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Results of a Comprehensive Well Test Program to Assess the Zugdidi-Tsaishi Geothermal Field, Republic of Georgia

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ABSTRACT

Republic of Georgia has substantial geothermal potential. In the Zugdidi-Tsaishi area, geothermal water was historically used for district heating and other direct uses. During the armed hostilities (in 1992-93) near this area, the geothermal district heating facilities in the area were destroyed. In the reconstruction effort, an assessment of the geothermal field was conducted through a comprehensive well test program during 1997-98.

The field has two aquifers, an upper one and a lower one; of the 13 wells used in the test program, 10 are completed in the upper aquifer and 3 in the lower aquifer. The test program was designed to be a minimum cost program utilizing as much of the existing local facilities as possible. The goals of the test program were; (1) to determine whether the two aquifers are in hydrologic communication and (2) to estimate the storage and flow properties of each aquifer.

The test program lasted three months; various wells completed in both the upper and lower aquifers were brought on line and shut in at different times. Some wells were found to have significant leakage during the test period while the flow rate data from certain other wells were unavailable. During the test, the water level was monitored in some wells and the wellhead pressure in certain artesian wells. Therefore, constructing adequate flow rate and pressure histories of the wells proved challenging. Even though this made for an unexpectedly complicated, multi-rate, multi-well test program, the objectives of the program were achieved satisfactorily.

The data were analyzed using superposition of the "line-source solution" to the "diffusivity equation" for fluid flow in porous media in both space and time. Using the measured and inferred production histories of the wells, the observed and calculated pressure histories of the observation wells were matched satisfactorily by trial and error.

The analysis of the results showed the two aquifers do not communicate hydrologically. The flow capacity of each aquifer was estimated to be high, in the range of 128 to 159 Darcy-meters. The storage capacity of each aquifer was estimated to be 0.44×10^{-3} to 1.15×10^{-3} meters per bar, which is typical of such shallow aquifers. The analysis further showed that the reserves of geothermal fluid per square kilometer of field area is 3 to 8 million cubic meters (3 to 8 million tons) in each aquifer.

Introduction

The Zugdidi-Tsaishi Geothermal Area in the Republic of Georgia was first discovered in 1951, when a well drilled to explore coal deposits in this area produced geothermal fluids at a temperature of 82°C. Since then, a total of 18 wells have been drilled in the area with the purpose of developing the field for direct heat utilization. These wells have a combined total flow capacity of approximately 30,000 m^3/day, at temperatures ranging from 82°C to 106°C.

The Zugdidi-Tsaishi geothermal reservoir is found in two different geologic intervals. Most of the existing wells are completed in the upper reservoir, which consists of Upper Cretaceous limestone units with an estimated thickness of up to 550m. The depth to the base of the reservoir reaches a maximum of approximately 2,950m. A deeper reservoir is found in Lower Cretaceous (Neocomian) limestone and dolomite deposits, with thicknesses up to 750m. The depth to the base of this lower reservoir reaches a maximum of approximately 3,700m. Only three wells (10-t, 17-t and 18-t) were completed in the lower reservoir.

The test program involved 13 wells (Figure 1) and lasted three months (October 15, 1997 through January 15, 1998). During the entire test period, wells 1-op, 1-t and 12-t were flowing continuously at 17 l/sec, 32 l/sec and 37 l/sec, respectively. On November 7, 1997 at 14:30, well 8-t (producing from the upper horizon) was put on production. A second well, 14-t (producing from the upper horizon) was put on production at 12:00 on November 23, 1997. The two wells produced simultaneously until December 10, 1997, when both wells were shut in. At 12:00 on December 25, 1997, well 10-t (producing from the lower horizon) was put on production. Well 10-t was shut in on January 8, 1998. Up to November 18, 1997, wells 17-t and 18-t were leaking at the rates of 6 l/sec and 15 l/sec, respectively; on

November 19, 1997 both wells were repaired and the leaks eliminated. During December 16-18, 1997, well 8-t was produced again but we have no rate history for these two wells for that period, and therefore this episode of flow could not be included in our quantitative analysis.

During the flow period, the water level in the weir box was monitored for wells 8-t, 14-t and 10-t; from these data, the flow rate history of these wells could be constructed. Throughout the period of October 21, 1997 through January 14, 1998, water level was monitored in observation wells 21-t, 9-t, 5-t and 3 (Zugdidi). During the test period, wellhead pressures were also monitored at wells 2-t, 8-t, 10-t, 14-t, 17-t and 18-t; except for well 2-t, all these wells have been produced at least for some time during the test. However, wellhead pressures of the production wells (8-t, 10-t and 14-t) were not monitored during production; this precluded any quantitative analysis of the flow efficiency of these wells and estimation of their hydrologic properties.

Of the 13 wells involved in this test program; wells 1-t, 1-op, 2-t, 3-Zugdidi, 5-t, 8-t, 9-t, 12-t, 14-t and 21-t are completed in the upper horizon while wells 10-t, 17-t and 18-t are completed in the lower horizon.

Test Results

Data Base

Figure 2 shows the production rate of history of wells 8-t, 10-t and 14-t calculated using the above formulas. Figure 2 also shows production rate histories of wells 1-op, 1-t, 12-t, 17-t and 18-t. Figure 3 shows the wellhead pressure histories measured at wells 2-t, 17-t and 18-t. Finally, Figure 4 shows the elevation (with respect to the sea level) of the water level in the well measured as a function of time at the observation wells 3 (Zugdidi), 5-t, 9-t and 21-t. Figure 1 indicates which wells were production wells (solid dot inside a square) and which were used as pressure or water level observation wells (solid dot inside a circle). Wells 17-t and 18-t were produced sometimes but we do not have complete rate histories of these two wells. Wells 17-t and 18-t were used as observation wells during the production of well 10-t; all three wells are completed at the lower horizon. Adequate wellhead pressure data were not available from well 2-t to allow quantitative analysis.

Data Analysis Procedure

Figure 4 indicates that four upper horizon wells (3-Zugdidi, 5-t, 9-t, 21-t) showed water level changes in response to production from two upper horizon wells, 8-t and 14-t. Therefore, the pressure (that is, water level) interference in these wells could be analyzed quantitatively. Figures 5 through 8 show the lower level data from these wells on an expanded scale. Figure 3 indicates that two lower horizon wells (17-t and 18-t) showed wellhead pressure changes in response to production from the lower horizon well 10-t. Therefore, interference between the production well 10-t and observation wells 17-t and 18-t could be analyzed quantitatively. However, it is clear from Figures 5 through 8 that the four upper horizon observation wells did not show any response when the lower horizon well 10-t was put on production (during December 25, 1997 through January 8, 1998). Therefore, the upper horizon wells do not communicate with the lower horizon.

The water level monitoring data from the upper horizon wells (3-Zugdidi, 5-t, 9-t, 21-t) and the wellhead pressure monitoring data from the lower horizon wells (17-t, 18-t) were analyzed using multi-well, multi-rate analytical simulation. This analytical modeling approach uses the concept of mathematical superposition in time and in space of the "line-source solution" to calculate the pressure response at any point in a reservoir due to the production from one or more wells at variable rates. The model uses the measured flow rate history of the wells to calculate the theoretical pressure (or water level) response as a function of time at any given point in the reservoir. Certain reservoir and well characteristics are required as input to the model. The input parameters are: reservoir fluid viscosity, specific volume of the reservoir fluid, wellbore diameter, "skin factor" (if the observation well is an active well), reservoir flow capacity (or transmissivity), reservoir storage capacity, reservoir temperature, specific volume of the injected water, initial reservoir pressure, and the distance between each production well and the observation point. Chemical constituents may also be important; however, the water from this reservoir is known to be low in dissolved chemicals, and it is therefore assumed that the reservoir fluid is pure water.

The calculated pressure behavior from the model is then compared with the observed pressure behavior. If the simulated pressure and observed pressure behaviors agree within a chosen tolerance, the behavior of the well is assumed to be "matched". That is, the assumed model with the chosen parameters is considered to be "calibrated". If the calculated and observed pressure behaviors do not match, one or more of the input parameters to the model are changed and the pressure behavior is recalculated. This trial-and-error process is continued until the calculated pressure behavior matches the observed behavior within the chosen tolerance for that well. The tolerance is chosen based on the sensitivity and accuracy of the pressure measurements. Once the match is obtained, the hydrologic properties used to get the match can be considered to be reliable estimates for the reservoir.

Data Analysis Results

Figure 5 compares the measured water level data from well 3-Zugdidi with the level calculated by the above-described analysis. The match is excellent. From this match we have estimated a flow capacity of 134 Darcy·m and a storage capacity of 1.105×10^{-3} m/bar between this well and the upper horizon production wells 8-t and 14-t. In achieving this match, the production history of the lower horizon well 10-t had to be ignored, implying that the lower and upper horizon wells do not communicate.

Figures 6 through 8 show similar matches for the upper horizon wells 5-t, 9-t and 21-t, respectively. Again, the matches are good and the hydrologic properties obtained are similar to those obtained for well 3-Zugdidi. Table 1 is a list of the hydrologic properties calculated from the interference test data from all four upper horizon wells and the two lower horizon wells.

Figure 9 and 10 show similar matches between the observed and calculated wellhead pressures of the lower horizon wells 17-t and 18-t, respectively. It is clear that these two wells responded readily to production from the lower horizon well 10-t. The calculated hydrologic properties from these matches are listed in Table 1. It is interesting to note that the data from well 17-t allowed a good match while the data from well 18-t did not. For well 18-t, the calculated storage capacity for the match shown in Figure 10 was unusually high compared to that from well 17-t. On the other hand, the match was no better when the storage capacity was kept at the level seen from well 17-t but the flow capacity was raised to a very high level. It was impossible to obtain a satisfactory match for well 18-t. The cause of this could be inaccuracies in production or pressure records, or heterogeneities within the lower horizon.

From Table 1, it is apparent that the upper horizon is fairly homogenous and extensive, with very small variations in the hydrologic properties over several kilometers. Furthermore, the upper horizon has relatively high flow and storage capacities compared to many shallow geothermal aquifers. Since only one lower horizon well yielded reliable results, no firm conclusions about its hydrologic properties can be made. However, from the results obtained from well 17-t, the lower horizon appears to have a lower flow capacity than the upper horizon but a similar storage capacity.

Finally, the amount of fluid in storage in the reservoir can be calculated from the storage capacity values estimated from matching of the test results. Storage capacity (S) is defined as:

$$S = \phi \, Ct \, h \ (\text{m/bar})$$

Where ϕ = porosity of the reservoir (fraction),
C_t = total compressibility of the reservoir rock and fluid (bar^{-1}), and
h = reservoir thickness (m).

For typical aquifers, the total compressibility is about $0.145 \times 10\text{-}3 \ \text{bar}^{-1}$. Therefore, $\phi h = S/0.145 \times 10^{-3}$. It should be noted that ϕh is essentially the reservoir pore volume per unit area (that is, m^3 of pore volume per m^2 of surface area). For this reservoir, the storage capacity varies from 0.44×10^{-3} to 1.15×10^{-3} m/bar (Table 1). Therefore, reservoir pore volume per unit area is in the range of 3 to 8m. In other words, 3 to 8 m^3 of fluid is available per m^2 of surface area. Hence, the fluid reserve should be about 3 to 8 million cubic meters (or 3 to 8 million tons) per square kilometer in either horizon.

Conclusions

The following conclusions have been drawn from analyses of the results of the test program.

1. The upper and lower horizons do not communicate hydrologically.
2. Test results from all four observation wells completed in the upper horizon were interpreted satisfactorily.
3. The flow capacity of the upper horizon is in the range of 128 to 159 Darcy·meters, which is relatively high for such aquifers.
4. The storage capacity of the upper horizon is in the range of 0.44×10^{-3} to 1.15×10^{-3} meters per bar, which is typical for shallow aquifers.
5. Of the two observation wells in the lower horizon, only one yielded reliable results; therefore, no firm conclusions about the hydraulic properties of the lower horizon can be made. However, the results from well 17-t suggest that the lower horizon may have a lower flow capacity than the upper horizon, but a similar storage capacity.
6. From the test data, the reserves of geothermal fluid per square kilometer is estimated to be 3 to 8 million cubic meters, or about 3 to 8 million tons in either horizon.

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Table 1. Hydrologic Properties Calculated from Interference Test Data.

Upper Horizon

Observation Well	Production Wells	Flow Capacity Darcy·m	Storage Capacity (m/bar)
3 (Zugdidi)	8-t and 14-t	134.0	1.105×10^{3}
5-t	8-t and 14-t	158.5	1.15×10^{3}
9-t	8-t and 14-t	128.0	0.44×10^{3}
21-t	8-t and 14-t	152.0	0.44×10^{3}

Lower Horizon

Observation Well	Production Wells	Flow Capacity Darcy·m	Storage Capacity (m/bar)
17-t	10-t	70	0.44×10^{3}
18-t	10-t	183 to 503	0.44×10^{3} to 0.38×10^{2}

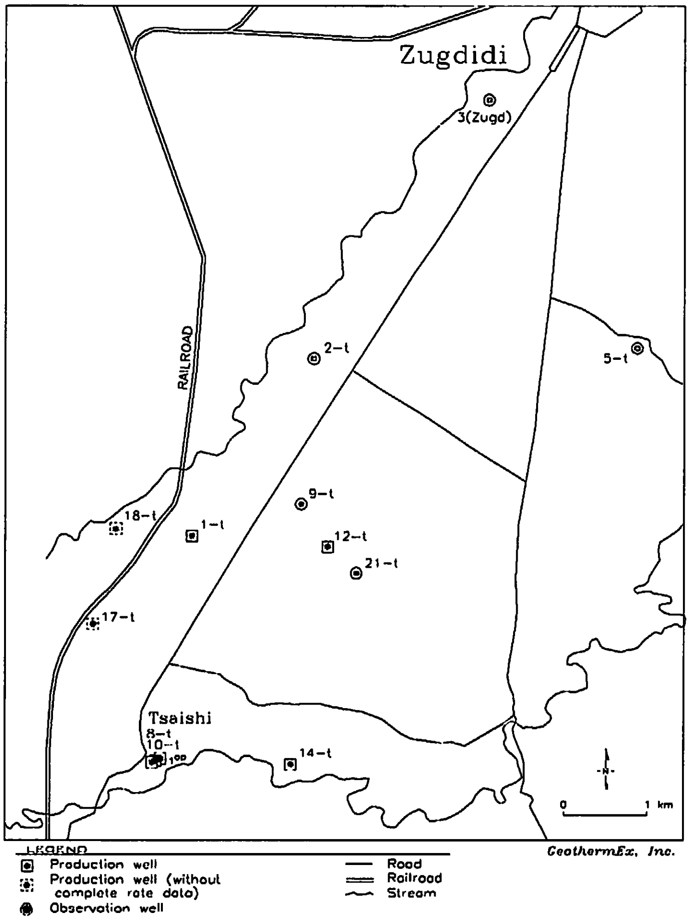

Figure 1. Location map.

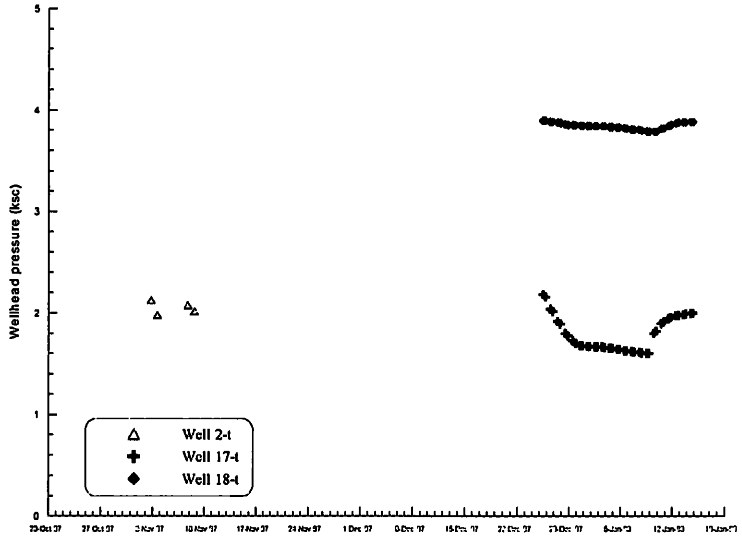

Figure 3. Flow test parameters versus time.

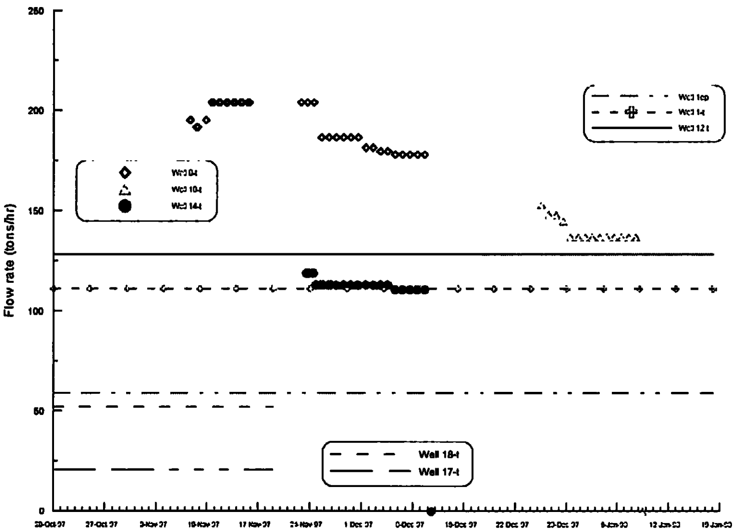

Figure 2. Flowrates of Zugdidi wells.

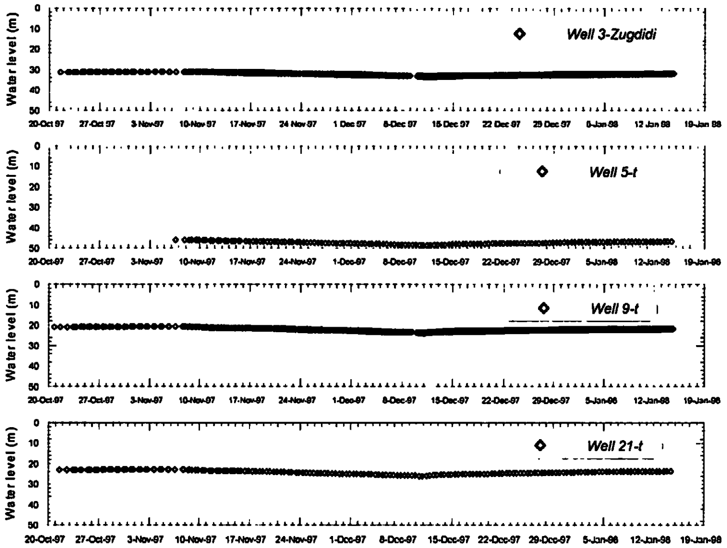

Figure 4. Water levels versus time.

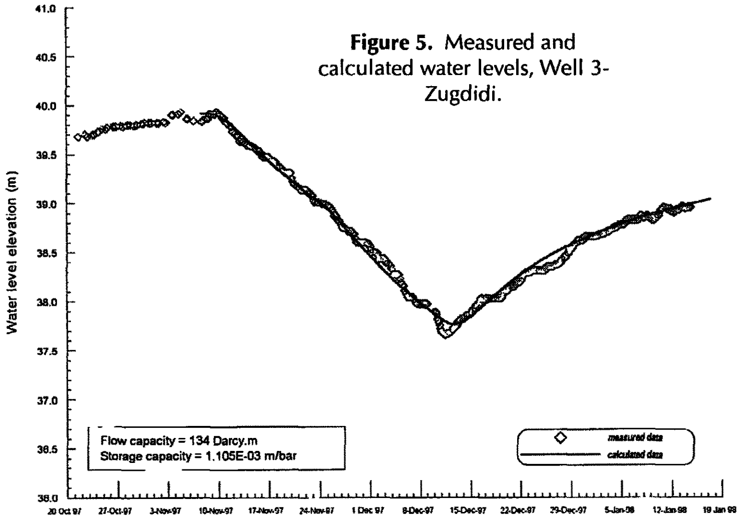

Figure 5. Measured and calculated water levels, Well 3-Zugdidi.

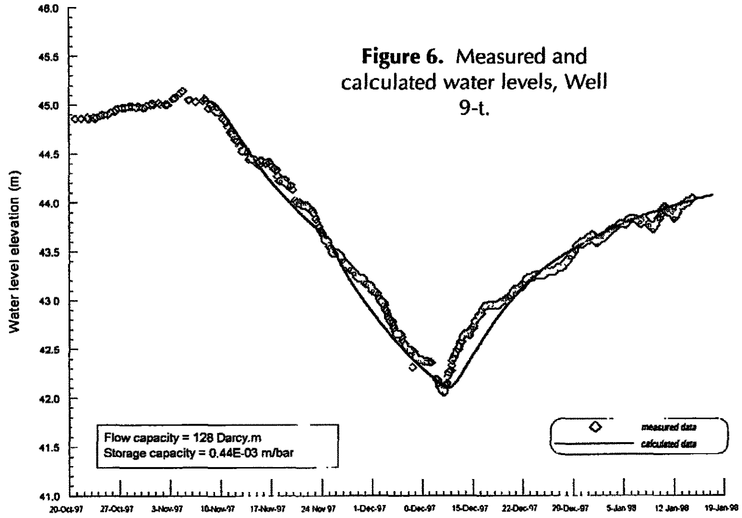

Figure 6. Measured and calculated water levels, Well 9-t.

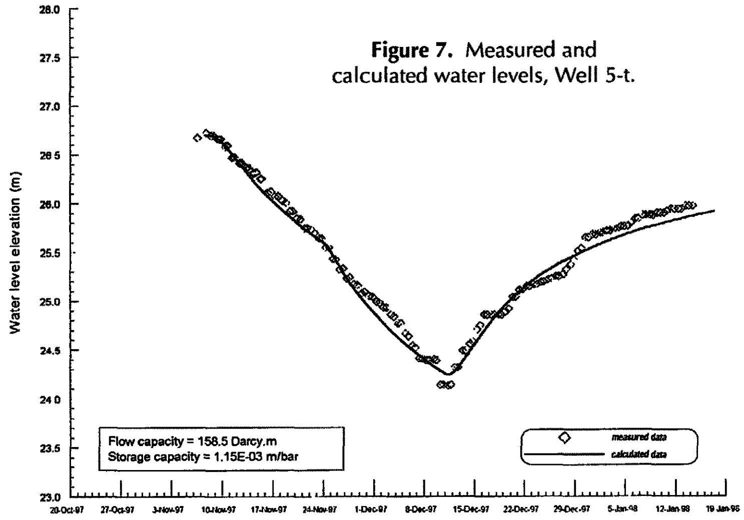

Figure 7. Measured and calculated water levels, Well 5-t.

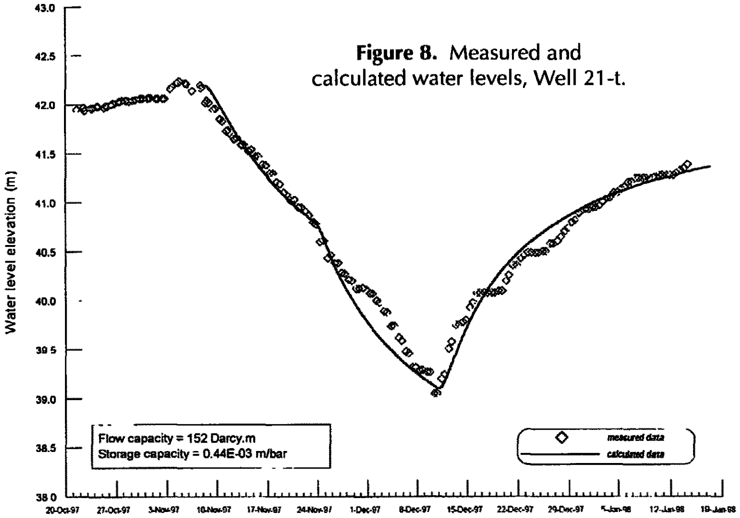

Figure 8. Measured and calculated water levels, Well 21-t.

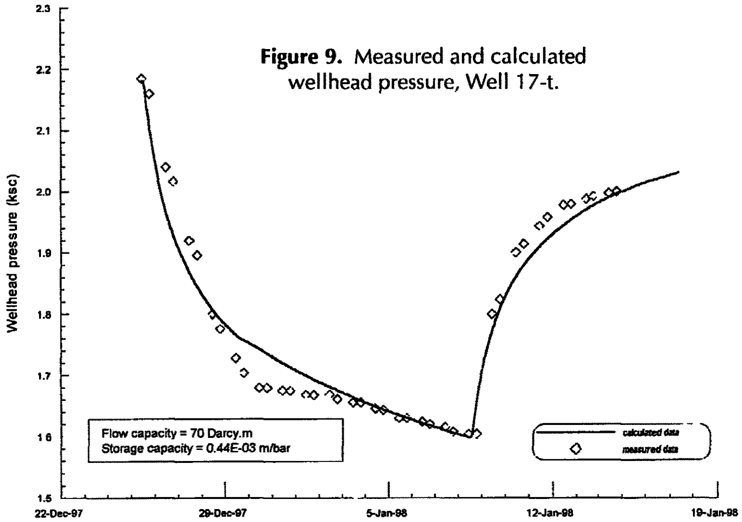

Figure 9. Measured and calculated wellhead pressure, Well 17-t.

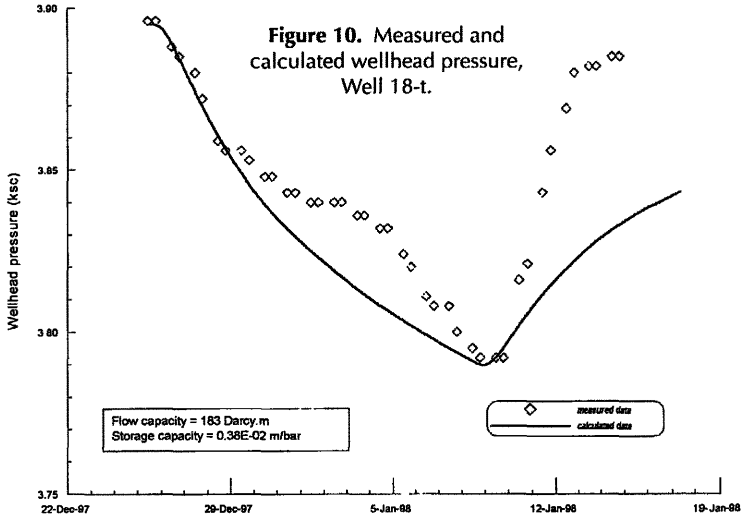

Figure 10. Measured and calculated wellhead pressure, Well 18-t.