Proceedings Ninth Workshop Geothermal Reservoir Engineering
Stanford University, Stanford, California, December 1983
SGP-TR-74

MODELING STUDIES OF GEOTHERMAL SYSTEMS WITH A FREE WATER SURFACE

Gudmundur S. Bodvarsson and Karst(
Earth Sciences Division
Lawrence Berkeley Laborator
University of California
Berkeley, California 9472

Introduction

Numerical simulators developed for geothermal reservoir engineering applications generally only consider systems which are saturated with liquid water and/or steam. However, most geothermal fields are in hydraulic communication with shallow ground water aquifers having free surface (water level), so that production or injection operations will cause movement of the surface, and of the air in the pore spaces above the water level. In some geothermal fields the water level is located hundreds of meters below the surface (e.g. Olkaria, Kenya; Bjornsson, 1978), so that an extensive unsaturated zone is present. In others the caprock may be very leaky or nonexistent [e.g., Klamath Falls, Oregon (Sammel, 1976); Cerro Prieto, Mexico; (Grant et al., 1984] in which case there is good hydraulic communication between the geothermal reservoir and the shallow unconfined aquifers. Thus, there is a need to explore the effect of shallow free-surface aquifers on reservoir behavior during production or injection operations.

In a free-surface aquifer the water table moves depending upon the rate of recharge or discharge. This results in a high overall storativity; typically two orders of magnitude higher than that of compressed liquid systems, but one or two orders of magnitude lower than that for liquid-steam reservoirs. As a consequence, various data analysis methods developed for compressed liquid aquifers (such as conventional well test analysis methods) are not applicable to aquifer with a free surface (Bodvarsson and Zais, 1982).

We have developed a numerical simulator for the modeling of air-steam-water systems. In this paper we apply the simulator to various problems involving injection into or production from a geothermal reservoir in hydraulic communication with a shallow free-surface aquifer. First, we consider a one-dimensional column problem and study the water level movement during exploitation using different capillary pressure functions. Second, a two-dimensional radial model is used to study and compare reservoir depletion for cases with and without a free-surface aquifer. Finally, the contamination of a shallow free-surface aquifer due to cold water injection is investigated. The primary aim of these studies is to obtain an understanding of the response of a reservoir in hydraulic communication with a unconfined aquifer during exploitation or injection and to determine under which circumstances conventional modeling techniques (fully saturated systems) can be applied to such systems.

Methodology

In our modeling studies we employ a numerical simulator called "TOUGH" (= transport of unsaturated groundwater and heat; Pruess, 1983), which treats the two-phase flow of water and air in liquid and gaseous phases together with heat flow in a fully coupled way. The governing equations account for Darcy flow with relative permeability and capillary pressure effects. Gaseous diffusion can be handled also, but this has been omitted in the calculations presented here. The energy balance includes the latent heat effects of vaporization and condensation, along with conductive and convective heat flow. Water, air, and rock are assumed to be in local thermodynamic equilibrium at all times. The flow domain can include liquid, gaseous, and two-phase regions. The thermophysical properties of water substance are accurately represented by the steam table equations as given by the International Formulation Committee (1967). Air is approximated as an ideal gas, and additivity of partial pressures is assumed for air-vapor mixtures. The (small) solubility of air in liquid water is represented by Henry's law.

Production From A Vertical Column

The first problem considered is a vertical column with a main reservoir, caprock, shallow unconfined aquifer and an unsaturated zone. The grid used and the permeabilities assigned to different zones are shown in Figure 1. The water table is located at a depth of 200 m; below that there is a shallow aquifer. The aquifer is separated by a 200 m thick caprock from a 600 m thick geothermal reservoir. Atmospheric conditions are maintained at the ground surface (P = 1bar, T = 10°C). Other parameters that do not vary spatially are given in Table 1.

The capillary pressure function used and the relative permeabilities are shown in Figure 2. In general, capillary pressure functions depend greatly on the pore size distribution of the rocks, with larger capillary pressure for smaller pore size. As Figure 2 shows, we assume a maximum capillary pressure of 15 bars, which was chosen rather arbitrarily, but may be reasonable for the small pores typically found in volcanic rocks. The relative permeability functions used are linear with 30% irreducible liquid saturation and 5% irreducible gas saturation. We have found that these functions are compatible with field data from the Krafla geothermal field, Iceland (Pruess et al., 1983).

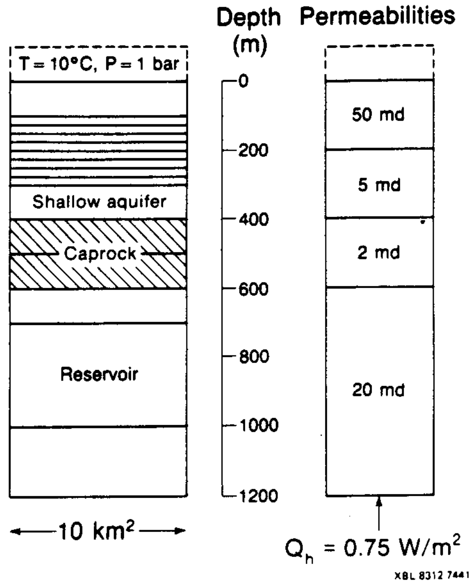

Figure 1. Schematic diagram of 1-D vertical column model.

Table 1. Specifications for column problems. Parameters that do not vary spatially.

Porosity	:	10%
Rock grain density	:	2650 kg/m^3
Rock specific heat	:	1000 J/kg
Heat conductivity	:	2.0 W/m·°C
Rock compressibility	:	0 pa^{-1}

Before exploitation, stable initial conditions were obtained for a constant heat flux of 0.75 W/m^2 (Fig. 3). Two cases were considered; one where the capillary effects were neglected (solid lines), and the second one where the capillary function shown in Figure 2 was used. Figure 3 shows that capillary effects tend to reduce sharp saturation gradients and expand the two-phase zone. On the other hand, when capillary effects are neglected, the gas saturation tends to stabilize at the irreducible liquid saturation (S_ℓ = 0.7 for our relative permeability curves). Because of the expanded unsaturated zone with pressure close to 1 bar, the case with capillary effects always has slightly lower pressure. The temperature profile (identical for both cases) shows the two possible heat transfer mechanism for this problem. In the upper part of the system the heat is transported mainly by conduction, resulting in a linear temperature profile with a large gradient. The main reservoir beneath the caprock is in two-phase conditions, and the heat is transported mainly by counter flow of steam and water with a smaller temperature gradient.

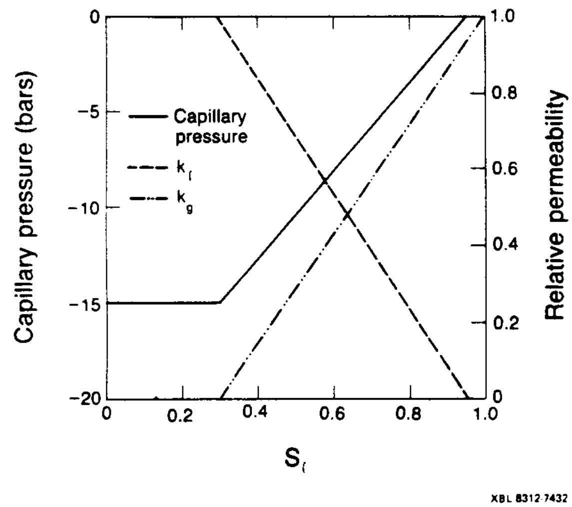

Figure 2. Capillary pressure and relative permeability functions used in the study.

During exploitation 500 kg/s of fluids were produced from the reservoir (approximately equivalent to 50 MW$_e$). The resulting pressure and gas saturation profiles at selected times are shown in Figures 4 and 5. The figures show that during exploitation the water level declines and steam saturation increases in the reservoir. In the case where capillary pressure is neglected this causes a distinct minimum in the gas saturation in the caprock. When capillary pressure effects are included the gas saturation in the caprock is much higher as they tend to diminish saturation differences. Near the bottom of the reservoir the capillary pressure effects tend to hold onto the liquid, resulting in lower gas saturations at late times (30 years). However, vapor static conditions develop in the reservoir at late times (Fig. 4).

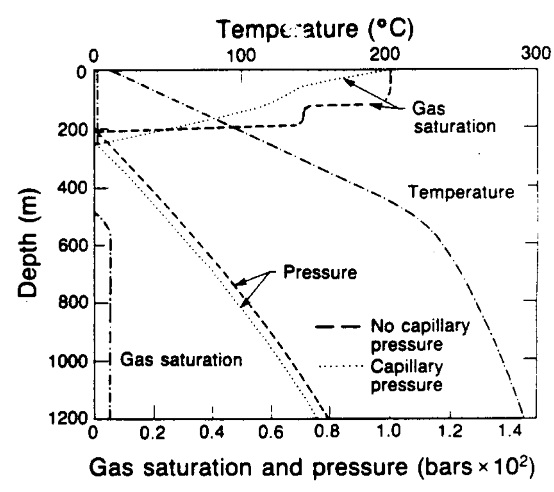

Figure 3. Initial thermodynamic conditions for the column problem.

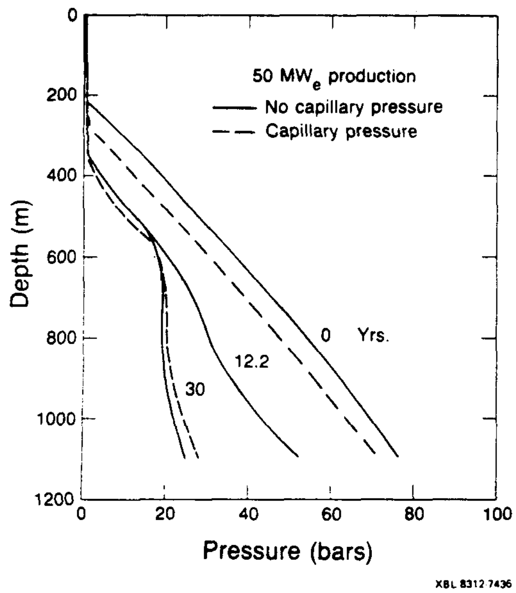

Figure 4. Pressure profiles at various times during expolitation.

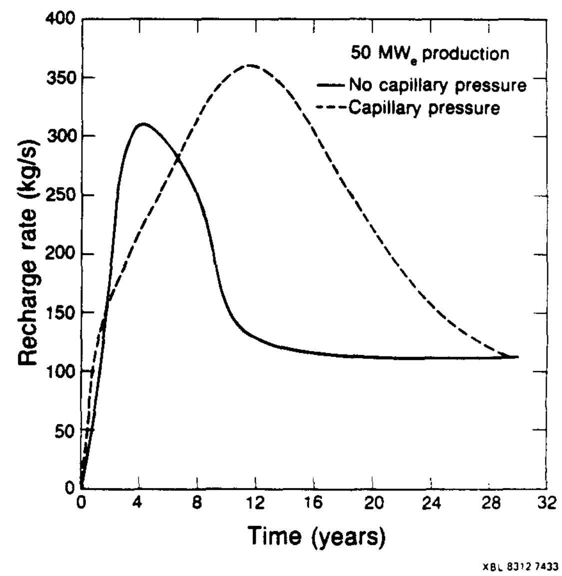

Figure 6. The recharge rate into the reservoir versus time.

Figure 6 shows the total fluid recharge from the shallow free surface aquifer to the reservoir for the two cases (with and without capillary pressure effects). Both cases show a rapid rise in the recharge rate reflecting pressure decline in the reservoir, but the maximum recharge rate occurs later when capillary effects are included. The reason for this is that capillary effects tend to slow the release of water in place in the caprock and the shallow aquifer. The decline of the recharge rate at later times occurs due to the lowering of the water table and increasing gas saturation in the shallow zones.

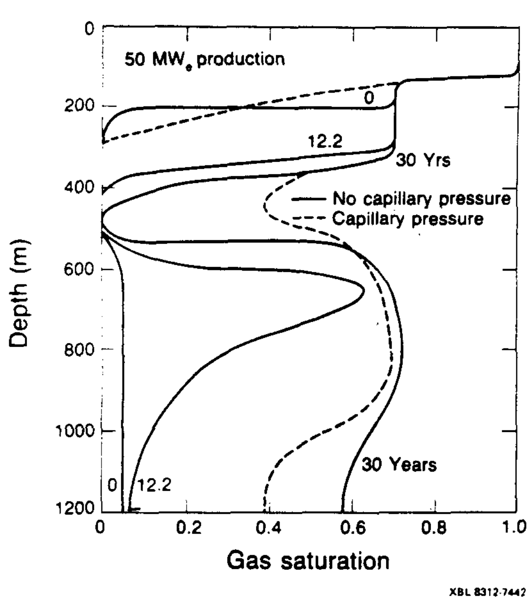

Figure 5. Gas saturation profiles at various times during exploitation.

Production From A Two-Dimensional Radial Model

The primary objective of this section and that immediately following is to examine to what extent conventional modeling techniques for single-component water systems can be applied to problems involving shallow unconfined aquifers. The approach employed is to simulate the same problem using the air-water formulation as well as using fully saturated (steam-water) approximations. Any differences that arise are then due to the approximations employed at the free-surface boundary.

The first problem selected is a two-dimensional radial problem using the same vertical space discretization employed in the column model (Fig. 7). In the radial direction we use a coarse grid consisting of 6 elements which extend to 10 km. The formation parameters and the initial conditions are also identical to those used in the column model. A fixed extraction rate of 1500 kg/s (~ 150 MW$_e$) is prescribed for the element labeled "P" in Figure 7. The enthalpy of the produced fluids from that node is determined from the mobilities of the individual phases. In this study we neglect capillary pressure effects.

In modeling the problem as a confined system, the unsaturated zone above the shallow aquifer (the top 200 m) is neglected. Thus, the top 5 layers in the grid (Fig. 7) as well as the boundary nodes at the top (for constant temperature and pressure) are deleted. However, in order to maintain stable initial conditions, heat sinks of appropriate strength corresponding to 0.75 W/m^2 are placed in the elements in the top row (top layer of the aquifer). In this manner, identical initial conditions can be used for both the unsaturated and the confined aquifer problem and the results should be directly comparable.

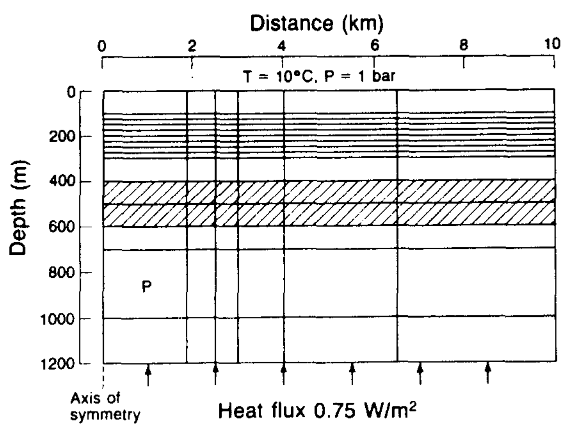

Figure 7. Mesh used in the 2-D radial production problems. "P" denotes the production node.

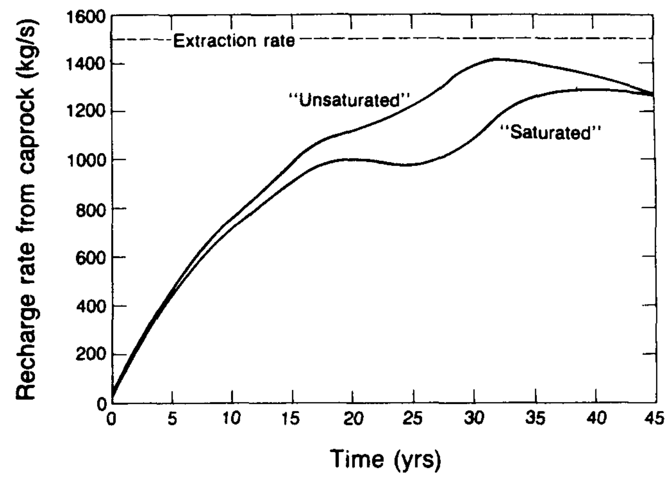

Figure 9. Total recharge rate into the reservoir from the shallow aquifer during exploitation.

The results for the pressure and vapor saturation in the production node versus time are shown in Figure 8; Figure 9 shows the total recharge rate from the caprock into the reservoir versus time. Figure 8 shows that at early times the effects of exploitation on the pressure decline and boiling at the production node are identical for the two cases. The recharge rates for both cases increase rapidly, partly because of the pressure decline in the reservoir and partly because of pressure rise in the shallow aquifer due to upflow of steam and condensation (Bodvarsson et al., 1982). Later on, the pressure decline in the "unsaturated" case is slower than in the "compressed liquid" case, because of greater recharge from the free-surface aquifer (Fig. 9). The high storage coefficient of the free-surface aquifer allows more rapid recharge to the reservoir without a large decline in the water table. The recharge rate for the "compressed liquid" reaches a stable level after about 20 years, due to the low compressibility, but then increases sharply after approximately 25 years when two phase conditions evolve at the top of the shallow aquifer. At intermediate times the recharge rate for the "unsaturated" case is 20-25% higher than that for the "compressed liquid" case, causing larger

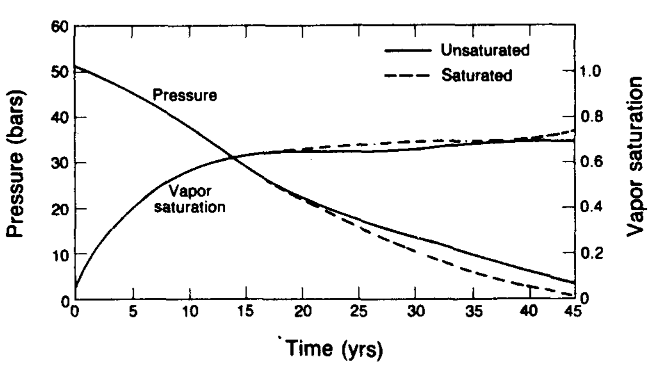

Figure 8. Pressure and gas saturation at the production mode.

pressure declines and vapor saturation buildup in the production node for the latter case. At late times the recharge rates become very similar as rather uniform depletion of the entire system occurs.

In general the system behavior is very similar for both cases, mainly because a two-phase zone evolves at the top of the aquifer in the "compressed liquid" case. This two-phase zone has a high compressibility and thus behaves very similarly to a free surface boundary condition. However, in cases where the recharge from above is a serious problem, due to cooling of the reservoir, it may be necessary to accurately model the recharge by proper treatment of the free surface.

We have also considered cases where the caprock is non-existent and thus the entire resevoir is unconfined. In these cases we have considered low temperature reservoirs of rather high permeability so that boiling due to exploitation would not occur. One would expect a-priori that for such systems the upper boundary condition at the free surface would dominate the reservoir response, so that models that do not include the air component would give inaccurate results. However, the results from our preliminary studies indicate that this is not the case. For the "compressed liquid" models the initial pressure decline will be unrealistically large, but then a two-phase zone will develop at the top of the shallow aquifer with pressure corresponding to the saturation pressure at the prevailing temperature. Subsequently the two-phase zone will advance downward in the same manner as the unsaturated zone in the air-water model. In the air-water model the pressure in the unsaturated zone will be close to 1 bar whereas for the "compressed liquid" model the two-phase zone will typically have a pressure of 0.2 - 0.5 bars. However, this slight difference will not have a significant effect on the overall reservoir depletion, and thus for most practical purposes we feel that single-component water-steam models are adequate for the modeling of the exploitation of reservoirs with hydraulic connections to shallow free surface aquifers.

Injection into a Reservoir with a Fault Connection to a Shallow Aquifer

The example considered in this section illustrates effects of reinjection into a liquid-dominated geothermal reservoir which is hydraulically connected to a shallow unconfined aquifer by means of a vertical fault. Of particular interest in this type of problem is the migration of reservoir water into the shallow aquifer as a consequence of reinjection, which may create environmental hazards.

The injection configuration and the overall geometry of the flow system are shown in Figures 10 and 11. The injectors are placed in a "line drive" pattern at 100 m spacing. At a distance of 126 m from the injection line there is a vertical fault. The line connecting the injection wells is an approximate line of symmetry, because problem parameters were chosen in such a way (see Table 2) that the rate of flow up the fault is negligibly small compared to lateral flow in the reservoir (less than 5%). We model one symmetry element, which is a vertical slice with a thickness of 100 m. This is shown in the vertical cross section in Figure 2. The reservoir is represented by five grid layers of 100 m thickness each. The injection rate into each grid layer is constant at 10 kg/s. Constant pressure boundary conditions, corresponding to the initial gravity-equilibrated pressure distribution, are assumed at the left and right boundaries of reservoir and aquifer. The lower boundary of the reservoir, and the boundaries of the caprock, are assumed "no flow". Boundary conditions of $p = 1$ bar, $T = 20°C$ are maintained at the ground surface. Detailed problem parameters are given in Table 2.

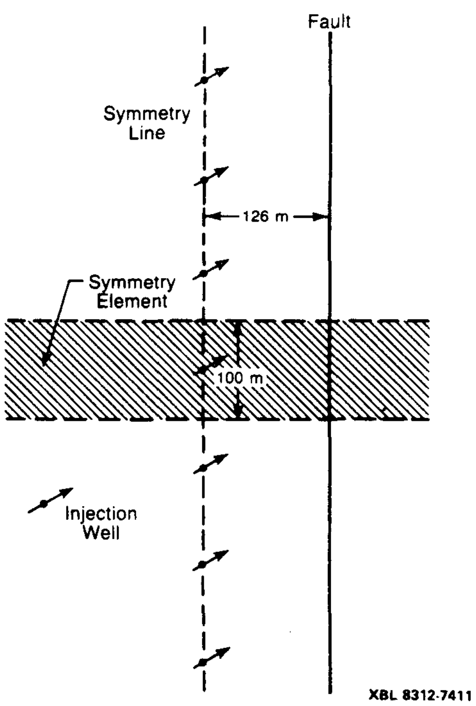

Figure 10. Schematic diagram of the injection well configuration and the leaky fault.

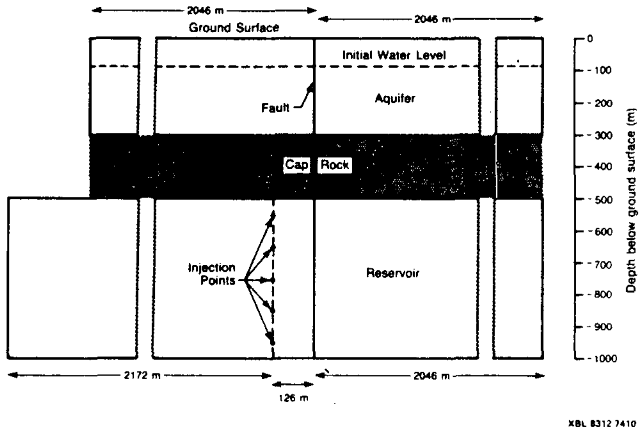

Figure 11. A vertical cross section of the interconnection between the shallow aquifer and the reservoir.

In response to injection, pressures in the reservoir increase, causing some upflow of water in the fault zone. The water levels in the fault zone and the shallow aquifer rise above their initial depth of -90 m. Figure 12 shows the water levels at various times as a function of the distance from the fault. For comparison we have also carried out a simulation using a fully saturated system, i.e., placing the upper boundary of the system at the initial water level of -90 m. (This corresponds to treating the aquifer as fully confined.) Figure 13 shows velocities of water migration up the fault for the two cases. The velocities differ by as much as 50%. Non-reactive solids dissolved in the reservoir water will begin to reach the shallow aquifer approximately 25 days after injection is started. In the confined case, pressures near the top of the aquifer rise to approximately 9.5 bars, whereas pressures remain near 1 bar at the free-water surface in the unconfined case. Pressures and temperatures in the reservoir differ by no more than 1-2% between the two cases. Thus an explicit treatment of the free surface is not necessary if only predictions of reservoir behavior are desired. However, reliable predictions of effects of injection on the shallow aquifer are only possible when a two-component water-air approach is used.

Table 2. Parameters for injection problem.

	Aquifer	Fault	Reservoir
Formation parameters			
Permeability $(m)^2$	100×10^{-15}	400×10^{-15}	50×10^{-15}
Porosity (%)	20	20	10
Initial conditions			
Initial Temperature (°C)	20	20/250	250
Initial Pressure (bars)	gravity equilibrium, with 1 bar at ground surface		
Initial Water Level (m)	-90	-90	
Injection			
Total Rate (kg/s)			50
Enthalpy (kJ/kg)			419
Width of fault (m)		1.0	

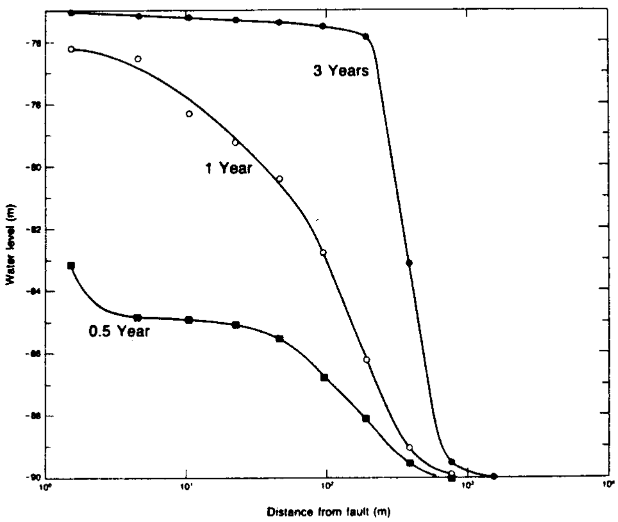

Figure 12. The rise of the water level in the shallow aquifer versus time during injection.

Summary and Conclusions

In this paper we solve some reservoir problems involving an unconfined shallow aquifer. The main purpose of these simulations is twofold:

(i) To obtain some understanding of the interaction between geothermal reservoirs and shallow unconfined aquifers and the effects of capillary pressure for such problems.

(ii) To study to what extent conventional geothermal simulators for fully saturated media can be applied to problems involving free-surface aquifers.

The results obtained indicate that capillary pressure effects tend to enlarge the two-phase zone and smooth out large gas saturation gradients within the zone. The free-surface aquifer provides recharge to the main geothermal reservoir, and if a rigorous air-water simulator is not used, the recharge rate may be underestimated. This can have serious implications especially in cases where the caprock is very leaky and problems with reservoir cooling due to recharge of cooler fluids from above are evident. However, for most reservoir problems our results show that the use of conventional single-component geothermal simulators for the modeling of the interaction of shallow unconfined aquifers with the reservoir during expolitation gives reasonable results. This is especially true in cases where boiling occurs in the reservoir or in the shallow aquifer as a result of exploition, because in these cases the reservoir response is dominated by the two-phase zone. On the other hand, our results indicate that for an assessment of possible contamination of shallow unconfined aquifers during injection, one must use a rigorous air-water model for a detailed analysis. In these cases, the discharge rate to the shallow aquifer and its pressure distribution during injection cannot be accurately calculated with a model for a saturated medium. As the discharge rate to the shallow aquifer is the most important parameter for contamination studies it appears that air-water models are necessary for such problems.

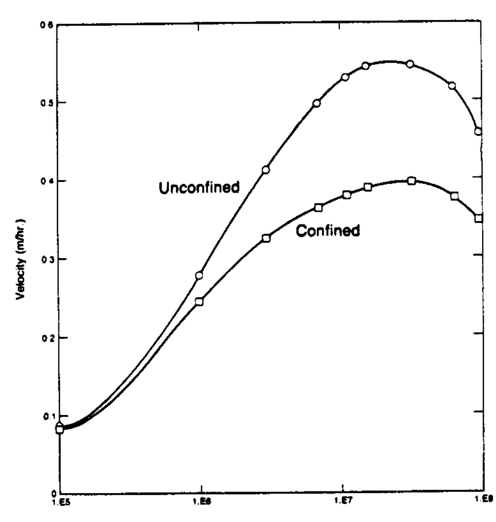

Figure 13. The velocity of the fluid migration up the fault as a function of time.

Acknowledgment

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Division of Geothermal Energy and Hydropower Technologies of the U.S. Department of Energy under Contract NO. DE-AC-3-76SF00098.

References

Bjornsson, S., 1978, "Estimation of the reservoir potential of the Olkaria geothermal field in Kenya", Nordic Symposium on Geothermal Energy, Goteborg, Sweden.

Bodvarsson, G., and Zais, E.J., 1982, Geothermal reservoir testing by piezometric surface drawdown/buildup", SPE-11142, paper presented at the 57th Annual meeting of the Society Of Petroleum Engineers, New Orleans. Sept. 26-29, 1982.

Bodvarsson, G.S., Pruess, K., Lippmann, M.J. and Bjornsson,S., 1982, "Improved Energy recovery from geothermal reservoirs". J Petro. Techn. Vol 34, No.9 p. 1920-1928.

Grant, M.A., Truesdell, A.H. and Manion, M.A., 1984, "Production induced boiling and cold water entry in the Cerro Prieto geothermal reservoir indicated by chemical and physical measurements", Geothermics, Vol.13, pp.117-140.

International Formulation Committee, 1967, "A formulation of the thermodynamic properties of ordinary water substance", IFC Secretariat, Dusseldorf, Germany.

Pruess, K., 1983 "Tough - a numerical model for strongly heat driven flow in partially saturated media". Annual report of the Earth Sciences Division, Lawrence Berkeley Laboratory, in preperation.

Pruess, K., Bodvarsson, G.S., Stefansson, V, and Eliasson, E.T., 1983, "The Krafla geothermal field. 4. Well performance and reservoir depletion", paper submitted to Water Resources Research.

Sammel, E.A, 1976 " Hydrologic reconnaissance of the geothermal area near Klamath Falls, Oregon", report WRI-76-127, U.S. Geological Survey Menlo Park, California, 129pp.