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A THEORETICAL STUDY OF THE EFFECT OF BORE DIAMETER ON WELL OUTPUTS

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INTRODUCTION

When a reservoir is sufficiently permeable, it is able to supply fluid at a greater rate than that which the well is able to deliver to the surface. Under such conditions, reservoir pressure drawdown is usually insignificant and variations in wellhead pressure during discharge are associated with changes in the wellbore frictional pressure drop. This phenomenon is commonly termed "wellbore controlled flow" as it occurs when friction effects in the wellbore are substantial in relation to the available pressure drop from the reservoir to the wellhead and in relation to reservoir pressure drawdown.

Apart from reservoir permeability and its effect on pressure drawdown, the other factor that influences wellbore controlled flow is the static reservoir pressure. When well inflow pressures are low the effects of friction in the wellbore are comparatively more restrictive as the fictional pressure drop becomes significant with respect to the overall pressure difference from the reservoir to the wellhead.

It follows that when wellbore controlled flow occurs, increasing the wellbore diameter should greatly improve well output characteristics.

This study is aimed at assessing the effects of wellbore diameter on the output of wells in the Eburru Geothermal Field, Kenya. Measured well dimensions and estimated reservoir parameters at Eburru Well One (EW-01) were used to assess the improvement in well output expected from large diameter wells. The calculations were repeated for several assumed values of reservoir permeability-thickness product in order to investigate its importance in controlling well output improvement.

EW-01

The drilling of EW-01 was completed in March 1989 to a maximum depth of 2468 m. The casing programme is typical for a geothermal well and includes a $9^5/_8$ inch diameter production casing extending from the surface to 1202 m depth and a 7 inch diameter slotted liner from 1202 m to well bottom.

When shut in a water level forms at about 700 m below the surface indicating that reservoir pressure is low in relation to its depth (ie. about 70 bars underpressured in comparison to a normally pressured reservoir).

A Pressure Falloff Test conducted soon after completion indicated a permeability-thickness product (kh) of approximately 2 Darcy metres with a negative skin factor ($S \approx -3$). Downhole measurements suggest the well's major feed zone is centred at about 2300 m depth where the reservoir contains liquid water at about 260°C (GENZL/KPC 1989).

PROCEDURE

In order to obtain realistic predictions of well output it is necessary to assess both the pressure drop, from feed zone to wellhead, and the changes in reservoir pressure in response to the extraction of fluid. In any case the downhole pressure in the well at its feed zone must match that in the reservoir at the sandface (at the same depth) which in turn must correspond to the pressure drawdown associated with the discharge. In order to satisfy these criteria, the basic procedure followed in this study was to calculate the expected reservoir pressure response to various levels of production for several different values of the reservoir permeability-thickness product (kh). These relationships were then used to provide the feed zone pressure input for wellbore simulations which predict wellhead conditions for the relevant discharge rate and well casings programme.

Simulations were duplicated for standard well casings (ie. 7 and $9^5/_8$ inch diameter slotted liner and casing) and for large diameters ($9^5/_8$ and $13^3/_8$ inch diameter slotted liner and casing).

Both the reservoir pressure response calculations and the wellbore simulation predictions were firstly verified by their matching and comparison to observed pressure drawdown and downhole pressure profiles measured in EW-01 during discharge. The verification process helped to refine estimates of kh and to demonstrate the level of accuracy of the wellbore simulation.

RESULTS AND DISCUSSION

Pressure Drawdown Prediction

Estimates of pressure drawdown at the well's sandface were made using a solution to the Diffusivity Equation which describes transient flow through a porous medium assuming that Darcy's Law is applicable. An approximation to this solution is shown as Equation 1.

$$\Delta P = \frac{Q\upsilon}{4\pi kh}\left[\ln\left(\frac{4kt}{\phi\mu c r^2}\right) - \gamma\right] \qquad (1)$$

where

ΔP = Pressure drawdown = $P_r - P_f$
P_r = Stable reservoir pressure
P_f = Pressure during discharge at time t and distance r from the well.
Q = Mass flow of fluid (assumed constant)
υ = Kinematic viscosity of reservoir fluids
k = Reservoir permeability
h = Reservoir thickness
ϕ = Reservoir porosity
μ = Dynamic viscosity of reservoir fluids
c = Compressibility
γ = 0.5772

Equation 1 was used to confirm estimates of kh for EW-01 by matching the pressure drawdown measured at three different flow rates (profiles shown in Figure 1, 2 and 3). Liquid water parameters (at T = 260°C) were used even though flashing in the formation was occurring during discharge. The justification for the use of liquid parameters (for viscosities and compressibility) is that the majority of fluid moving in the reservoir is liquid and that the two-phase zone is restricted to a small region around the well. Negligible skin effect was also assumed (ie. S = 0).

It was found that in order to correctly predict the feed zone pressures measured during discharge, it was necessary to use a value of 0.6 Darcy metres for the permeability-thickness product. This value is significantly less than that calculated from the Pressure Falloff Test (ie 2.5 Darcy m). Such a large discrepancy can be attributed to the fact that during cold water injection associated with the Pressure Falloff Test, thermal contraction and cracking of reservoir rocks may have led to a temporary, localised increase in kh, a phenomenon often observed in geothermal well testing (Grant et al 1982).

It should also be noted that Equation 1 contains inherent inaccuracy associated with flow near the wellbore. Turbulence in the reservoir near the well is not taken into account in Equation 1 and is expected to add to the pressure drawdown particularly at high discharge rates.

The predicted feed zone pressures based on the reservoir pressure response are shown in Table 1 together with the corresponding measured values.

	Q = 22.6 kg/s	23.2 kg/s	25.5 kg/s
Measured	49.1 bara	41.4	35.2
kh = 2.5 Dm	109.0	108.6	106.8
kh = 0.6 Dm	48.4	46.6	40.0

Table 1: Measured and Predicted Feed Zone Pressures (2300m depth) for EW-01

Equation 1 was then used to predict the reservoir response to various levels of production assuming 7 different values of kh (ie. kh = 0.6, 1.0, 2.0, 3.0, 5.0, 10 and 20 Darcy m). A plot relating discharge rate to feed zone pressure after 30 days discharge was prepared for each kh value and is shown in Figure 4.

Assumptions used in the application of Equation 1 are:

flow in the reservoir is described by Darcy's Law,
constant mass flow, Q for 30 days (t),
no skin effect,
liquid water parameters at 260°C are applicable for fluid viscosities and compressibility,
reservoir thickness (h) is 100 m,
reservoir porosity (ϕ) is 0.10.

A further verification of the accuracy of Equation 1 by numerical reservoir simulations is detailed in the Appendix. This exercise demonstrates that Equation 1 provides pressure drawdown predictions in almost exact agreement with numerical reservoir simulations provided the reservoir is infinite acting. The size of reservoir needed to maintain this condition (ie. approximately 15km radius) suggests that in real life, boundary conditions will impact on pressure drawdown. The infinite acting reservoir assumption is therefore probably not valid. However, the absence of information on the nature and location of reservoir boundaries at Eburru precludes a more rigorous pressure drawdown solution.

Wellbore Simulation

A wellbore simulation programme based on the Hagedorn and Brown Method (Hagedorn and Brown, 1965) was used to calculate pressures in the discharging well.

EW-01 was tested on discharge from May to July 1989. Three downhole pressure profiles were measured during discharge at three different flow rates. The wellbore simulator was used to match the flowing pressure profiles to confirm its reliability. Figures 1, 2 and 3 show the three measured profiles together with the simulated predictions. While the simulated profiles do not exactly match those measured over the entire depth of the well, the correspondence is reasonable at the perceived feed depth (2300m). Inaccuracies in the simulation may be attributed to the existence of more than one feed zone contributing to the flow.

A series of output curves was produced using the simulator to predict wellhead pressures given the relevant kh values, flows and the corresponding feed zone pressures taken from Figure 4. Output curves for each value of kh were produced using both the standard and large diameter ($13^3/_8$ inch diameter production casing and $9^5/_8$ diameter slotted liner) casings. Seven pairs of output curves were produced and are shown in Figures 5 to 11.

Outputs from large and standard diameter wells were compared by plotting the ratio Q_l/Q_s against kh for a typical operating wellhead pressure of 10 bara. Where Q_l and Q_s are the mass discharge rates predicted for wells with large and standard diameter casings, respectively (at a wellhead pressure of 10 bara). This plot is presented in Figure 12.

It can be seen that the increase in well output associated with large diameter casings is strongly dependent on the reservoir permeability-thickness product. At low values of kh the increase in well output is not substantial. For example when kh = 1.0 Darcy m a large diameter well will produce about 30% more fluid than a standard well operating at a wellhead pressure of 10 bara. Figure 12 shows that as the reservoir kh increases above 1 Darcy m the improvement in well output increases dramatically. At 5 Darcy m, the improvement is about 90% and at 20 Darcy m the large diameter well will produce about 120% more than the standard well. For the case of EW-01 with an estimated kh of only about 0.6 Darcy m, the expected improvement is only about 15% and would probably not justify the added expense of drilling a large diameter well.

The results of this study as presented in Figure 12 in theory, only apply to the feed zone depth, reservoir pressure and fluid enthalpy observed in Well EW-01. However, as fluid enthalpy and reservoir pressure are not expected to vary substantially throughout the field, the principal conclusions of this study should apply to other deep wells drilled at Eburru.

In order to determine whether the drilling of large diameter wells at Eburru is justifiable it will be necessary to determine the likely added expense associated with the drilling and completion of a larger diameter well and then compare with the expected improvement in well output predicted in this study.

CONCLUSIONS

The effect of increasing wellbore diameter on the discharge performance of a well at Eburru appears to be strongly related to reservoir permeability. As the kh increases the improvement in productivity also increases. For the feed zone depth, fluid enthalpy and reservoir pressure encountered in EW-01, kh greater than 2 Darcy m is required to improve productivity by more than 60%. For a kh less than 1 Darcy m, the expected improvement is not substantial (less than 30% improved productivity).

The discharge characteristics exhibited by EW-01 suggest that the Pressure Falloff Test provided an erroneously high estimate of kh. A value of 0.6 Darcy metres is considered indicative of the reservoir performance under discharge conditions.

The study has also shown that for the conditions encountered in Well EW-01 a simple approximate solution to the Diffusivity Equation can be used with reasonable confidence to predict well pressure drawdown during discharge.

ACKNOWLEDGMENTS

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The wellbore simulator used in this study was supplied by Prof. D. Freeston of the Geothermal Institute, University of Auckland and was adapted for use on personal computers by Mr P Ouma of KPC.

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Hagedorn and Brown (1965): Experimental Study of Pressure Gradients Occurring During Continuous Two-Phase flow in Small Diameter Vertical Conduits. Journal Petroleum Technology April, pp 475 - 484.

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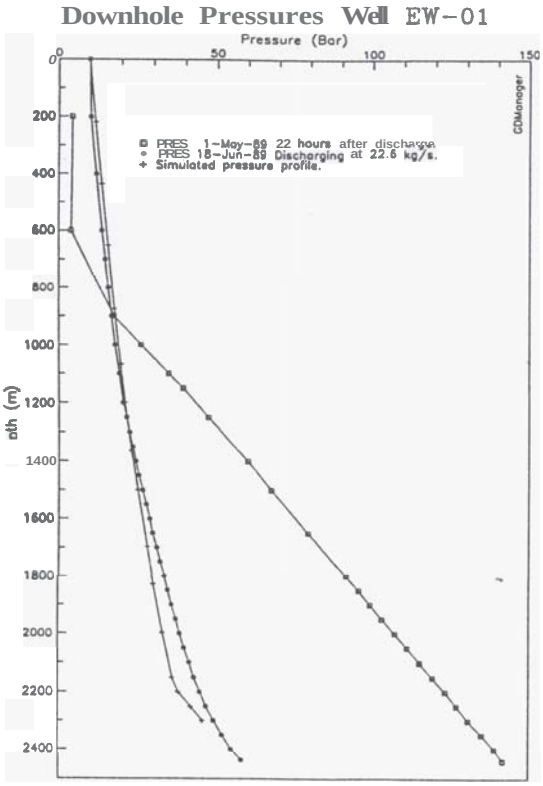


Figure 1

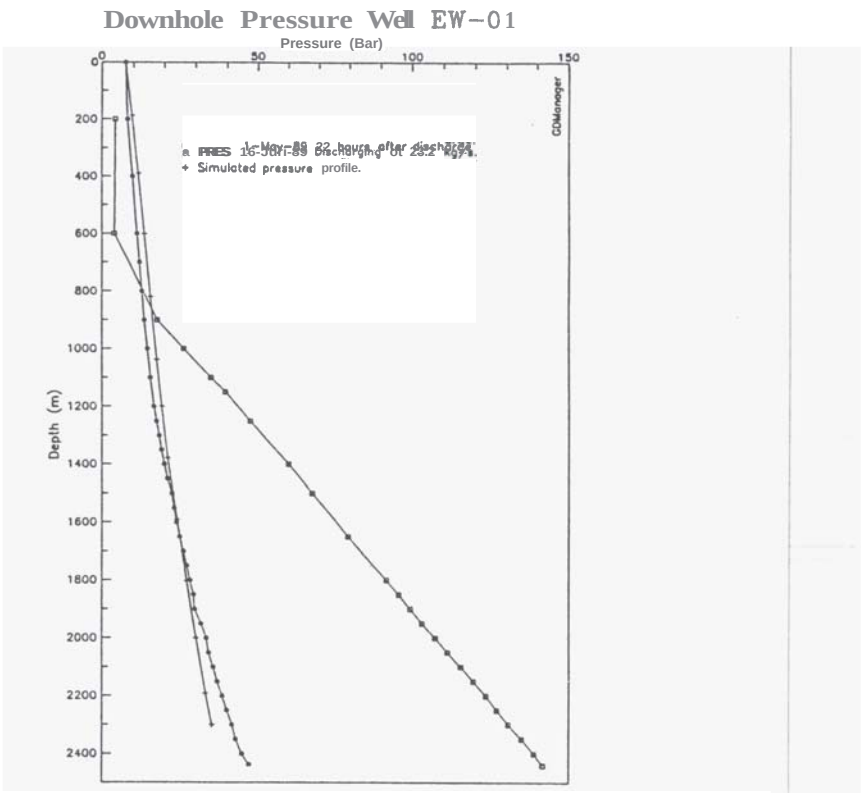


Figure 2

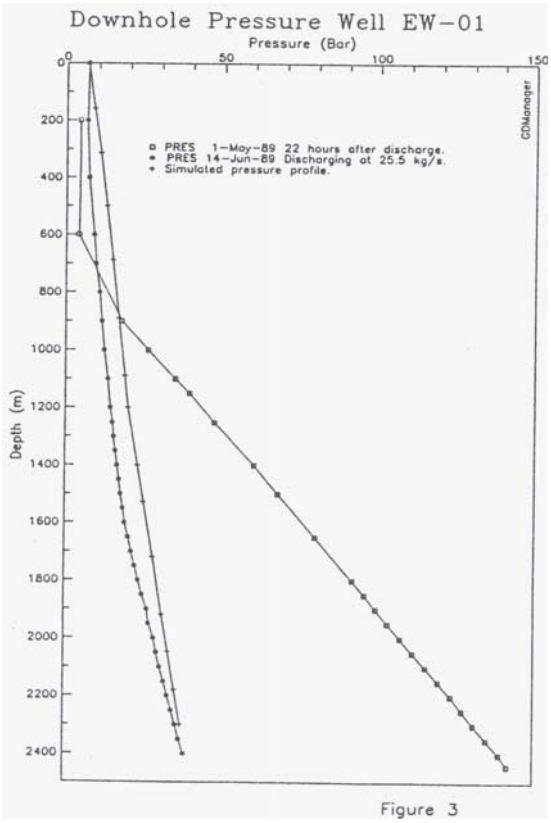


Figure 3

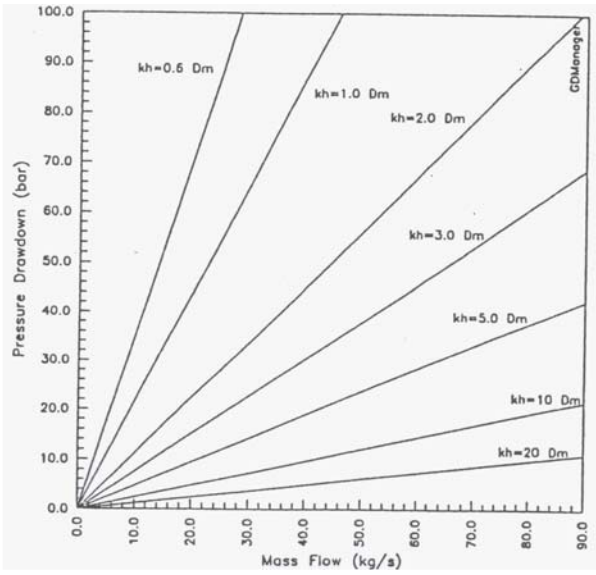


Figure 4

EW–01 Well Output Characteristics
kh = 0.6 Darcy metre

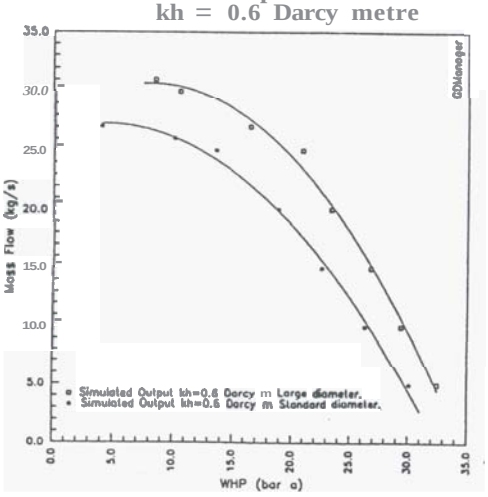


Figure 5

EW–01 Well Output Characteristics
kh = 1.0 Darcy metres

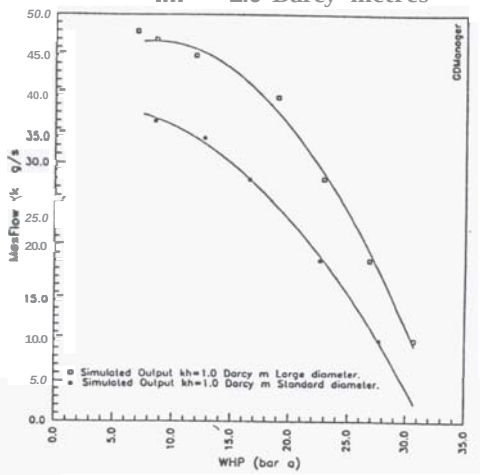


Figure 6

EW–01 Well Output Characteristics
kh = 2 Darcy metres

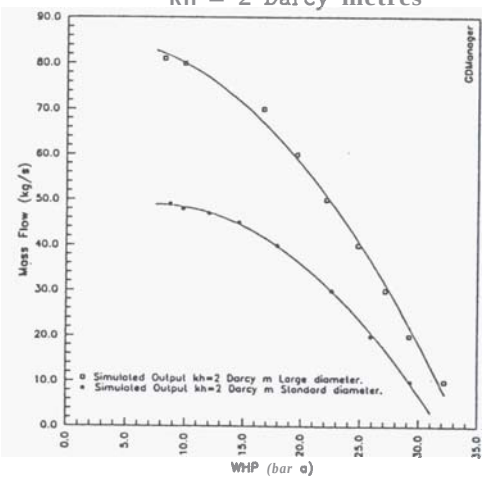


Figure 7

EW–01 Well Output Characteristics
kh = 3 Darcy metres

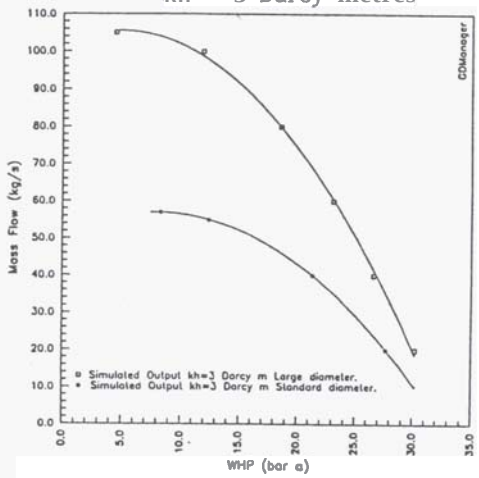


Figure 8

EW–01 Well Output Characteristics
kh = 5 Darcy metres

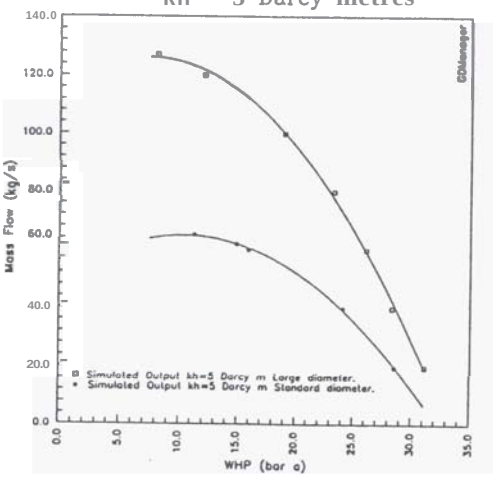


Figure 9

EW–01 Well Output Characteristics
kh = 10 Darcy metres

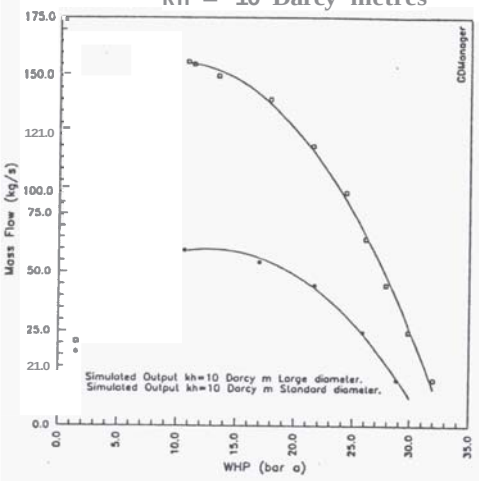


Figure 10

EW-01 Well Output Characteristics
kh = 20 Darcy metres

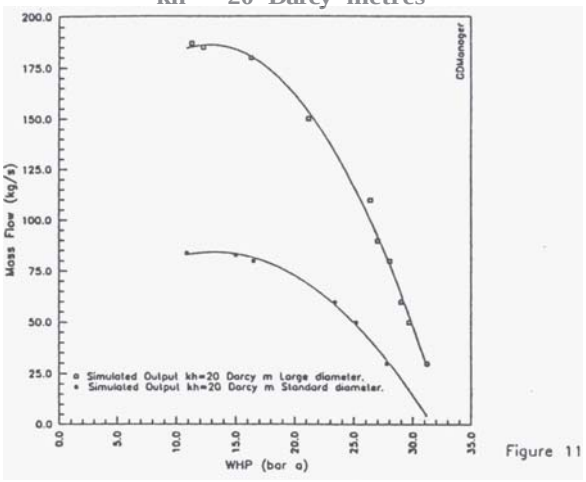


Figure 11

Well Output Comparison
Large and Standard Diameter Casings

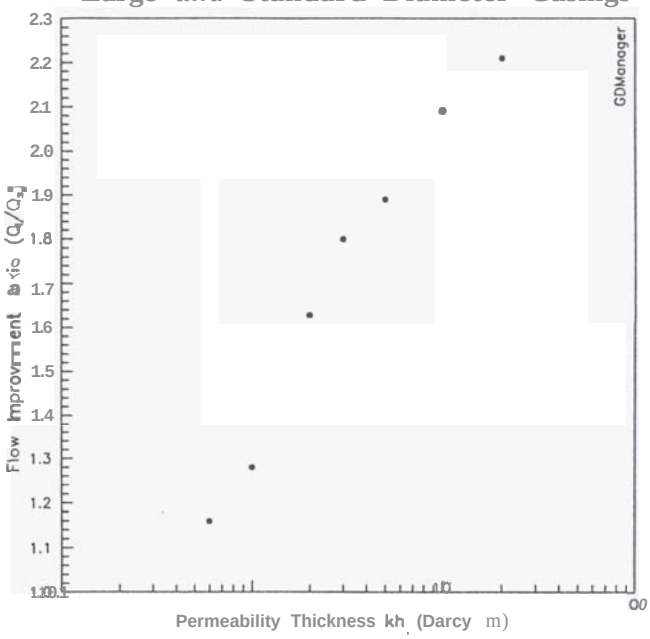


Figure 12

APPENDIX

The accuracy of Equation 1 was checked by comparing pressure drawdown predictions with those calculated by a numerical reservoir simulation package. A radial grid model, 100m thick and consisting of 54 concentric, annular blocks was used.

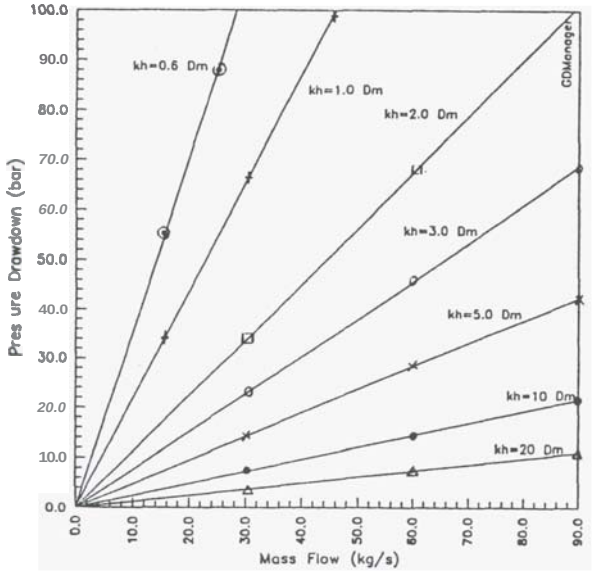
The model included a single, centrally located well and extended to a maximum radial distance of 15km. Initial runs using a smaller model with maximum radius of 7.4km was found to be too small to preserve the infinite acting reservoir assumption.

Simulations were run with constant well discharge rates for 30 days duration, and well pressures were indicated as those 0.1m from the centre of the grid. Three discharge rates for each value of kh were used in separate simulations. Results are shown in Figure 13 together with those predicted using Equation 1.

The agreement between Equation 1 and the reservoir simulations is excellent and suggests that the use of Equation 1 to predict pressure drawdown in this case is justified.

Simulations also demonstrated that in order to match the observed feed zone pressures (shown in Table 1) a value of kh of approximately 0.6 Darcy metres is required.

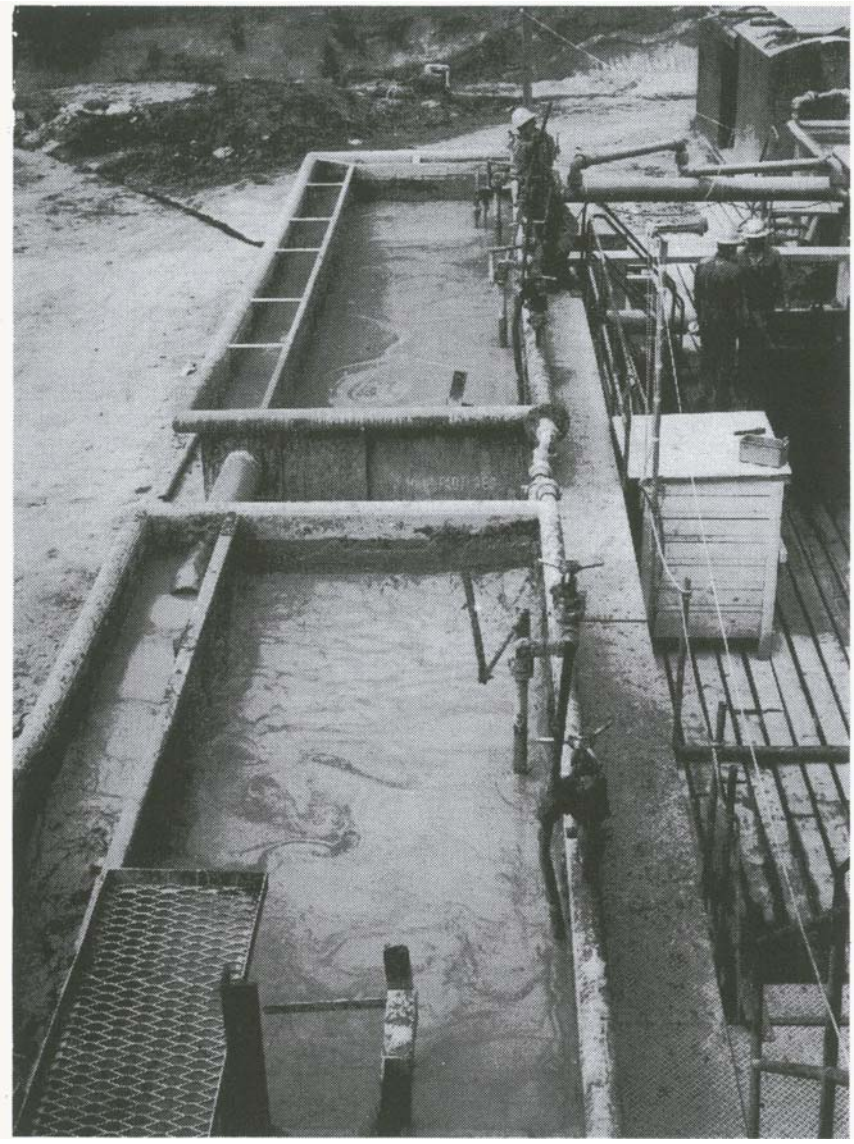
Figure 13. Pressure Drawdowns Calculated from Equation 1 Compared with Simulated Results



Pressure Drawdowns Calculated from Equation 1

Simulated Results

3 kh = 0.6 Darcy metres
+ kh = 1.0 Darcy metres
o kh = 2.0 Darcy metres
o kh = 3.0 Darcy metres
× kh = 5.0 Darcy metres
• kh = 10 Darcy metres
Δ kh = 20 Darcy metres



MUD TANKS FOR GC350 RIG. Photo: D. L. Homer, NZ Geological Survey.