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A Study on the Production and Reservoir Performance of Balcova-Narlidere Geothermal Field

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ABSTRACT

In this work, we present a study evaluating and predicting the production and reservoir performance of the Balcova-Narlidere geothermal field, Turkey. The results of temperature profiles, well tests, pumping tests, well logging surveys and core and chemical analysis to determine the rock and fluid properties and as well as to characterize the Balcova-Narlıdere geothermal reservoir are evaluated and presented. One shallow and another deep, two concealed outflowing, horizons were identified with temperatures of 110°C and 140°C, respectively. Our natural state modeling study suggested a net recharge mass rate of about 51 kg/s and net heat recharge of about 33 MWt. The natural state model provided satisfactory matches of temperature vs. depth data measured at all wells. Based on static temperature measurements obtained from the wells throughout the field, a 3-D temperature distribution map was constructed. Initially about 50% of the produced fluid was reinjected into the shallow part of the reservoir. However our study indicated an inefficient reinjection with a premature reduction in the temperature of the fluids produced from the nearby shallow wells. Therefore the field management switched to a new reinjection scheme utilizing a new deep well drilled particularly for reinjection purposes. The reservoir limits were studied, and the volume of water in place and stored heat were estimated by various methods. The results of reservoir modeling studies conducted using a stochastic stored heat model and a lumped parameter model are given.

1. INTRODUCTION

The Balcova-Narlidere geothermal field is situated in the Izmir bay of the Aegean Coast of Turkey, and contains a liquid dominated reservoir. Figure 1 shows the location map of the field. At Balcova-Narlidere, there are 12 shallow wells and 9 deep wells. The geothermal water produced with a maximum temperature of 140 °C has been utilized to support a district heating system with a capacity of approximately 5000 residences in 1996. The number of residences heated by the system increased to nearly 8200 in the 2003-04 heating season.

The Balcova-Narlidere geothermal field is known as the oldest geothermal system in Turkey. The first well was drilled by General Directorate of Mineral Research and Exploration (MTA) in 1963. There are about 50 wells drilled to date and they are classified as gradient, shallow and deep wells. The field started to feed a district heating system with a capacity of approximately 5000 residences in 1996. The field reached a heating capacity of 7114 residences (711 400 m^2) (Toksoy et al., 2002) at the end of 2002 and has recently reached to 8200 residences.

The Balcova-Narlidere geothermal field is a low-temperature water geothermal system associated with a major fracture zone. Geothermal fluid is produced from 9 deep and 12 shallow wells, and some of the wells are used for reinjection. Figure 2 shows the location of wells in the Balcova-Narlidere geothermal field.

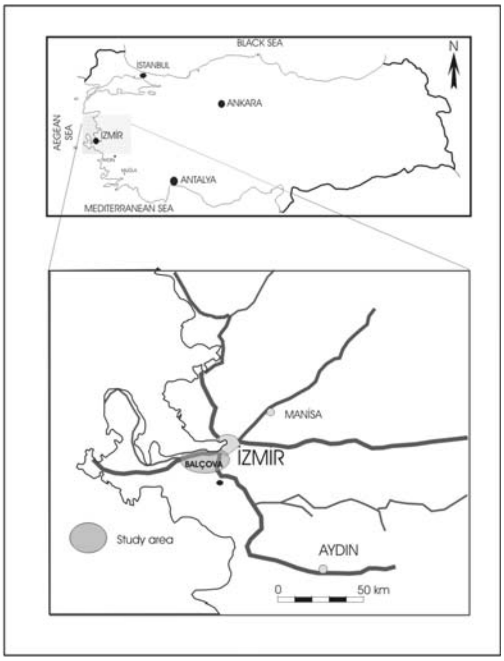


Figure 1: Location map of the Balcova-Narlidere field.

A total of 21 wells (9 deep and 12 shallow wells) have been operated since 1996. The deepest well in the field is BD-5 with a depth of 1100 m and the shallowest well is B-9 with a depth of 48.5 m. Seven deep wells: BD-1, BD-2, BD-3, BD-4, BD-5, BD-6 and BD-7, and five shallow wells, B-1, B-4, B-5, B-7 and B-10 are being used for production continuously or periodically. The deep wells have been produced in winter and the shallow wells have been produced in summer months in general. Until September 2002, three shallow wells, B-2, B-9 and B-12 were used for reinjection. However the reinjection was switched to deep wells in 2002 and a new well, BD-8, drilled in 2001 has been used for reinjection since then. The depths and the temperatures of the shallow and deep wells are presented in Table 1, and the locations of the wells are shown in Figure 2.

A production/reservoir project (Satman et al., 2002), funded by the management of the field, was conducted at the Balcova-Narlidere geothermal field. This paper discusses the fundamental findings of the project conducted and presents the recent developments in the field.

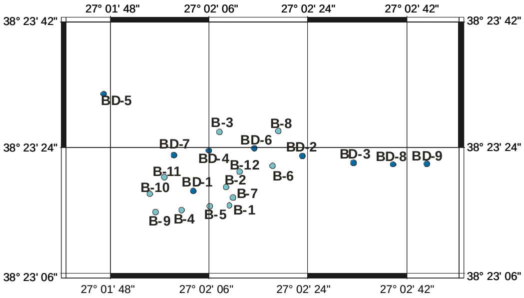


Figure 2: The location of wells in the Balcova-Narlidere geothermal field.

Table 1: The depths and the temperatures of the wells in the Balcova-Narlidere geothermal field.

Well	Depth (m)	Temperature (°C)
B-1	104	115
B-2	150	113
B-3	161	112
B-4	125	112
B-5	108.5	114
B-6	150	93
B-7	120	115
B-8	155	93
B-9	48.5	122
B-10	125	114
B-11	125	109
B-12	120	100
BD-1	564	140
BD-2	677	133
BD-3	750	140
BD-4	624	140
BD-5	1100	130
BD-6	605	140
BD-7	702	140
BD-8	625	133
BD-9	770	140

2. GEOSCIENTIFIC WORK

The Balçova geothermal area is situated in the extensively exposed Izmir Flysch unit of Upper Cretaceous age. The field is located at the northern margin of the Seferihisar Horst where the flysch outcrops. While to the south of the field, talus breccias cover the northern flank of the Seferihisar Horst, young and recent sediments infill Izmir bay further north. For that reason, it is very important to recognize the features of Izmir Flysch to understand the subsurface geology of the field. Izmir Flysch is composed of different rock units, such as sandstone, clayey schist, phyllite, limestone, limestone olistoliths, granodiorite, serpentinite and diabase.

On the other hand, the information about the structural discontinuities, faults, are important to perceive the movements of geothermal fluids. A sequence of tectonic activities has affected the Izmir Flysch unit so intensely that the original occurrence of the basin has completely changed. After the sedimentation stage of the flysch, the basin started to close because of crustal shortening, and the flysch masses were folded. At this stage shear zones were generated. Compression continued long after the Miocene and limiting SW-NE oriented inverse faults were formed (Ongur, 2001). Recent tectonic activities have also created a series of east-west oriented faults and related fractures that first formed the Izmir graben (Izmir Bay) and later helped the formation of Balçova-Narlidere hydrothermal system. The most important fault of the area is the east-west oriented Izmir fault, which is locally called Agamemnon Fault, and extends over 30 km (Ongur, 2001). The Agamemnon fault is known to be the most important conduit of the geothermal system to transport the fluids to the surface. There are a series of east-west oriented faults with slopes of 60-80° stepping down to the north and they might be joining at depth. A structural map of Balçova-Narlidere area proposed by Ongur (2001) is based on alluvium thickness and alluvium-flysch contacts observed in wells (Fig. 3).

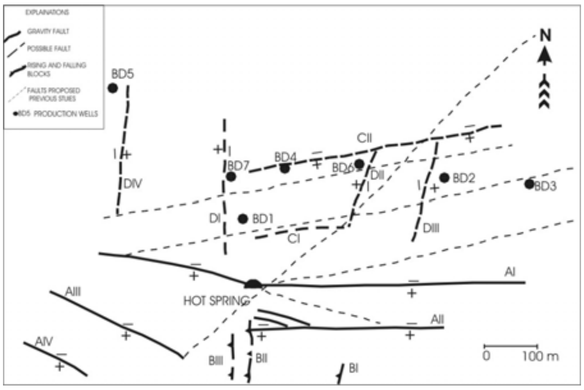


Figure 3: Structural map of the Balcova-Narlidere field and well locations at sea level reference. (modified from Ongur, 2001)

The first resistivity survey by Tezcan (1963) identified dispersion of the geothermal fluids to the north departing from the Agamemnon fault, and later SP survey by Ercan et al. (1986) brought up some structural occurrences. Latest geophysical surveys (CSAMT, resistivity and SP) explored the extension of the known field to the north and they confirmed only limited geothermal fluid dispersion through a deep horizon in that direction.

Hydrogeological investigations (Satman et al., 2002) identified a recharge area on the Seferihisar Horst in the south of the field by following geomorphology, and recharge potential is estimated to be 470 l/s.

3. RESERVOIR CHARACTERIZATION

Temperature profiles, well tests, well logs, core analysis and water analysis were evaluated to determine rock and fluid properties in the reservoir.

The temperature profiles of shallow and deep wells drilled in Balcova field were evaluated (Fig. 4). The presence of a shallow and a deep hot water aquifer was observed from those profiles. While the shallow aquifer has temperatures of 100-110°C, the deep aquifer has higher temperatures ranging from 120°C to 140°C. The cap rock in the outflowing region of the Balcova geothermal system seems to have permeable features. The temperature profiles given in Fig. 4 indicate that the cap rock over eastern wells is impermeable.

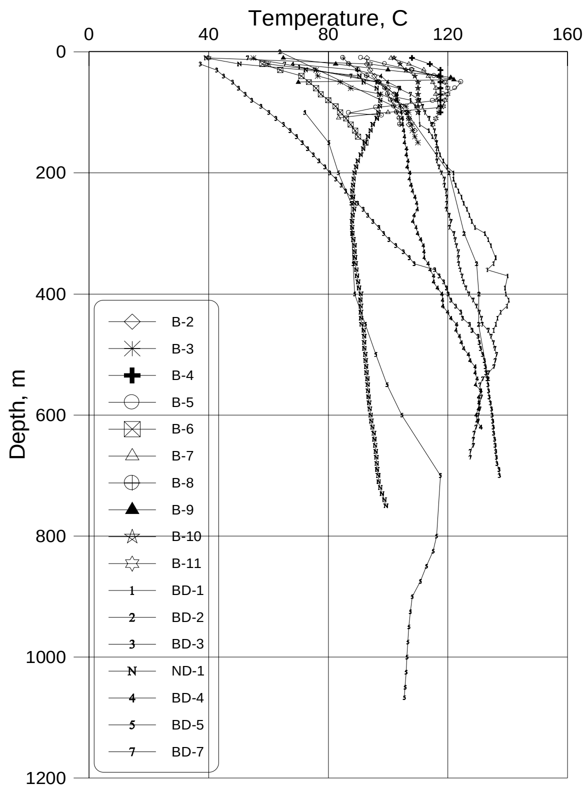


Figure 4: Temperature profiles of Balcova wells.

The productivities and near wellbore transmissivities of wells BD-2, BD-5 and BD-7 were determined by well tests conducted in those wells, and important information was obtained regarding reservoir/production characteristics of the geothermal system (Onur et al., 2002). The well tests indicated that the tested wells produced from the fracture network created by leaky and sealed faults. The results of well tests seem to confirm the faults DI, DII, DIV and CII (Fig. 3), which were previously determined from the alluvium and flysch contacts. The transmissivities obtained from those tests are presented in Table 2.

Well tests could not be conducted in some wells, because they have pumps installed and they were producing continuously in the heating season. Therefore, pumping tests were carried out in those wells to obtain information and as a result, inflow performance relationship (IPR) curves of those wells were determined. Fig. 5 shows the results of pumping tests conducted in wells BD-6 and BD-7. The IPR curves clearly show the effect of turbulence on flow to wellbore. It is also evident that the productivity of the BD-6 well is higher than the productivity of the BD-7 well. After the evaluation of those tests, productivities and dynamic water levels were determined in addition to static water levels and maximum flow rates of wells. Besides, performances of the wells were compared and an evaluation of the field was made on the basis of individual wells.

A quantitative evaluation is done on the density and porosity measurements from the available well logs in gradient and shallow wells drilled in alluvium and upper sections of the flysch. Qualitative evaluation carried out in deep wells distinguished three different zones within the flysch producing zone. In addition to flysch-alluvium contact between surface and pay zone, two different zones were distinguished in the upper section of the flysch (Satman et al. 2001).

Table 2. Transmissivities of Balcova wells (modified from Onur et al., 2002).

Wells	Transmissivities (D-m)	Findings
BD-2	31-62	Close to a leaky fault
BD-5	2-11	Close to a leaky fault
BD-6	58 (near well)-116	Close to a sealed fault
BD-7	3.3 (near well)-121	Close to a leaky fault

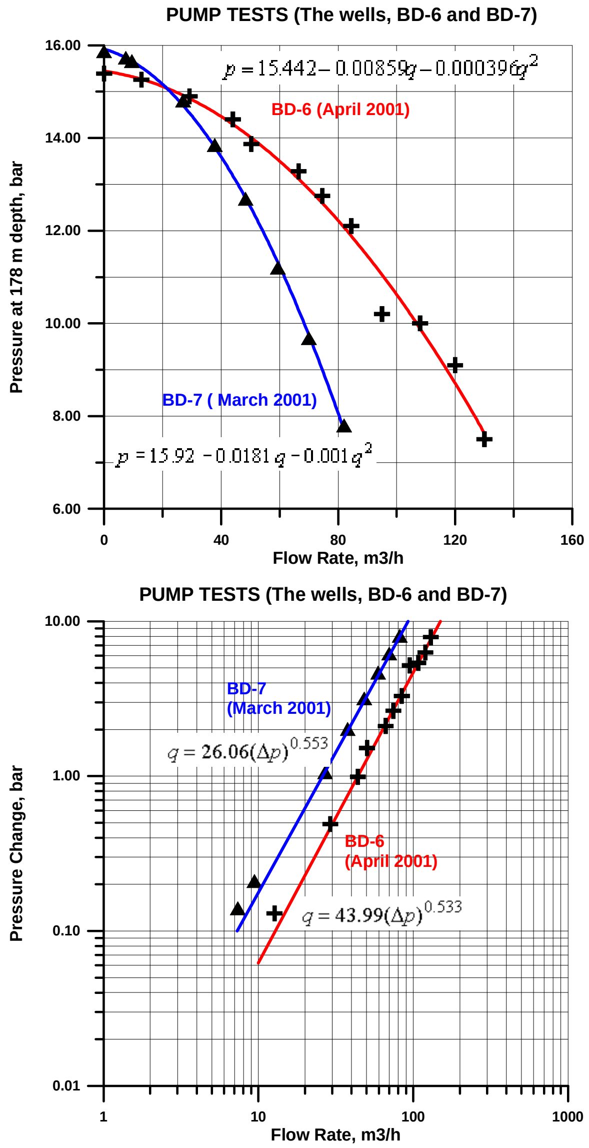


Figure 5: IPR curves for the wells BD-6 and BD-7, obtained from pumping tests in Balcova wells.

In the context of reservoir characterization, core analysis was carried out on a core cut at 514 m in well BD-1. The density and the porosity of the core were found 2.65 g/cm^3 and 2.75 %, respectively. Later, petrographic evaluation on a thin section of the core revealed that the rock had been subjected to severe compression and diagenesis during the geological time scale. Diagenesis (pressure-solution relationship) is deduced from the quartz grains unification. On the other hand, voids remained in the matrix after the compression are later filled by the materials such as calcite and chalcedony, and therefore, it can be easily understood that the matrix porosity of the rock does not have any practical significance.

Geochemical investigation was carried out after the analysis of water samples taken from shallow and deep wells beside the hot springs. The Balcova geothermal waters have a very low total dissolved solids (~ 1500 ppm) and are very close to fresh ground waters. Compositions of typical Balcova waters from surface, shallow and deep wells are classified as $S_1A_1A_2$ and $A_1S_1A_2$ in Sulin classification and are considered to be soda waters. The Cl-SO_4-HCO_3 ternary diagram in Fig. 6 confirms this classification. Shallow and deep waters are similar with small differences. The ternary diagram of SiO_2-SO_4-HCO_3 points also that these waters are in soda water classification and extra SO_4 ions indicate surface water influence. Low Mg content of deep well waters is an indication that deep waters might have higher temperatures.

Non-condensing gas content of the produced water, mainly CO_2, was measured to be a maximum of 800 ppm.

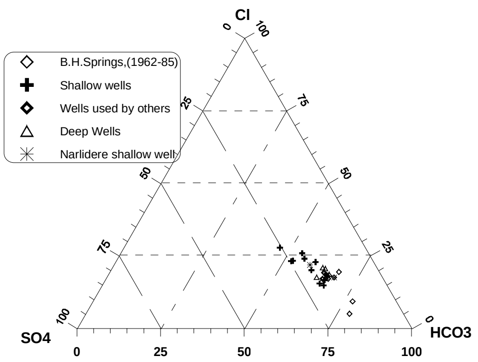


Figure 6: Cl-SO_4-HCO_3 ternary diagram.

Cation geothermometers indicate higher temperatures (~200°C) than the silica ones (~150°C), which is normally expected since silica geothermometers indicate supply water temperatures while cation ones point out the deep temperatures of the geothermal system. While silica temperatures are close to the reservoir temperatures, the chloride mixing model confirms high temperatures for deep waters.

The isotopic characteristics of the shallow and deep geothermal waters are different, but they both have meteoric origin. Isotope depletion of thermal waters relative to a nearby dam water indicates that the fluids might originate from higher terrain (i.e. colder climate). In fact, the altitude of recharge area is calculated to be 500 m by using δ^2H values (Aksoy and Filiz, 2001). Increasing tritium values observed from the samples at one year interval clearly indicate that young waters are entering into the field.

Static temperature surveys taken in the Balcova-Narlidere wells were evaluated and a 3D temperature distribution obtained by using "inverse distance" 3D interpolation technique (Fig. 7). By following the trends of 3D temperature distribution the location for a new well, the BD-8 well, was proposed and the temperature profile of drilled well matched the temperature profile estimated by 3D distribution. The match between the measured and model temperatures shown in Fig. 8 is good and seems to prove the model. Other results obtained from the 3D temperature distributions enabled us to reasonably estimate stored heat and the volume of the Balcova reservoir. The stored heat in the geothermal system with a reference temperature of 28°C used in simulation is estimated as 8.2×10^{14} J, which covers a reservoir volume of 3.7 km^3. The stored heat over 80°C in the geothermal system is around 2.3 km^3. If 80°C, which is used in the district heating system, is used as a reference temperature, then the useful stored heat is estimated to be 1.34×10^{14} J.

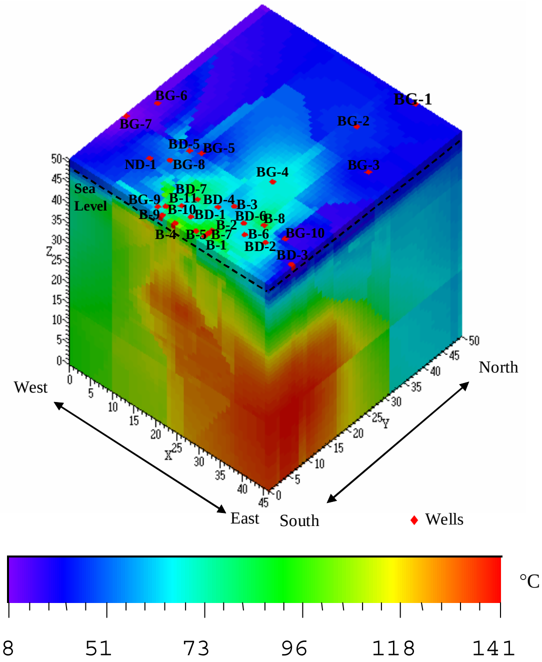


Figure 7: 3D temperature distributions for Balcova geothermal field.

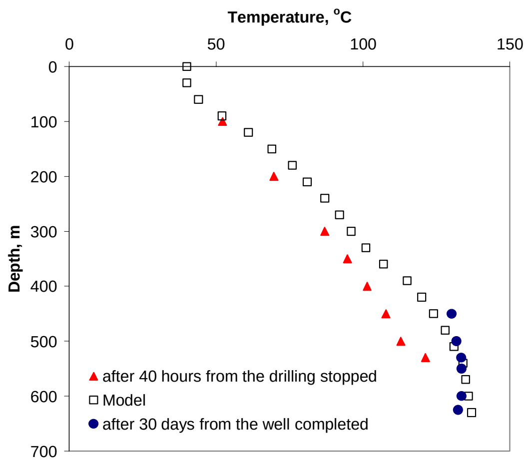


Figure 8: A match of the measured and model temperature vs. depth data for the BD-8 well.

The Balcova-Narlidere geothermal system is a convective hydrothermal type commonly occurring in areas of active geological faulting and folding, and areas where the regional heat flow is above normal, as in much of western Turkey. Figure 9 illustrates a simplified conceptual hydrogeological model of the Balcova-Narlidere geothermal field, assuming a resource located along the Agemennon fault zone. The water infiltrates down in the southern part of the fault zone to a depth where it is heated sufficiently that it can rise along the northern part of the same fault zone. This simple model is believed to represent the basic mechanism for the fault related low-temperature Balcova-Narlidere geothermal resource. The model given in Figure 9 is meant to be illustrative and not exact. Some of the thermal water flows laterally away from the fault in the unconsolidated alluvium that fills the region to the north and some also flows to the north at a deeper horizon as indicated in the model.

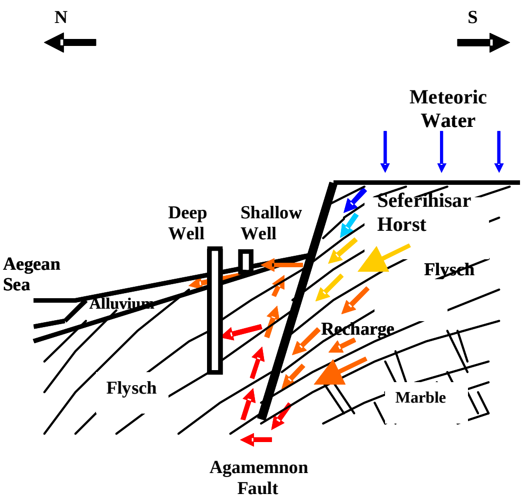


Figure 9: A simplified conceptual model for the Balcova-Narlidere geothermal system.

4. PRODUCTION-REINJECTION STATE OF THE FIELD

A total of 2 million m^3 of fluid was produced from the field; of which 1.4 million m^3 were reinjected in year 2000 when approximately 5700 equivalent households were heated. 43% of the fluid produced and 51% of the heat produced were provided by the deep wells. Deep wells were used for production purposes in cold season whereas shallow wells were used in warm season. While yearly production and reinjection in shallow wells were equal, yearly production in deep wells exceeded the reinjection by 600 thousand m^3. 62% of produced fluid and 71% of produced heat were provided by deep wells in Feb. 2001. On the other hand, 14% and 86% of disposal water was reinjected into deep and shallow wells, respectively.

The production/reinjection and water level changes are measured in 8 shallow and 8 deep wells, some periodically and some intermittently. Figure 10 shows the net production (production-reinjection) data of shallow wells, deep wells and whole field, respectively. The shallow wells were used for reinjection and the deep wells for production until September 2002. However the reinjection into shallow wells was stopped in September 2002 (Figure 10). BD-8 is being used for reinjection since September 2002.

In 2003, a total of nearly 3.0 million m^3 of fluid was produced from the field and 1.21 million m^3 was reinjected into the deep wells. 53% of the fluid production was through the deep wells. The net production (production-reinjection) from the deeper part of the reservoir was kept at 375 thousand m^3 whereas the shallow wells were used only for production. In contrast to the initial exploitation program, the recent field management approach emphasizes the reinjection into deep wells, which was recommended by the project conducted in the field (Satman et al. 2002).

The water level data of a deep well, the BD-1 well, is presented in Figure 11. The BD-1 well with a moderate depth is located near the center of the field (see Figure 2 and Table 1) and has been used as an observation well. It has the longest duration of water level recording.

The shallow well, B-9, was used for reinjection purposes at the early exploitation stages of the field. However, the reinjection evaluation studies conducted within the context of the project concluded that reinjection into the shallow zone was an inefficient operation. Tracer tests by Aksoy (2001) showed that the hydraulic front formed by reinjection into the B-9 well broke through at the neighboring shallow wells, B-4 and B-10, approximately after 40 h and the heat front reached the same wells after 14 days. The wellhead temperatures of B-4 and B-10 decreased rapidly after the initial heat front breakthrough. Fig. 12 illustrates the change in wellhead producing temperature of the B-4 well as a result of reinjection into the B-9 well. A one-dimensional modeling study was conducted to calculate the effects of reinjection on the producing water temperature of the B-4 well. The injection well, B-9, and the producing well, B-4, were assumed to be a doublet. Temperature changes calculated from the model are also shown in Fig. 12. It is clearly understood that the reinjection was an operation that produced cold disposal water after flowing through shallow formations. In other words, the operation was an inefficient reinjection application through formations between 50 m and 150 m. Reinjected cold water was cooling the formation within the drainage area and hence the water produced from B-4 and B-10.

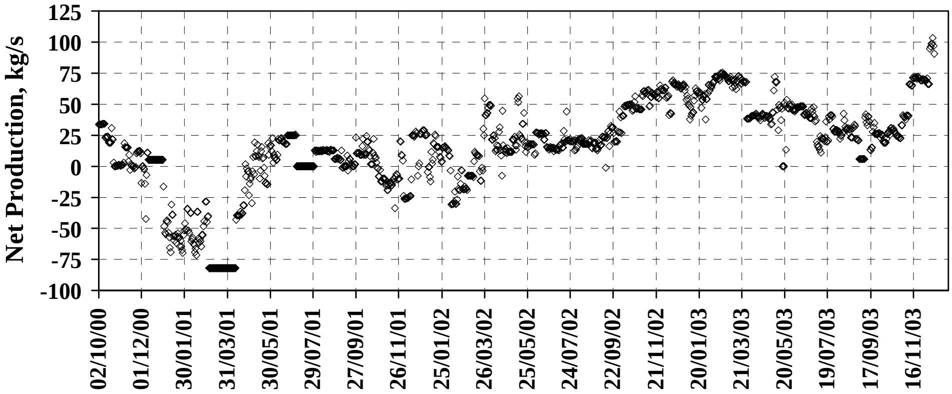
Since the aim of the reinjection should be in principle to feed the productive deep reservoir, the management of Balcova Geothermal Ltd. abandoned shallow water reinjection, and the recently drilled well, the BD-8 well, was completed for reinjection purpose and was connected into the reinjection line in the 2003-2004 heating season. Based on the reinjection experience discussed above the management was recommended to switch to the deep wells for reinjection. In the long term the production should be coming from the deep wells in the central outflowing region and reinjection should be directed to the surrounding deep wells.

5. MODELING STUDIES

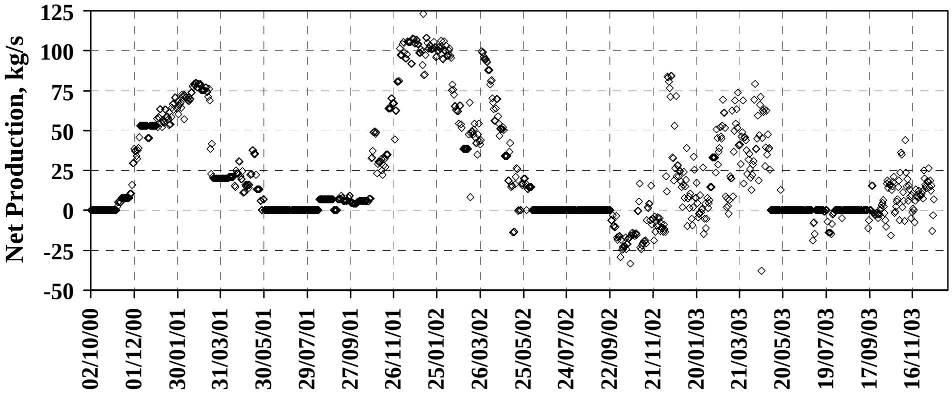
A stored heat model, a lumped-parameter model, as well as 3D modeling were used for the evaluation of the field.

5.1. Stored Heat Model

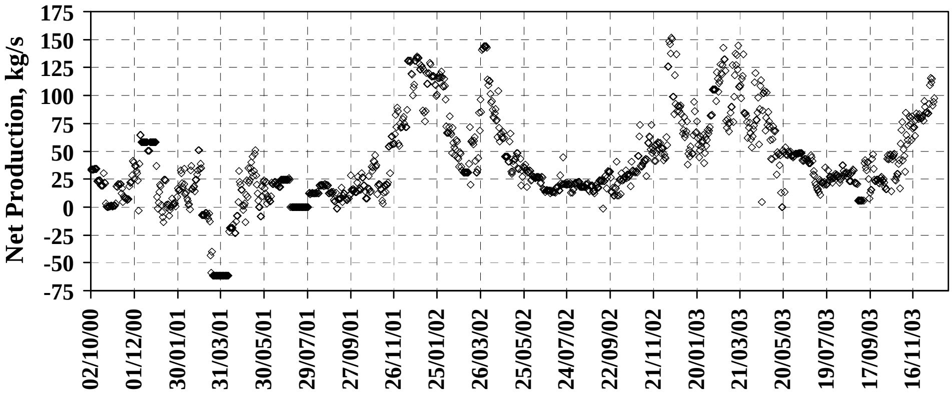
In this model, Balçova geothermal reservoir is delimited within the boundaries recognized by the various studies (geological, geophysical, etc.) conducted until that time. The district heating potential of the Balcova-Narlidere geothermal system is estimated by taking into account stored heat in the reservoir, the recoverability of heat energy, conversion efficiency, heat load and load factor. In other words, the Balcova-Narlidere geothermal reservoir is considered as a heat-producing system declining over time from an initial reservoir temperature to an abandonment temperature (80°C). Since the parameters utilized in this type of models have uncertainties, a stochastic method (Monte Carlo simulation technique) was used to minimize the risk on the results by entering the parameters as distributions. Two different types of sensitivity analysis were also conducted to identify significant input parameters and the results are shown in Fig. 13. As seen from Fig. 13, the potential of the field was found to be 12.5 MW_t, 25.5 MW_t and 50.5 MW_t with percentiles of 90%, 50% and 10%, respectively. The expected value of 25.5 MW_t from the fiftieth percentile must be taken as the potential of the area delimited by isotemperature contours constructed with the information available up to 1000 m. This model could be updated with the recent information obtained from newly drilled wells.



Net Production history of shallow wells



Net production history of deep wells



Net production history of the field

Figure 10: Net production histories for shallow wells, deep wells and the whole field.

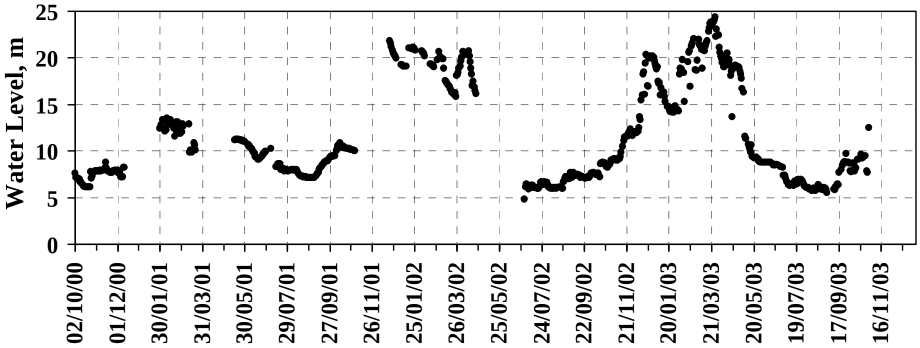


Figure 11. Water level data of BD-1

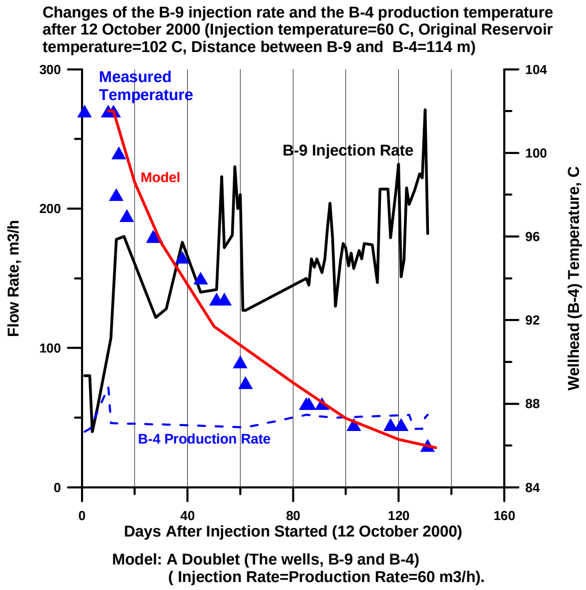


Figure 12: Modeling results for reinjection and production doublets B-9 and B-4 (Satman et al., 2001).

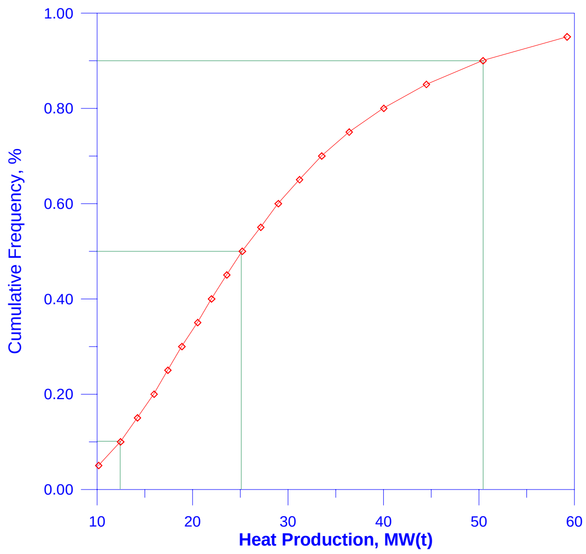


Figure 13: Results of stochastic model.

5.2. Lumped-Parameter Model

The Balcova-Narlidere geothermal system formed a low-temperature water reservoir and hence it is known that it contains compressed water within a partly confined reservoir. By assuming that the pressure is active in flow and that the temperature change in flow can be neglected (an isothermal medium), a lumped-parameter model was established and volumetric balance was investigated.

A simple lumped-parameter model (one-tank model) was applied by using the net production (production-reinjection) data of the whole field (deep+shallow) and the measured water level values of the BD-1 well. The early time water level data of the BD-1 well could not be matched properly. The reason for that could be the changing the production/reinjection schedule of the field at 24.09.2002 when the reinjection was switched from the shallow zone to deep zone. The shallow wells, B-1, B-9 and B-12, were used for reinjection until 24.09.02, and the deep well, BD-8, was used after.

In this model, static pressures (static water levels) were investigated by using production-reinjection difference of year 2000 for deep wells in monthly periods. The data of the BD-1 well matched the model results with the assumption that the static water level behavior of the BD-1 well is thought to represent the geothermal reservoir behavior. As a result, the parameters representing the system such as reservoir storage capacity (κ_r, the product of effective compressibility and reservoir fluid volume) and reservoir recharge coefficient (α_a, productivity index of the aquifer) were determined to be 8.25x10^7 kg/bar and 77.67 kg/(bar.s), respectively (Sarak, 2004). The parameters indicate that the natural recharge is strong and the performance of deep wells is sustainable with the reported production-reinjection data.

According to the results obtained from the lumped-parameter model, the parameters determining reservoir performance seem to be production, reinjection and natural recharge. Since it is not possible to change the natural recharge, production and reinjection should be controlled for the sustainable exploitation. While the production will increase the pressure decline in the reservoir, the reinjection and the natural recharge will decrease it. Therefore, if an increase in the production from the reservoir is required, the reinjection should be proportionally increased.

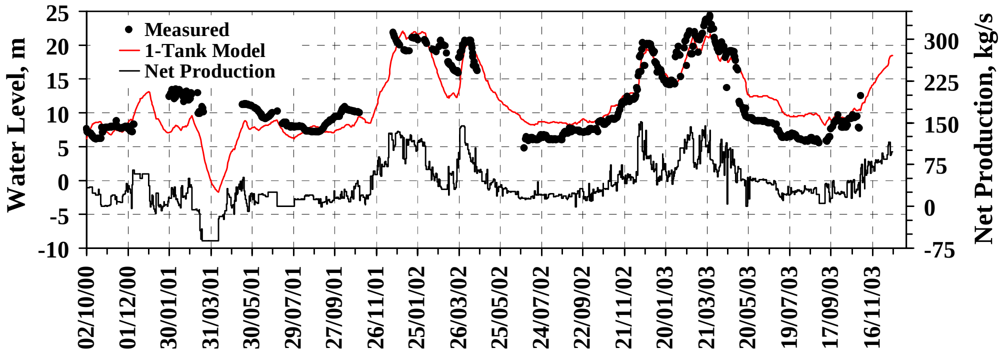


Figure 14. Simulation result of BD-1 (All data were matched) (α_r=77.67 kg/bar-s, κ_r=8.25x10^7 kg/bar).

A study was also conducted to predict the reservoir water level/pressure response for several production scenarios. The details of the prediction study are not discussed here but are given in Sarak (2004) and also in a companion paper by Sarak et al. (2005).

All the production wells in the Balcova-Narlidere field are operated by pumps set in the wellbores. The setting depth of the pumps in the deep wells is 150 m from the surface whereas it is about 70 m in the shallow wells. To avoid the possible cavitation in the pump, a minimum liquid level above the pump of 30 m in deep wells and 15 m in shallow wells must be maintained. The maximum allowable drawdown determines the production potential of the field. Thus the minimum liquid levels are the limiting constraints in operation of the field.

Based on the water level changes and the production/reinjection data (see Figs. 10 and 11) as well as the maximum allowable drawdowns, the reservoir could be able to sustain some increase in production. In case of a production increase, it was recommended that the field should be operated by rearranging the reinjection amount such that the production-reinjection difference should remain the same.

6. CONCLUSIONS

A production and reservoir engineering study was carried out within the context of the Balcova-Narlidere project. The systematic investigation and development of a geothermal field from the production and reservoir engineering viewpoint has been discussed as a main theme in the project work conducted. The lack of geoscientific information and production-reservoir engineering data during the exploitation stage were identified; and for complementing those, in addition to the geological, geophysical and well testing works the necessary methods were developed to establish a data base by monitoring the field. Moreover, modeling studies whose results are partially presented in this paper were conducted to identify better the geothermal system and the reservoir. Furthermore, as discussed in detail within the paper, proposals were developed to use the reinjection operation effectively. Finally, strategies were developed for the future developments of the field.

On the basis of this work, we state that:

- Monitoring is essential for better understanding and modeling of production and reservoir performance of the Balcova-Narlidere geothermal field. This aspect requires significant improvement in Balcova-Narlidere, particularly in view of foreseeable increase in production during the coming years.
- The deeper part of the reservoir reached by the deep wells should be used and targeted for production and reinjection purposes.
- The reinjection into the deeper part of the reservoir should be preferred and is vital to the sustainable management of the field.

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