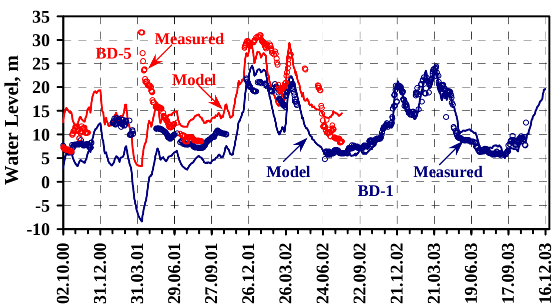

Figure 12: Simulation results for BD-1 and BD-5.

It can be seen that choosing a representative well of the geothermal system is very important to model the system reasonably. In such a case, it could be appropriate to chose BD-1 water level measurements in modeling since this well is located near the center of the field and is affected by the recharge and the production from the deep and shallow wells besides having a more continuous and longer period of available water level data.

3.4 The Duration and Continuity of the Data

To demonstrate this problem, two geothermal fields (Laugarnes and Glerardalur) located in Iceland and one field (Balcova-Narlidere) located in Turkey were studied.

The Laugarnes and Glerardalur fields are discussed in Axelsson and Gunnlaugsson (2000) and Axelsson (1989). Axelsson (1989) used the water level data to simulate the pressure responses of the fields and to estimate their production capacities.

Figures 13, 14 and 15 show the water level changes and production histories of the Laugarnes, Glerardalur and Balcova-Narlidere geothermal systems, respectively.

The production data of Balcova-Narlidere field shown in Figure 15 are the total production data of shallow and deep reservoirs, and the water level data corresponds to the observed data of well BD-1.

It should be noted that the duration of data measurements is about 20 years in Laugarnes field and about 7 years in Glerardalur field (Figures 13 and 14). Moreover, both water level and production data are measured periodically. However, in the Balcova-Narlidere field case, water level measurements were not continuous and the duration is about 3 years.

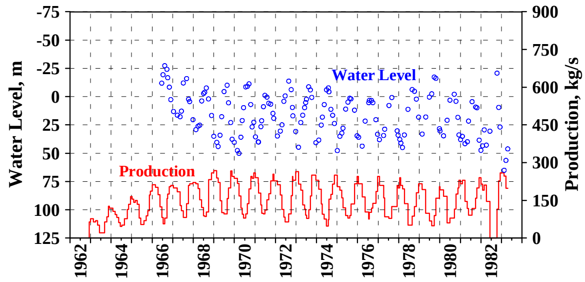

Figure 13: Water level changes and production history of Laugarnes field.

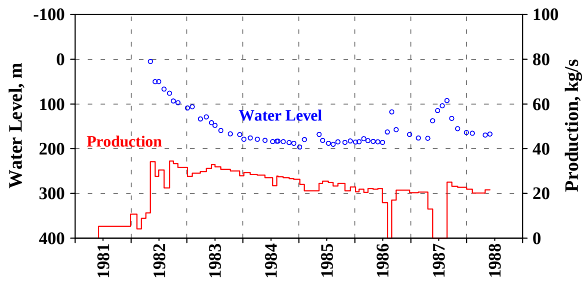

Figure 14: Water level changes and production history of Glerardalur field.

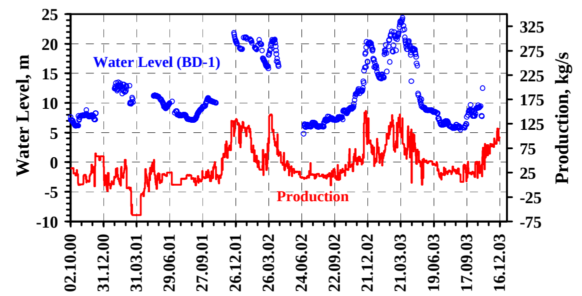

Figure 15: Water level changes and production history of Balcova-Narlidere field.

Based on Axelsson's work, production performances of both fields in Iceland (Laugarnes and Glerardalur) can be modeled by a 3-tank (closed) model. However, our studies as discussed later indicate that a 2-tank (open) model seems to be a preferable model to represent the geothermal system in Laugarnes and Glerardalur fields (Sarak et al., 2003b and Sarak, 2004).

Nonlinear regression analyses based on our 1- and 2-tank (open/closed) models were performed, using the production and water level data of these three fields to estimate the parameters. The best fit was obtained with the 1-tank model parameters given in Table 6 and the 2-tank (open) model parameters in Table 7.

Table 6: Regression results for 1-tank model.

Model Parameters	1-Tank Model		
	Laugarnes	Glerardalur	Balcova-Narlidere
α_r, kg/bar-s	20.47 (±0.55)	1.38 (±0.13)	58.78 (±1.74)
κ_r, kg/bar	$1.0x10^8$ (±$1.5x10^7$)	$5.48x10^7$ (±$7.7x10^6$)	$5.0x10^7$ (±$4.88x10^6$)
RMS, bar	1.140	1.268	0.307

Table 7: Regression results for 2-tank model.

Model Parameters	2-Tank (Open) Model		
	Laugarnes	Glerardalur	Balcova-Narlidere
α_a, kg/bar-s	36.81 (±4.56)	1.42 (±0.077)	248.9 (±3530.1)
κ_a, kg/bar	$1.05x10^{10}$ (±$2.7x10^9$)	$8.75x10^7$ (±$9.9x10^6$)	$6.73x10^7$ (±$1.39x10^9$)
α_r, kg/bar-s	30.46 (±1.83)	2.97 (±0.44)	76.85 (±336.73)
κ_r, kg/bar	$8.94x10^7$ (±$1.2x10^7$)	$8.15x10^6$ (±$1.8x10^6$)	$4.63x10^7$ (±$3.33x10^7$)
RMS, bar	0.566	0.546	0.307

Our regression work indicates that if the measured data are of insufficient duration and not recorded continuously, as in the case of Balcova-Narlidere field, then the simple models such as the 1-tank model simulate the water level or pressure behavior better. If the duration of measured data is long enough and recorded continuously (Laugarnes and Glerardalur) then the more complex models such as 2-and 3-tank models simulate the water level or pressure behavior better (Tables 6 and 7).

The simulation results of 1- and 2-tank (open) models for Laugarnes, Glerardalur and Balcova-Narlidere fields are plotted in Figures 16, 17 and 18, respectively.

The best matches between the measured and model data (with lowest RMS values and confidence intervals) are obtained by the complex models in the cases where the duration of the field data is long enough (Figures 16 and 17).

In the Balcova-Narlidere field case, the 2-tank (open) model gives similar matches to the 1-tank model (Figure 18), however, the confidence intervals of the 2-tank model computed for the reservoir and aquifer parameters (Table 7) are quite wide indicating the inadequacy of the 2-tank (open) model. Probably a longer period of measured data is required to increase the reliability of the model.

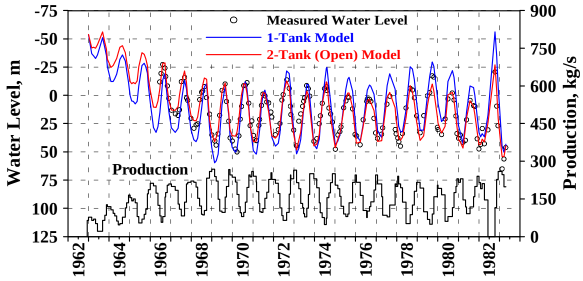

Figure 16: Simulation results of Laugarnes field.

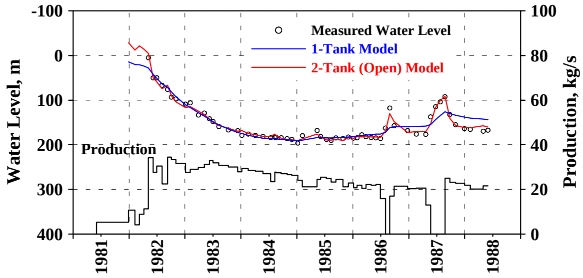

Figure 17: Simulation results of Glerardalur field.

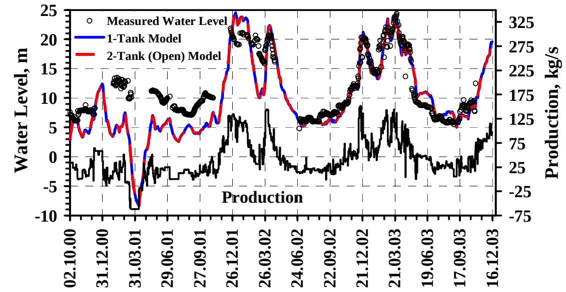

Figure 18: Simulation results of Balcova-Narlidere field.

Based on the observations of the production and reinjection behavior of the Balcova-Narlidere field (Satman et al., 2002), among the 1- and 2-tank lumped models, the 2-reservoir tanks with/without aquifer models could be an appropriate model to represent the production/ reinjection-water level response behavior of the Balcova-Narlidere field.

The 2-reservoir tanks with/without aquifer models were applied by using the water level data of BD-1 representing the deep reservoir, and B-12 representing the shallow reservoir. In each modeling, the water level response of one deep well and one shallow well were modeled. The simulation results of the 2-reservoir with and without aquifer models are shown in Table 8.

Table 8 indicates that the 2-reservoir tanks with aquifer model does not give satisfactory results. The confidence intervals of the aquifer parameters (α_a, κ_a) are computed to be wide and so not reliable.

The 2-reservoir tanks without aquifer model results for deep and shallow reservoirs are plotted in Figure 19. Although the confidence intervals for the model parameters given in Table 8 seem acceptable, the matches in Figure 19 exhibit discrepancies between the measured and model data for the shallow and deep reservoirs in the case of the 2-reservoir tanks without aquifer model. This might be due to following reasons: (1) the 2-reservoir tanks without aquifer models could not represent the field data successfully, (2) the production/reinjection and/or the water level data have some errors, (3) the duration of the available data is not long enough to see the unique features of the 2-reservoir tanks without aquifer models.

Table 8: Regression results of 2-reservoir tanks with and without aquifer models.

Model Parameters	2-Reservoir Tanks Without Aquifer	2-Reservoir Tanks With Aquifer
α_{r1}, kg/bar-s	44.12 (±2.78)	45.98 (±3.22)
κ_{r1}, kg/bar	$1.67x10^7$ ($\pm 4.7x10^6$)	$1.57x10^7$ ($\pm 4.9x10^6$)
α_{r2}, kg/bar-s	39.09 (±2.35)	39.95 (±2.74)
κ_{r2}, kg/bar	$3.48x10^7$ ($\pm 5.1x10^6$)	$3.51x10^7$ ($\pm 5.5x10^6$)
α_{r12}, kg/bar-s	14.94 (±2.84)	13.52 (±2.97)
α_a, kg/bar-s	--	999.98 (±4816.5)
κ_a, kg/bar	--	$2.99x10^{10}$ ($\pm 2.2x10^{11}$)
$RMS_{shall.}$,bar	0.190	0.199
RMS, $_{deep}$,bar	0.224	0.216

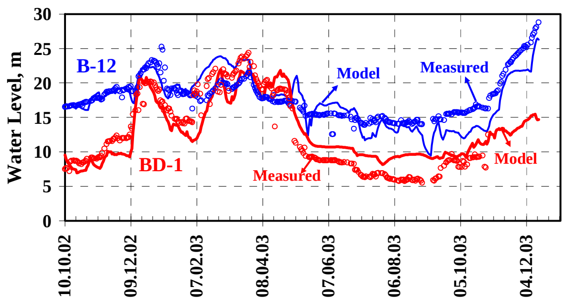

Figure 19: Simulation results of 2-reservoir tanks without aquifer model.

3.5 The Effect of the Initial Guesses

Gradient-based algorithms (the Levenberg-Marquardt method in our applications) can end up getting stuck in local minima, and thus can provide nonunique parameter estimates. It is important to use smart initial guesses for the parameter values. In particular, this would be the case where models with a large number of unknown parameters are chosen and/or the observed data contain large measurement errors. The geological, geophysical and hydrogeological data could be convenient for choosing the initial smart guesses (see the discussions in Section 3.2).

The analytical equations and the asymptotic expressions of our models particularly related to the long-term steady- or pseudosteady-state behavior of the water level/pressure data could also be useful to obtain a good set of initial guesses for the parameters prior to performing nonlinear regression analysis.

For example, the observed water level behavior shown in Figure 14 for the Glerardalur field resembles the behavior of a system with a constant pressure outer boundary. Figure 14 exhibits a relatively constant production rate and the water level declines sharply at early times and then reaches a constant value at late times. Performing graphical analysis of the data by using the asymptotic expressions given by Sarak et al., 2003a and Sarak, 2004, reservoir storage capacity, κ_r, and reservoir recharge constant, α_r, can be easily calculated as $2x10^7$ kg/bar and 1.13 kg/bar-s, respectively. Based on these values, we can choose our initial guesses of the parameters and perform nonlinear regression.

3.6 The Periodicity of the Data

Besides the duration of the data, the periodicity of the data also effects the modeling results. Using the daily measured data could give more reliable results than using the monthly data.

Data with shorter periods reflect the water level behavior in response to the production effect more realistically than the data with longer periods.

Moreover, the averaging approach involved in the long-period data may introduce some errors. Using the short-period data avoids this type of errors.

4. CONCLUSIONS

In this work, lumped-parameter models were used to match the measured pressure or water level response in some field cases. The measured production/reinjection and water level data of Laugarnes Field, Glerardalur Field, and Balcova-Narlidere Field were investigated and modeled. The problems involved in field applications are presented and discussed. Our specific conclusions can be summarized as:

1. The inaccuracy as well as the discontinuity of the input data such as the production/reinjection flow rates and the water level (or pressure) measurements greatly affect the confidence intervals and RMS values computed from the matching analysis of the model. Therefore, continuous water level, and production/reinjection data as well as accurate measurements are definitely required to increase the reliability of the model parameters and to obtain the better matches.

2. A longer history of production/reinjection and water level data is preferred in order to reflect the long-term behavior of the geothermal system and the characteristics of the parts of the system.

3. The type of model suggested from the regression analysis should be supported and confirmed by the additional geological, geophysical and hydrological data.

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