

F-18

RESULTS OF AQUIFER TESTING
CONDUCTED ON PRODUCTION WELLS
AT CRATERS OF THE MOON
NATIONAL MONUMENT

prepared by

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SUMMARY AND RECOMMENDATIONS

Pumping tests were conducted on two water wells operated by the National Park Service at Craters of the Moon National Monument in October, 1992, in order to develop a preliminary model of the geology and hydraulic response of the aquifer to pumping stress. A step-drawdown test showed that the South Well's efficiency was in excess of 95%, indicating that its screen size and completion design were properly engineered and that it has no hydraulic limitations to withdrawing water from the aquifer.

The aquifer is comprised of poorly sorted alluvial sand and gravel mixed with volcanic cinders, and vertically bounded by low-permeability volcanic ash, silt and clay-rich sediments and bedrock. The aquifer is known to be laterally bounded by low-permeability or impermeable bedrock (undifferentiated Challis Volcanics), some 30-35 feet to the east of the water wells' intake zones. In addition, a possible subsurface recharge boundary in or near the mouth of Little Cottonwood Creek may significantly affect the wells' behavior.

A constant-discharge aquifer test conducted on the South Well was used to estimate the hydraulic characteristics of the aquifer. Transmissivity in the vicinity of the South Well was determined to be approximately 0.0015 ft²/sec (940 gpd/ft or 10 m²/day). However, because the wells are very close to each other and to the bedrock margin of the valley, this estimate may be low by up to a factor of 4.

A simple analytical model of the aquifer was developed and calibrated against water level responses observed during the 10/92 aquifer test, in order to examine the effects of the known bedrock boundary east of the production wells and an inferred recharge boundary to the north. These results indicate that long-term sustained pumpage from the production wells will not be possible unless a local recharge source exists. In other words, the identification and quantification of the putative recharge boundary may be the key to determining whether the wells are capable of providing sustained yields of 10 gallons/minute (gpm) or more, under long-term and/or continuous pumping scenarios.

Due to the low water levels prevailing at the time of these tests, a sustained pump discharge rate of only 9 gallons per minute (0.02 cfs) could be maintained for just 6 hours before excessive drawdown shut off the pump. Because of the complexity of this aquifer (the demonstrated importance of its hydrologic boundary conditions and the lack of detailed information about those boundaries that could be deduced from the aquifer test

before excessive drawdown forced its termination), a predictive model for well management cannot be developed with the limited amount of data presently available.

It is recommended that further well and aquifer tests be conducted, preferably after the aquifer's static water levels have rebounded somewhat from the prolonged drought of the past six years, so that a numerical model of the wells' responses can be constructed and calibrated against observed water level responses under different hydrologic conditions. Such a numerical model could then be used to develop a well management policy for both wet and dry years.

RECOMMENDATIONS FOR FUTURE WORK:

- 1) systematic monitoring of ground water levels throughout the course of a year, to characterize the system's response to precipitation, stream flow and spring recharge events;
- 2) long-term (>72 hour) pumping tests on both production wells to quantify local hydrologic boundaries (particularly the inferred recharge boundary in the vicinity of Little Cottonwood Creek's mouth) and to better define the aquifer's hydrogeologic conditions (water table vs confined vs leaky); and
- 3) integration of these data by developing and calibrating a model of the aquifer's hydraulic response to pumping stress, to serve as a management tool for evaluating the future development of this aquifer's water resource for the COM National Monument.

INTRODUCTION AND STATEMENT OF THE PROBLEM

The National Park Service (NPS) operates two shallow water supply wells at the Craters of the Moon National Monument (COM) which are used to supplement water supplies obtained from nearby springs, for park use. The two wells are located 30 feet apart in a small alluvial aquifer bounded on the east and west by fractured and presumably low-permeability volcanic bedrock, and on the south by tongues of basalt lava which appear to interfinger with the alluvial basin fill (Harder, 1968; Figure 1a). This alluvial aquifer apparently receives much of its recharge from intermittent streams which infiltrate into the valley alluvium at the mouths of Little Cottonwood and Leech Creeks (Bell and Harder, 1968), at the north and west sides of the valley, respectively (Figure 1a).

The original USGS reviews of the aquifer's water supply potential suggested that it may be susceptible to seasonal fluctuations in water supply; the impact of longer-term water deficits is essentially unknown, although what static ground water level data have been obtained from borings (Figure 1b, 1c) suggest that water levels may have declined substantially over the past 24 years. Historic pumping data on the older well completed in 1977 (hereinafter referred to as the "North Well") suggests that adequate water is available to augment spring flows. However, the effects of a new well (the "South Well") drilled in 1991 at a distance of 30 feet from the original well raises the question of how the two wells should be pumped in order to avoid excessive drawdowns that result from well interference. Little is known about the water-bearing zone or zones supplying water to the wells, and the hydraulic characteristics of the aquifer are essentially unknown.

SCOPE AND OBJECTIVES

The overall goal of this testing program was to obtain specific information about well conditions in the South Well and hydraulic characteristics of the aquifer in the vicinity of both wells, so that recommendations could be made concerning future pumping and development of the aquifer. A step-drawdown test on the South Well and a subsequent aquifer test, with water level observations in the North Well, were designed to provide information on the well bore conditions in the South Well, on aquifer properties existing between the two wells, and on the hydraulic impacts of the nearby, bedrock boundaries of the alluvial valley.

Using available data to provide preliminary hydraulic estimates of aquifer properties, an extended aquifer test was designed to provide data on the drawdown vs time response of the wells during pumping. The results of the test provided quantitative information on the aquifer's

hydraulic properties and were used to develop a hydrogeologic conceptual model of the aquifer. Using this information, several pumping scenarios were investigated with an analytical model to estimate limits on pumping rates for extended periods of time.

BACKGROUND DATA

Available geologic and hydrogeologic information on the aquifer, including test borings performed by the USGS, and data on the water wells that have been drilled in the aquifer were supplied by Mr. Kent Campbell of COM NPS staff. This information is attached in Appendices 1A, 1B and 1C. Geologic and hydrogeologic reconnaissance background reports are included in Appendix 1A, including local geology (Hydrogeologic Report A), spring flows and water quality (Hydrogeologic Report B), and test boring lithologic logs and a valley alluvium cross-section (Hydrogeologic Report C).

In 1968, the USGS augered two test holes in the valley, providing valuable information about subsurface geologic conditions. Since then, a total of three wells have been drilled in the valley in an attempt to develop ground water supplies for the site. The locations of the test holes and the three wells are shown on various sketch maps in the appendix and in Figure 1a; preliminary geologic cross-sections were constructed on the basis of available geologic data, and are shown in Figure 1b and 1c. Although the exact location of Test Hole 2 relative to the wells is not precisely known, based on the information in the appendices it is assumed that its location is slightly west of the South Well. From steel tape measurements taken in the field, the South Well is 141 ft due west of the eastern bedrock valley margin and 253 ft due east of the western bedrock valley margin.

The first production well (#1, now referred to as the North Well) was drilled in 1977, and has been producing adequate water since. In 1991, the Park Service had a second and third well drilled in an attempt to augment this ground water supply. Well #3 is now referred to as the South Well. The northernmost well (#2) was abandoned because it failed to produce more than 5-10 gallons per minute (gpm) during development, even though it is the deepest of the three (100 ft). Unlike the other wells and Test Hole 2, Well #2 was reported to have encountered water in fractured rock rather than alluvial or volcanic sediment.

A well completion report for the North Well and a drillers' log for the abandoned Well# 2 are attached in Appendix 1B. A lithologic description of well #1 is not available, although the test boring report (Hydrogeologic Report C, Appendix 1A) indicates the general lithology of this alluvial valley. Drill cuttings samples for well #3 were collected by Park Service staff during drilling and were examined at ISU for grain size and lithologic description. These data are attached as Appendix 1C, together with what well completion data are available and the drawdown and recovery data obtained from the well

development test. Mr. Kent Campbell, maintenance foreman at the site, believes the lithology of the North Well is very similar to that of the South Well.

No previous pump tests have been conducted on these wells, although a driller's well development test was performed on the South Well (#3) at the time of well completion (Appendix 1C). A summary of well water level responses to past pumping is shown in Table 1. Neither the North Well or the South Well had been pumped during 1992 prior to this testing because water supply from nearby springs was adequate to meet local needs.

Nearby springs flow year-round. Normally, they provide the site with 50-60 gpm of potable water in the early part of the year, with total discharge declining over the summer. During the dry Spring of 1992, early-season discharge from the springs never achieved normal high rates and remained approximately constant at about 22 gpm throughout the summer.

BACKGROUND DATA EVALUATION

Based on the USGS test boring logs and the well logs for the South Well and the abandoned well (#2), a conceptual geologic model of the alluvial aquifer was constructed for planning and evaluation purposes. Salient features are shown in Figure 1b and 1c, with well screen and pump depths and static water levels shown for reference. Note that the location of Test Hole 2 relative to the present wells has been inferred from its plotted map location (Appendix 1A) and field measurements made with a steel tape.

The depths and geologic characteristics of the aquifer shown in Figure 1b and 1c do not unambiguously define either a confined or an unconfined (water table) aquifer hydraulic condition, although the low water levels measured in September, 1992 suggest that an unconfined situation is possible. Partially confined and leaky aquifer conditions are also possible, if the vertical hydraulic conductivity of strata above the well screen depth is appreciably lower than in the horizontal direction. Any interpretation of water level response to pumping must therefore consider at least these alternative hydraulic scenarios.

As shown in Figure 1b, the coincidence of reported water and fractured rock in the abandoned well (#2) 100 ft north of the North Well raises the possibility that recharge to this aquifer may not be entirely derived from stream infiltration, and that deeper, spring-fed or regional ground water inflow from bedrock aquifers may be contributing. However, it is not known whether the "fractured rock" reported in the driller's log of the abandoned well represents bedrock or valley detritus. Furthermore, if such a recharge boundary actually exists north of the producing wells, it is at a significantly greater

distance from either well than is the eastern bedrock valley margin shown in Figure 1c. Therefore, the bedrock boundary to the east would be expected to be sensed by the wells during pumping before the effects of a more distant recharge boundary to the north became evident, assuming lateral hydraulic conductivity is roughly isotropic in the E-W and N-S directions.

Note that ground water levels in September-October, 1992 shown in Figure 1c are very low and that little saturated aquifer thickness remains to be exploited. Also, the slope of the valley walls, if projected into the subsurface, indicate that the lateral extent of the aquifer to the east may be extremely limited at the depth of the well screen. These features suggest that it may not be possible to conduct a prolonged aquifer test under the present hydrologic conditions simply because sufficient drawdown is unavailable.

HYDRAULIC PARAMETER ESTIMATES FROM BACKGROUND DATA

The only information available concerning the estimated yield and hydraulic characteristics of the North Well is from the well completion and pump installation report filed by the NPS (D. Barrett, 1977; Appendix 1B), in which 9 ft of drawdown was estimated for a 50 gallon per minute (gpm) pump rate ($=Q$). On this basis, the transmissivity (T) of the aquifer (T = hydraulic conductivity or "permeability" multiplied by the thickness of the water-bearing zone supplying water to the well) in the vicinity of the North Well would be ca. $0.015 \text{ ft}^2/\text{sec}$.

Well development data obtained upon completion of the South Well in 1991 provided the most useful information about the transmissivity of the aquifer. From a plot of drawdown (subsequently denoted " s ") vs logarithm of time of the initial, high-discharge rate portion of the test (80 gpm), a transmissivity of $0.002 \text{ ft}^2/\text{sec}$ was estimated, on the assumption that the aquifer is an ideal confined unit; extrapolating the linear relationship between s and $\log(t)$ of the high-rate portion of the development test data, the specific capacity after 24 hours pumping is about 1.3 gpm per foot of drawdown, which indicates a transmissivity of approximately $0.003 \text{ ft}^2/\text{sec}$. Using the lower discharge rate portion of the development test data (ca. 25 gpm, with approximately 25 ft of steady drawdown after 8 hours pumping), specific capacity is estimated at 1.4 gpm per foot of drawdown, with transmissivity of the order of $0.003\text{-}0.004 \text{ ft}^2/\text{sec}$. From the recovery data, a less reliable transmissivity estimate of $0.003\text{-}0.004 \text{ ft}^2/\text{sec}$ was obtained.

Thus, the best available estimates of transmissivity around the South Well is in the range of $0.002 - 0.004 \text{ ft}^2/\text{sec}$, which is adequate to design pumping tests on the South Well. In order to provide specific information on the well's efficiency and to determine the optimum pumping rate for an extended drawdown test, a step-drawdown test was

performed on the South Well prior to an extended pumping test.

STEP-DRAWDOWN TEST AND WELL EFFICIENCY

By pumping a well at several different, constant rates, in a series of step increases in discharge, the performance of the well can be evaluated (its efficiency) and the most suitable combination of drawdown and pump rate can be determined for a subsequent extended constant-rate aquifer test.

Water level data for both wells during a three-step test conducted 9/30/92 is shown in Figure 2a. By re-plotting these data as total drawdown since the time of the last discharge rate increase vs logarithm of time since the last discharge rate increase, three trends are obtained in Figure 2b. The slopes of the best-fit lines through these trends can be used to calculate the specific drawdown, or s/Q , for each pumping rate, and as shown in Figure 3, the linear relationship between s/Q and Q provides a direct estimate of the "well-loss coefficient", C (after Rorabaugh, 1953).

The total drawdown in a well being pumped at a rate Q is the sum of the drawdown due to the hydraulic head decrease in the adjacent aquifer ($=BQ$) plus the additional drawdown due to the energy losses incurred by water as it enters the well ($=CQ^2$). Using this concept, the efficiency of the well can be defined as the ideal, or aquifer drawdown ($=BQ$) divided by the total drawdown ($=BQ + CQ^2$). From the relationship shown in Figure 3, $B=0.40$ and $C=0.00155$. Thus, at a pumping rate $Q=20$ gpm, total drawdown would be 8.6 ft and well efficiency would be 93%. That is, at 20 gpm, the drawdown in the well due to turbulent energy losses is about 0.6 ft, so that the well can be considered to be fairly efficient in transferring water from the aquifer through the well screen to the pump. This is not surprising, since the well's screen design and size characteristics were matched to the sediment grain size distribution determined on actual samples of aquifer materials prior to well completion (H.T. Ore, 1991; J.A. Welhan, 1991).

Given the overall efficiency of the well's design, drawdown corrections for well losses during the aquifer test are predicted to be of the order of 3% and can be safely neglected.

AQUIFER TEST RESULTS

Based on the preceding information, an extended constant-rate aquifer test was designed using the South Well as the pumping well and the North Well as the observation well. The test was started on 10/1/92, with the intention of running the test for at least 24 hours. Test conditions are summarized in Table 2. Due to the inability to

accurately preset the desired discharge rate using the main gate valve in the valve house, the first attempt resulted in excessive drawdown after 10 minutes. This run was aborted and the well water levels were allowed to return to near-static values before re-starting the test at a lower discharge rate. Since the re-start occurred while a small amount of unrecovered drawdown remained (< 3 inches) in the wells, all subsequent drawdown data were corrected for this effect.

As shown in Figure 4, two offsets occurred in the drawdown-time trends of both wells within the first 200 seconds of the test. These offsets are due to discharge rate fluctuations caused by the lack of fine control that is available on pump discharge with the main gate valve. Unlike the aborted test in which initial discharge rate was too high, the initial discharge rate in this test was too low. Two flow rate increases were required during the first 3.5 minutes of pumping, when flow rate dropped below the desired value. Within about a minute of the start of the test the flow was increased substantially from 4 gpm; this resulted in a rapid drawdown rate increase. A second flow rate increase at about 2 minutes into the test was required when the discharge again decreased (as evidenced in the decreased rate of drawdown between 100 and 200 seconds in Figure 4). The final 9.2 ± 0.2 gpm rate was set with a third, relatively minor flow rate adjustment at 400 seconds, and the resulting flow rate was maintained for the duration of the test. These drawdown offsets are unfortunate, coming as they did in the early-time portion of the test, but their impact on the overall data interpretation is considered minor; corrections for these offsets were made in all calculated hydraulic parameters determined from curve fitting.

Although the aquifer test ideally should have been conducted for at least 24 hours to unambiguously define the pertinent aquifer hydraulic characteristics, an acceleration of drawdown was observed at about 50 minutes, such that excessive drawdown in the South Well after only about 7 hours of pumping initiated automatic pump cut-out. The accelerated drawdown rate was most likely the result of a nearby hydraulic barrier (eg: the eastern bedrock valley margin).

The observed slow rate of drawdown beyond about 400-1000 sec in the wells would be consistent with an unconfined (water table) scenario, although it could also be indicative of a leaky (partially confined) aquifer condition. A recharge boundary may also be responsible. These possibilities are investigated further in the following analysis.

INTERPRETATION OF AQUIFER RESPONSE

Two important features of the pumping test must be explained by any satisfactory hydraulic interpretation: 1) the decrease in the rates of drawdown after 400-1000 seconds in both the pumping and observation wells; and 2) an increase in the rates of drawdown in both wells at later times. Considering the geologic information and the conceptual

model shown in Figure 1, two hydraulic models are used to interpret these observations: a confined aquifer model with vertical leakage, where partially confining beds provide vertical recharge to offset pumping withdrawals, and an unconfined (water table) aquifer model with delayed gravity drainage. In the former, the accelerated rate of drawdown in late-time data can be interpreted as the effect of the nearest bedrock boundary, whereas in the latter, the accelerated drawdown may be due either to a bedrock boundary or a consequence of the water table model, or both. A third, less likely model, involves some combination of the above (or other) models together with a lateral recharge boundary.

In the analysis that follows, wellbore storage impacts were not considered and, where possible, intermediate-time data were used to estimate storativity. Partial penetration impacts were evaluated in an iterative process. First, partial penetration was assumed negligible and a trial fit of the observed data to type curves for an aquifer response model was obtained. Secondly, using the preliminary hydraulic parameters and vertical/horizontal permeability ratio determined from the trial fit, a new model type curve was generated with a partial penetration approximation routine (Walton, 1988) and the fitting process was repeated to determine new hydraulic parameter estimates. Aquifer thickness was assumed to be 20 ft, with the production well screened over 7 ft of that; the observation well was assumed to completely penetrate the aquifer. The above steps were repeated, wherein the new hydraulic parameter estimates were found not to differ significantly from those in the second iteration, and the calculated hydraulic parameter values were considered valid.

It should be noted that the effects of partial penetration in the present well-aquifer system are ambiguous and have a significant effect on well drawdown. In particular, the position of the South Well's screen appears to be poorly placed relative to the permeable zone in the aquifer (Figure 1b) and the thickness of the permeable, saturated portion of the aquifer around the North Well's intake is unknown. Lacking a cost-effective means for determining the requisite information on aquifer thickness, depth and well intake location, this means that accurate determinations of aquifer hydraulic properties will have to await future development of a numeric or semi-analytical hydraulic model and calibration of calculated aquifer drawdowns against observed drawdowns.

Leaky Aquifer Model

Drawdown-time data for the pumping well and observation well are shown in Figures 5a and 5b, respectively, matched to type curves for a leaky confined aquifer of infinite extent (type curves shown do not account for partial penetration effects). The r/B parameter describes the hydraulic characteristics of the semi-confining layer(s) which supply leakage to the aquifer during drawdown and which eventually cause the drawdowns to stabilize at constant values. From the best match between

the theoretical curves (including partial penetration impacts) and the observed data prior to the late-time increase in drawdown rate, the calculated transmissivity is $0.00124 \text{ ft}^2/\text{sec}$ (800 gpd/ft; $10 \text{ m}^2/\text{day}$). Thus, for a 20 ft thick aquifer, horizontal hydraulic conductivity would be $T/20 = 0.000062 \text{ ft/sec}$ (40 gpd/ft; 0.93 m/day). The observation well data can also be used to provide an estimate of the aquifer's storage coefficient or storativity, S . For the observation well data, this value was calculated to be 0.002, and is reasonable for a confined aquifer composed of silty gravel.

The best match r/B value for the observation well data is 3; therefore $B=10$. For an assumed 10 ft thick low-permeability confining layer, the calculated vertical hydraulic conductivity of the leaky confining layer is 0.000124 ft/sec (80 gpd/ft; 1.86 m/day). Since this is greater than the calculated horizontal hydraulic conductivity derived above, the assumption that the aquifer is confined and leaky appears suspect.

On the assumption that a bedrock boundary is responsible for the late-time deviation of water levels from the theoretical curve, the observation well data in Figure 5b can be used to estimate the radial distance to the boundary. From the superposition principle, and assuming that the boundary lies parallel to the N-S trend of the wells, the distance from the observation well to the assumed boundary is calculated to be approximately 31 ft. This distance is quite reasonable, given the known distance of the wells from the eastern valley margin and the slope of the valley bedrock surface, and fits the geologic model well (see Figure 1c).

Unconfined (Water Table) Model

Water level data from the observation well are plotted in Figure 6 and were matched to a theoretical curve incorporating partial penetration effects; calculated $T = 0.00145 \text{ ft}^2/\text{sec}$ (940 gpd/ft; $11.6 \text{ m}^2/\text{day}$). The value of transmissivity is very similar to that calculated from the leaky aquifer model and indicates that, for the early- and intermediate-time data, both models are consistent with the observed aquifer response. The "Beta" parameter in the unconfined aquifer analysis describes the contrast between vertical and horizontal hydraulic conductivity. From the best-fit match shown in Figure 6, $\text{Beta} = 0.2$, and vertical hydraulic conductivity is estimated to be 6.7% of horizontal hydraulic conductivity. For the types of sedimentary materials in this aquifer, this value is far more reasonable than the vertical hydraulic conductivity calculated from the leaky aquifer model, and suggests that an unconfined model better describes the early- and intermediate-time drawdowns in these wells.

In an unconfined model with delayed gravity drainage, water levels should show an accelerated rate of drawdown toward late times; therefore, a separate set of type curves were fit to the late-time data in Figure 7. Note that the slight inflection in the observed data

just prior to the acceleration in drawdown rate is believed to have been caused by movement of the water level sensor cable while securing the wellhead prior to leaving the site for the day.

The drawdown-time data for late-times (Figure 7) do not fit any of the theoretical late-time unconfined aquifer curves exceptionally well. The poor match of late-time data may indicate that the accelerated drawdown rate does not reflect a water table response. The calculated value of the aquifer's specific yield from the late time data, $S_y < 0.0061$, is substantially lower than would be expected for a water table aquifer, and suggests that the late-time water level response reflects the nearby bedrock boundary rather than the cessation of delayed gravity drainage. Furthermore, given the relatively short duration of the test, an accelerated drawdown rate would not have been expected to occur as early as it was observed, if it were due solely to unconfined aquifer drainage.

Assuming that the accelerated drawdown seen in late-time data is due to a boundary effect, then, the radial distance to the boundary from the observation well can be calculated as in the leaky aquifer model. In this case, the radial distance to an assumed N-S trending eastern bedrock boundary is almost identical to that calculated from the leaky aquifer model, or about 35 ft.

Recharge Boundary

The third possibility to be considered to explain the observed data is that of an aquifer which is first replenished by lateral recharge (leading to stabilization of drawdowns), followed by an increased rate of drawdown as the eastern bedrock valley margin is encountered. This scenario is based on the possibility of a "fractured rock" water-bearing zone in the abandoned well (#2) 100 ft north of the observation well (cf Fig. 1b), but could also involve lateral recharge from the mouth of either or both of Little Cottonwood and Leech Creeks. If a part of the system is capable of supplying water at a higher rate than the alluvial sediments in the immediate vicinity of the wells, its impact would be to slow the rate of drawdown and eventually produce a steady (equilibrium) drawdown condition. This may be an alternative explanation for the approach to steady drawdowns observed in the wells prior to 3000 seconds.

Such an hypothesis would imply that the distance to the recharge boundary is shorter than that to the bedrock valley margin, or that valley sediments are strongly anisotropic vis a vis flow parallel to vs perpendicular to the valley axis. As can be seen from the inferred geologic cross sections of Figures 1b and 1c, the distance to a possible high-permeability, fractured bedrock recharge boundary north of the wells may be as low as 10's of feet (Figure 1b) compared to 30 feet for the lateral distance to the valley margin (Figure 1c).

Determination of the effective distance to such a hypothetical

recharge boundary from the available data would not be reliable due to the relatively short duration of the test, and the fact that both a recharge and an impermeable boundary need to be invoked. However, estimates of the distance from the pumping well to a hypothetical high permeability boundary can still be made, and range from 20-35 ft north of the observation well for an E-W boundary north of the pumping site, and only slightly larger distances for a N-S boundary west of the wells. Since no known boundaries or permeability discontinuities exist west of the wells, the latter hypothesis is unsupported. In light of the water-bearing "fractured rock" identified in the abandoned well (#2) at relatively shallow depth (Figure 1b), the possibility of a nearby recharging fractured rock or rubble zone boundary to the north bears further consideration. From the preliminary geologic cross section constructed in Figure 1b, it is apparent that the estimated distances to such a boundary are, in fact, of the correct order of magnitude.

DATA SYNTHESIS AND AQUIFER EVALUATION

From the above analysis, it appears that the simplest model which explains the observed well responses and which satisfies the geologic constraints, involves an unconfined aquifer with a nearby impermeable bedrock boundary. Support for an impermeable boundary effect comes from the estimate of the pumping time required to observe a boundary effect if the boundary is 30-35 ft east of the wells at well screen depth; based on the calculated transmissivity and storativity, estimated time to detect such a boundary during the aquifer test is 50 minutes. Thus, the accelerated drawdown rate observed after 53 minutes is consistent with an impermeable boundary effect in this aquifer.

However, it must be recognized that, because the boundary is so close to the wells, its influence on these wells' drawdowns would be felt to some extent even within the first minutes of the test. This effect on the early-time drawdown data would be difficult to identify and to account for. Therefore, given these wells' sensitivity to partial penetration impacts, as well as the effects of such a close barrier boundary, it would be virtually impossible to describe the observed drawdowns unambiguously in terms of a simple hydraulic model. Nevertheless, it is useful to invoke a simple model to guide the development of our hypotheses concerning the response of the system to present and future pumping stresses, and for the following discussion, an unconfined aquifer model will be used as the basis for discussion.

In such a model, gravity drainage in an unconfined aquifer would produce near-steady drawdowns after about 15 minutes of pumping at 9 gpm, but the presence of a bedrock boundary would increase drawdown rate after about 1 hour. Since an unconfined model fits the known geologic and static water level information and provides a reasonable estimate of vertical/horizontal permeability contrast in these sediments, a more complex model involving both a recharge and an

impermeable aquifer boundary to explain the drawdown-time data is unwarranted at this time. However, a combined recharge-impermeable boundary model has not been quantitatively evaluated and cannot be excluded at this time. This possibility will be examined in the section on predictive modelling to follow.

The transmissivities and storage coefficients calculated from historical data and recent tests on the production wells are summarized in Table 3. The transmissivity values obtained from observation well data during the 10/92 aquifer test are lower than the transmissivity estimates derived from the 6/91 development test on the South Well. This discrepancy may be due to dewatering of the aquifer around the pumping well, leading to a reduction in saturated thickness. Referring to Figure 1b, the drastic decline in static water levels between 6/91 and 10/92 could account for as much as a factor of two decrease in the saturated thickness of the permeable gravel unit which supplies water to the South Well. Alternatively, the differences in the estimated transmissivities shown in Table 3 between 6/91 and 10/92 may reflect a zone of higher permeability which was contributing water to the well during the 6/91 development test when water levels were some 10 ft higher than at present.

Another possibility is the impact of the barrier boundary on the interpretation of early-time drawdown data. The proximity of the bedrock valley margin at the depth of the pump intake is such that its effect might have a substantial impact on drawdowns as early as the first few minutes of pumping. In that case, transmissivity estimates derived from the curve-matching procedures used in this work would be biased; that is, increased drawdowns due to the very early influence of the bedrock boundary would result in calculated transmissivities that are too low.

AQUIFER MODELLING

Since the transmissivity estimates obtained in this study pertain only to early-time responses in the aquifer, the effects of long-term pumping on the aquifer and the capability of either or both wells for sustained yield cannot be quantitatively predicted at this time. Given the effect of the bedrock boundary and the relatively rapid drawdown that was observed at a modest 9 gpm (0.02 cu.ft/sec) pumping rate during the 10/92 test, it is not difficult to show that well drawdown under the present (ie. low water table) hydrologic conditions would be excessive and that the aquifer could not be expected to support sustained withdrawals in excess of 10 gpm without a recharge source to stabilize drawdown. Well response under high water table conditions is unknown.

However, the possibility that a nearby recharge source may exist in or near the mouth of Little Cottonwood Creek raises the question of whether such a source could counter the increased drawdown induced by

the bedrock boundary near the wells, and therefore effectively increase the wells' capacity. In order to examine this question, a simple analytical model of the aquifer's response to pumping was used to predict the magnitude of the possible competing effects of nearby recharge and barrier boundaries on long-term pumping.

An attempt was made to reproduce the well responses observed in the 10/92 test with a simple analytical model of flow to a well in a Theis-type aquifer, with partial penetration effects considered and hydrologic boundaries mimicked by equal-strength image wells (Walton, 1989). Since the primary purpose of this exercise was to examine the possible importance of a recharge boundary on the ability of the production wells to provide a long-term sustained yield, a more sophisticated model, with unconfined or leaky aquifer boundary conditions, was not attempted.

Given the uncertainties in aquifer geometry (barrier vs recharge boundaries), the relative positions of well screens within the aquifer (Figure 1b, 1c), and the importance of partial penetration effects on well response that was identified above, a model calibration of this type is far too unreliable to be of use as a management tool for predicting well responses. However, it is useful for examining the various possible competing influences on well drawdown and for demonstrating the utility of a predictive model for aquifer management.

Since only early-time drawdown data were available for calibration purposes, a simple Theis-type approximation was considered entirely adequate for matching the observed drawdowns. Curve matching analysis of the production well's drawdown data (Figure 4), utilizing a Theis type curve, demonstrated that transmissivity and storativity estimates for a Theis model were very similar to those obtained from the unconfined aquifer analysis. A storativity of 0.002 was used throughout this modelling exercise, with various transmissivity values used to fit the calculated drawdowns with those observed in the 10/92 test.

The model was initially run with T and S values determined from the 10/92 aquifer test (Table 3), with a N-S barrier boundary located 30 feet due east of the pumping well. At a discharge rate of 9.2 gpm and for various possible partial penetration conditions, calculated drawdowns could not be matched to observed drawdowns. Transmissivity values up to 4 times higher than those calculated from curve-matching were required to match the predicted and observed drawdown responses in the model. This, plus the fact that the model showed the barrier boundary had a slight but measurable impact on drawdowns as early as three minutes after the start of pumping, suggests that the bedrock boundary may have been a much more severe source of interference on early-time drawdown than was originally considered in the curve-matching analysis described previously, and may have introduced a concomitant bias into the calculated transmissivities.

With only a bedrock boundary considered, drawdown at the pumping well after 50 minutes at a discharge rate of 9.2 gpm was calculated to be 4.7 ft (4.5 ft observed) and 6.8 ft after six hours (6.75 ft observed). Predicted drawdowns in the aquifer in the vicinity of the wells is shown in Figure 8a. Since the pump automatically shut off during the 10/92 test at this point due to excessive drawdown, it is apparent that under the geologic and hydrologic conditions of the model (ie. bedrock boundary only) the wells might be expected to provide sustained yields of the order of only a few gallons per minute.

In order to evaluate the influence of a possible recharge boundary on long-term pumping levels, the model was subsequently modified to include an E-W recharge boundary 50-100 ft north of the North Well (as suggested by the presence of water-bearing, fractured bedrock in Figure 1b), in addition to the N-S bedrock boundary. Because a recharge boundary would act to reduce the amount of total drawdown observed in the wells, its effect should be to stabilize long-term drawdowns. As shown in Figure 8b, contours of equal drawdown after 7 days pumping at 9.2 gpm have stabilized (after less than 2 days) and indicate that maximum drawdowns of about 5 ft can be maintained at the South Well in the presence of a recharge boundary, whereas drawdowns in excess of 8 ft would be expected after 1 week of continuous pumping in the absence of such a recharge source (Figure 8c).

The possible presence of a recharge boundary to the north of the wells also has important implications for our ability to develop a predictive model of aquifer response to pumping stress that will be of use as a management tool. The location and "strength" of such a recharge boundary dramatically alters the effective transmissivity that dictates the drawdown response of these wells. For example, if the position of the recharge boundary is moved to within 40 ft of the North Well (Figure 8d), stable drawdown in the South Well is achieved with a transmissivity that is within a factor of two of that calculated from the 10/92 curve-matching analysis. Thus, many combinations of recharge boundary position, its effective strength, aquifer transmissivity and well partial penetration effects can reproduce the well drawdowns observed in the 10/92 test. In other words, given the apparent complexity of this system, the drawdown data obtained from the 10/92 test is inadequate, by itself, to characterize the hydraulics of this aquifer.

A further application of the simple model used above is to examine alternative pumping scenarios. For example, if the 9.2 gpm discharge of the 10/92 test were split equally between the two wells, the drawdown predicted by the model (without a recharge source) is shown in Figure 8e. As is apparent, the drawdowns in the individual wells are about 6.5 ft, whereas drawdown in a single well pumping under the same conditions exceeds 8 ft (Figure 8c). From a management perspective, the ability to predict this type of response may represent the difference between the costly resetting of a pump at greater depth and simply reducing the effective discharge rate of both

pumps with a return flow line. Other uses of such a model could include examining the consequence of variable pumping rates, cyclic pumping and alternating pumping and recovery between the wells. The latter option, although not explored here, has the greatest potential for maximizing total yield while minimizing excessive drawdowns.

Although the presence of a recharge boundary is strictly conjectural, its possible presence has significant implications for the design of a well pumping scheme. As already suggested, a local recharge source could make long-term withdrawals from the wells practical. Furthermore, if it is shown to be present its actual characteristics may significantly affect the maximum rates at which these wells can be pumped.

In conclusion, these modelling results are not intended to be used quantitatively. However, they strongly suggest that the response of the aquifer is dominated by its hydrologic boundaries and that subsurface recharge may be the key factor that will allow the production wells to be pumped at reasonable rates over long periods of time. In addition, the complexity of the aquifer's boundary conditions suggests that development of a model of the aquifer will be very important for designing a safe, long-term pumping scheme and for providing flexibility in managing the aquifer in the future.

RECOMMENDATIONS FOR FURTHER WORK

The results of the aquifer and well tests conducted in October, 1992 have refined our knowledge of the aquifer and pointed out important boundary conditions and near-well effects that will have to be taken into account in any further work toward developing a useful predictive model of the aquifer for management purposes.

Based on these results, it is apparent that more detailed knowledge of the wells' characteristics and the aquifer's geometry is required. In particular, because of the small scale of this well-aquifer system, the importance of near-well hydraulic non-idealities (partial penetration effects), aquifer boundaries and short pumping times will have significant implications for any modelling effort.

Aquifer geometry, well characteristics and aquifer properties will need to be better defined via an iterative calibration of observed water level responses to pumping stress. Most importantly, additional aquifer response data must be gathered, in the form of extended pumping tests (> 72 hrs) and water level monitoring as the water table rebounds from the effects of the past six years of drought.

In order to effectively manage the aquifer and its response to future pumping withdrawals, a calibrated numerical or analytical model should be developed, utilizing information gained over the next year about the aquifer's responses to increased spring recharge and to precipitation and stream flow events, long-term seasonal water level fluctuations, and extended pumping stress.

Summary of Recommended Future Work:

- 1) systematic monitoring of ground water levels throughout the course of a year, to characterize the system's response to precipitation, stream flow and spring recharge events;
- 2) long-term (>72 hour) pumping tests on both production wells to quantify local hydrologic boundaries (particularly the inferred recharge boundary in the vicinity of Little Cottonwood Creek's mouth) and to better define the aquifer's hydrogeologic conditions (water table vs confined vs leaky); and
- 3) integration of these data by developing and calibrating a model of the aquifer's hydraulic response to pumping stress, to serve as a management tool for evaluating the future development of this aquifer's water resource for the COM National Monument.

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TABLE 1 - Summary of water level responses in wells #1 (North Well) and #3 (South Well) during past pumping conditions. Based on information obtained from K. Campbell (pers. comm., 1991) and Appendix 1.

<u>Conditions</u>	<u>Pumping Rate</u>	<u>Response</u>
<u>North Well (#1):</u>		
high water levels in early spring, declining through summer	11-13 gpm (continuous)	drawdown≈20 ft (in previous years)
" " "	20-25 gpm	well goes dry
immediately after well #3 was drilled	ca.12 gpm	well#1 pumped muddy water for about 30 minutes, then cleared
prior to installing casing in well #3, well #1 was pumped to observe its effect on well #3	21 gpm	no drawdown in well #3
<u>South Well (#3):</u>		
after completion, screening, development	25 gpm	no measurable drawdown after 24 hours of pumping; drawdown in #1 not measured

TABLE 2 - Aquifer test conditions, for 10/1/92 pumping test on South Well.

Pumping Well	South Well
Observation Well	North Well
Separation Distance	30 feet
Screened Interval in Pumping Well	57-64 ft bls (7 ft interval)
Screened Interval in Observation Well	59-69 ft bls (10 ft interval)
Pumping Well ID	8"
Observation Well ID	12"
Static Water Level Pumping Well	51.23 ft bls
Observation Well	47.56 ft bls
Target Pump Discharge Rate	10 gpm
Actual Pump Discharge Rate	9-9.4 gpm (mean of 9.2 gpm)

TABLE 3 - Summary of aquifer hydraulic properties

Source of Data	Transmissivity (ft ² /sec)	Storativity (dimensionless)

North Well, specific capacity estimate	0.015(approx.)	n.a.
South Well, development test 6/91		
@ 80 gpm	0.002-0.003	n.a.
@ 25 gpm	0.003-0.004	n.a.
recovery	0.003-0.004	n.a.
Pumping Well, aquifer test 10/92		
leaky aquifer model	0.00055	n.a.
unconfined aquifer model	0.00035	n.a.
Observation Well, aquifer test 10/92		
leaky aquifer model	0.00124	0.0020
unconfined aquifer model*	0.00145	0.0020

* The specific yield estimate calculated from a late-time data curve match is too low and is not reported since late-time drawdown in this test was interpreted to have been affected by an impermeable boundary; see text. The tabulated value represents the early-time storativity.

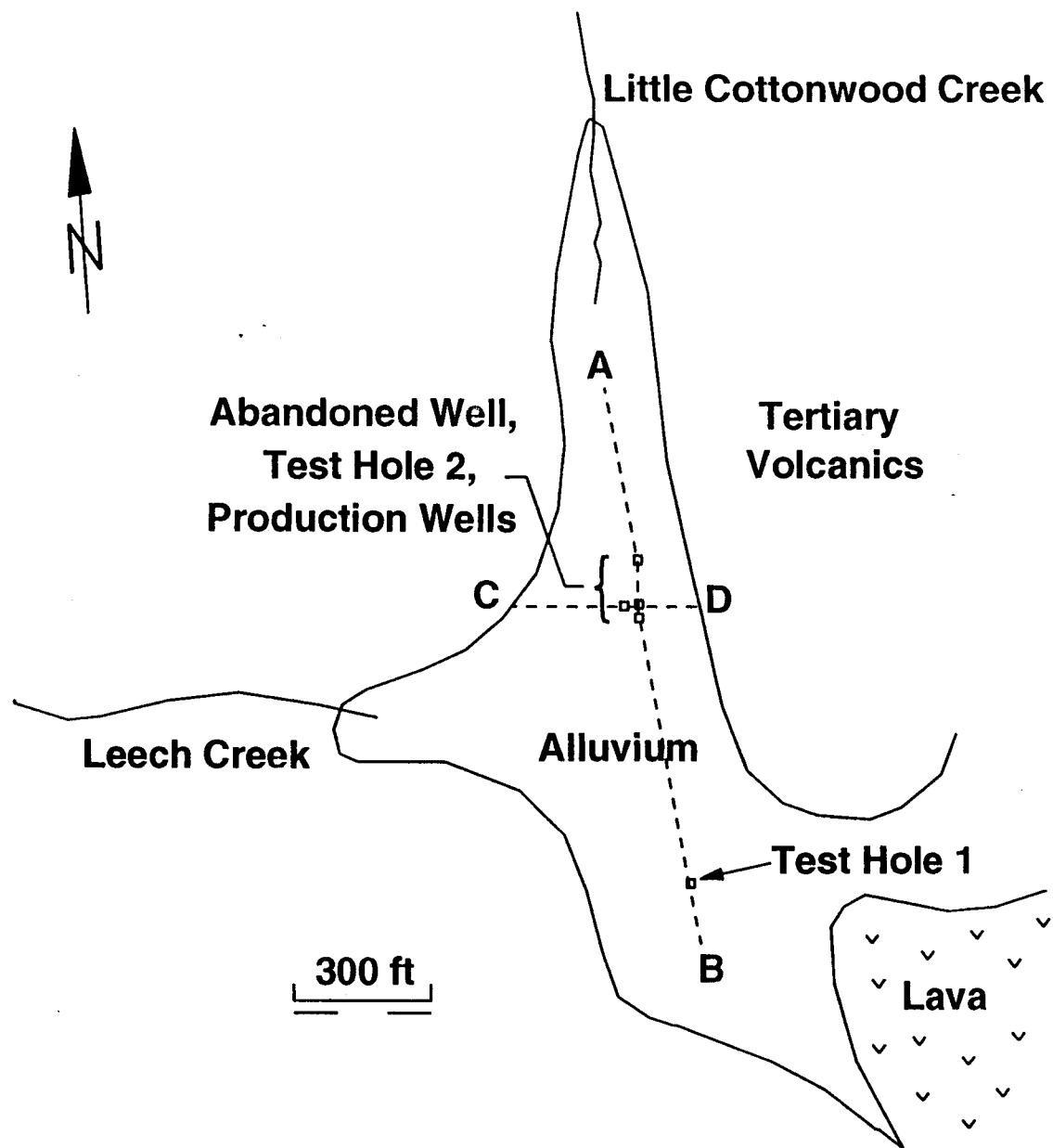


Figure 1a - Map of alluvial valley showing locations of geologic control points

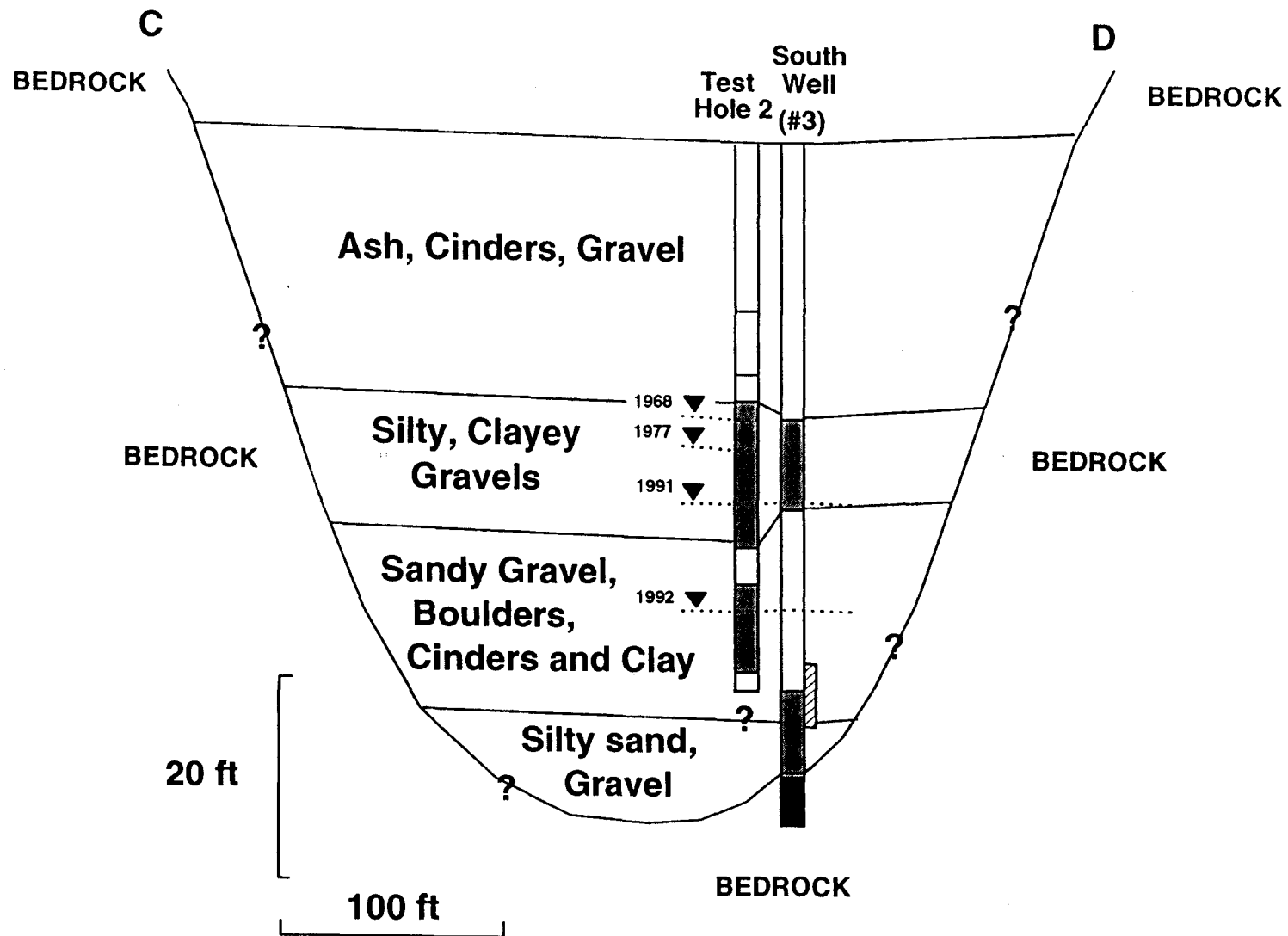


Figure 1c - Geologic cross-section C-D showing inferred bedrock boundaries at depth and relationship to water producing zone in South Well.

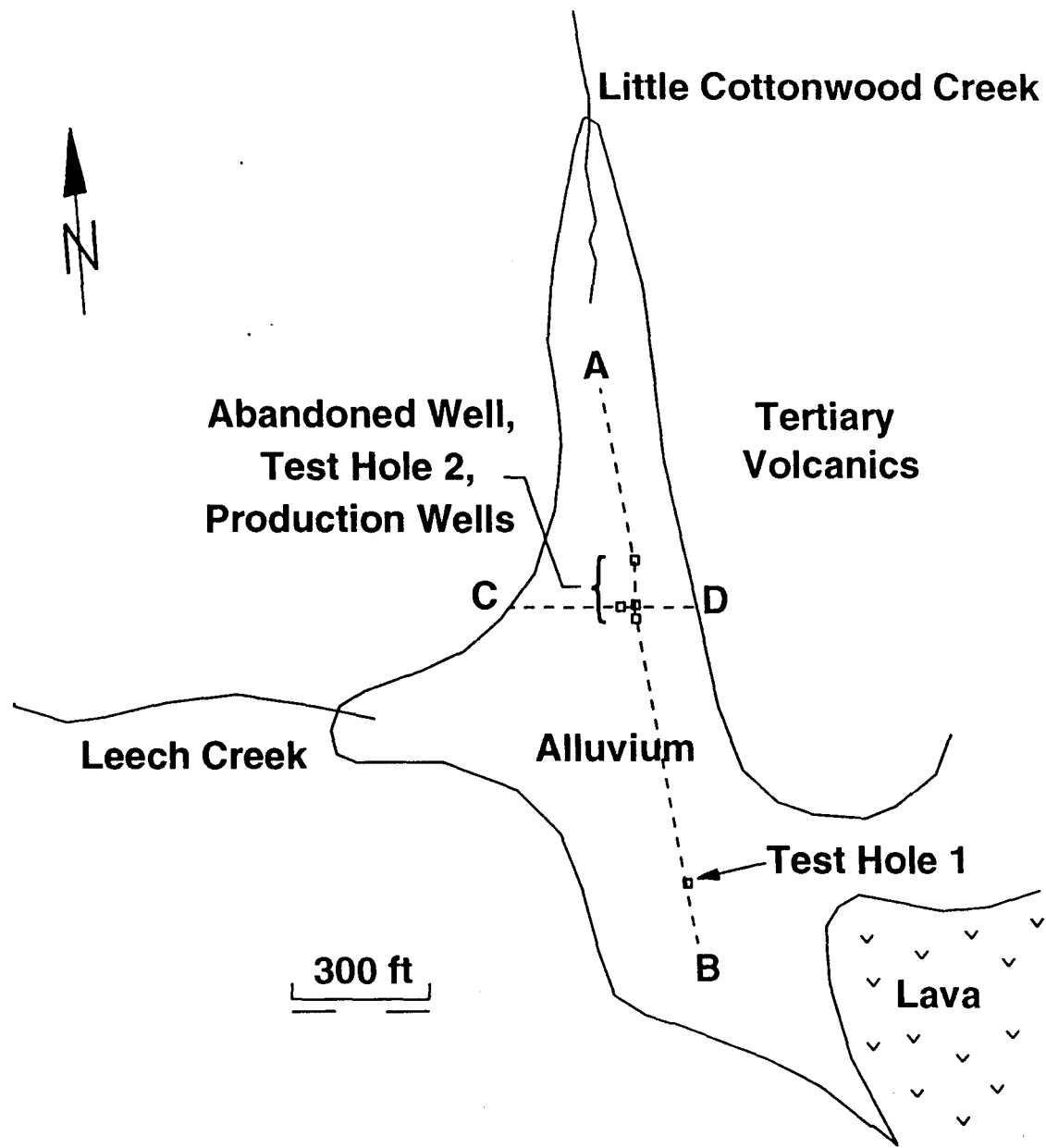


Figure 1a - Map of alluvial valley showing locations of geologic control points

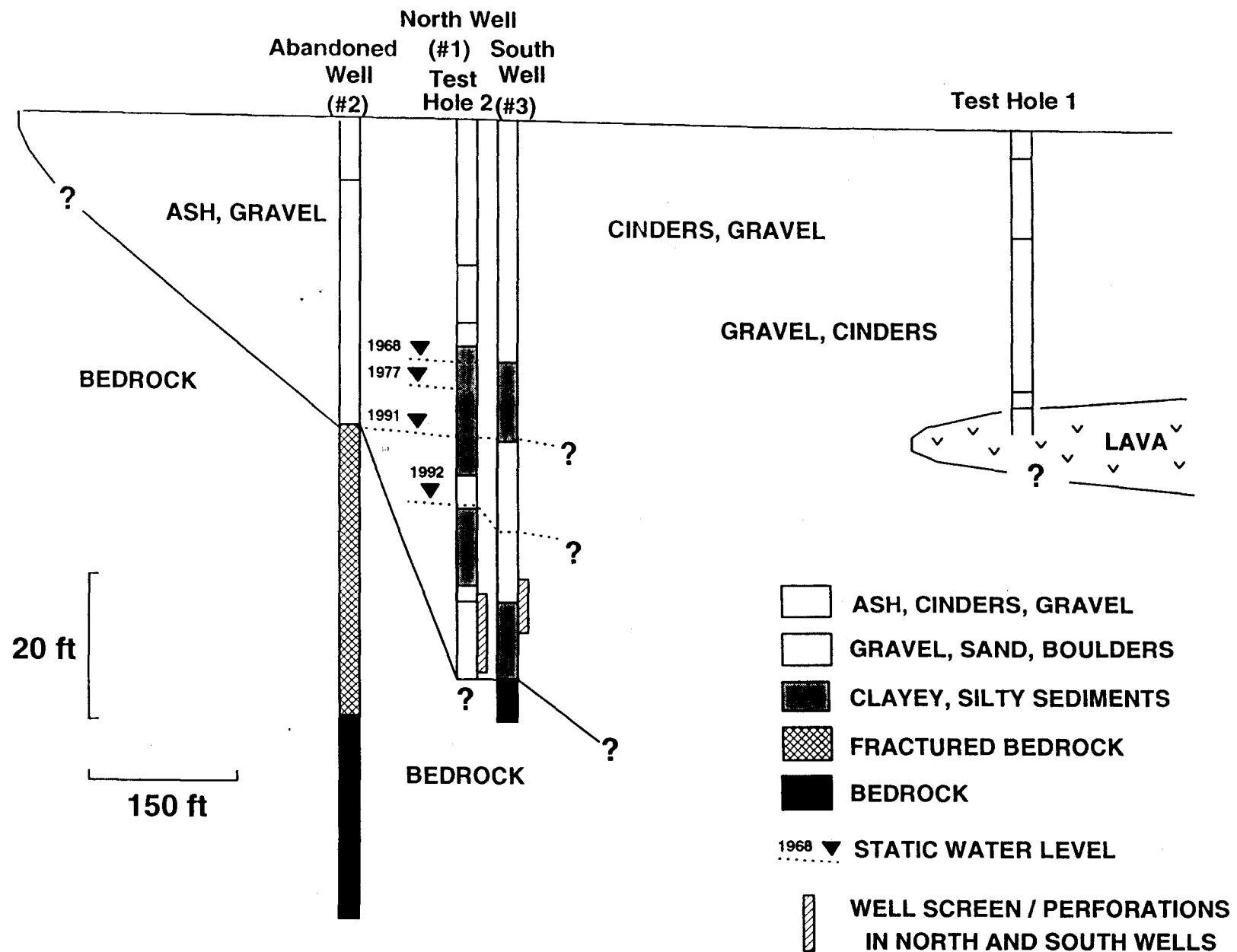


Figure 1b - Geologic cross-section A-B showing inferred geology of aquifer, measured static water levels and water producing zones in wells.

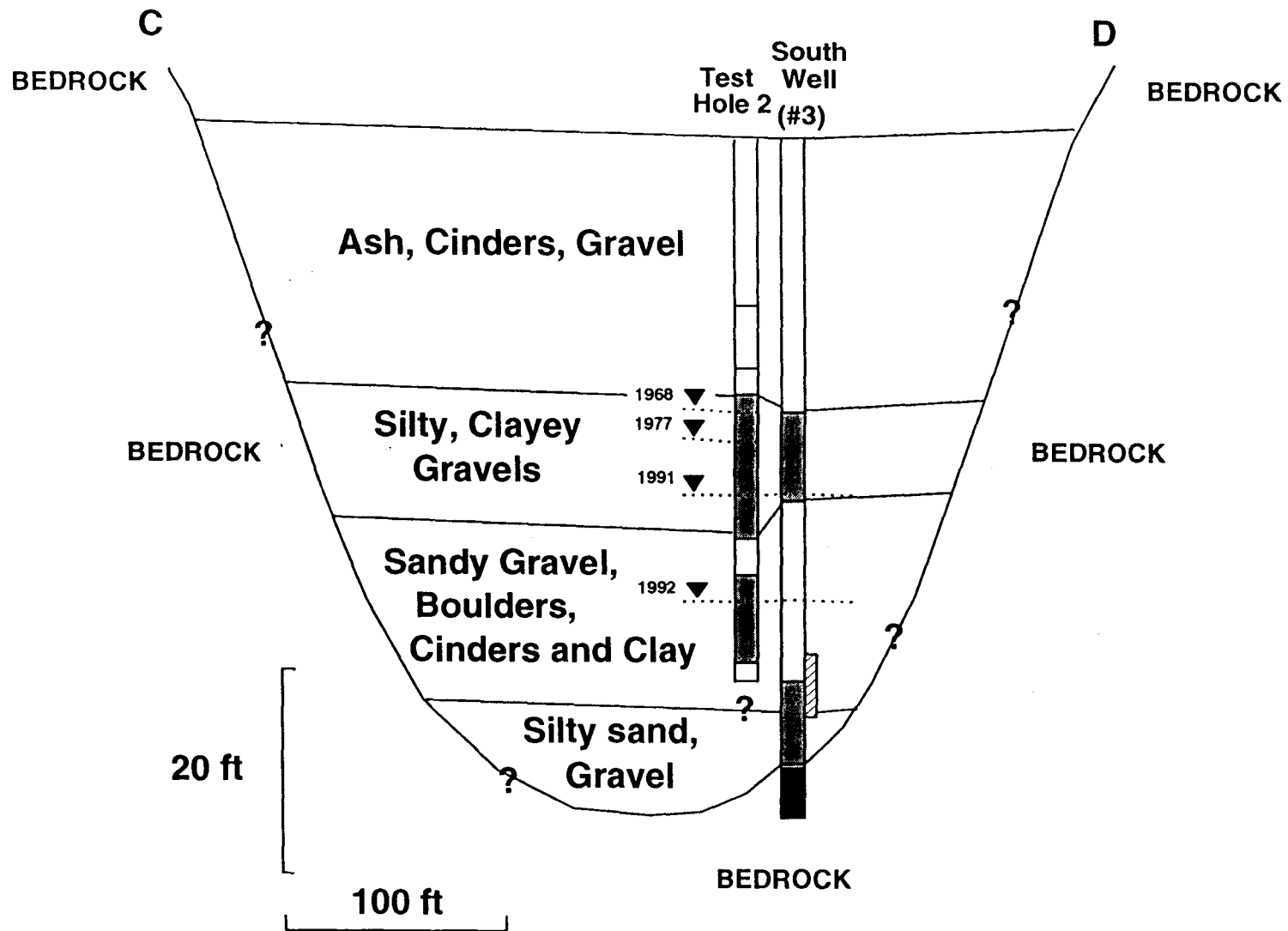


Figure 1c - Geologic cross-section C-D showing inferred bedrock boundaries at depth and relationship to water producing zone in South Well.

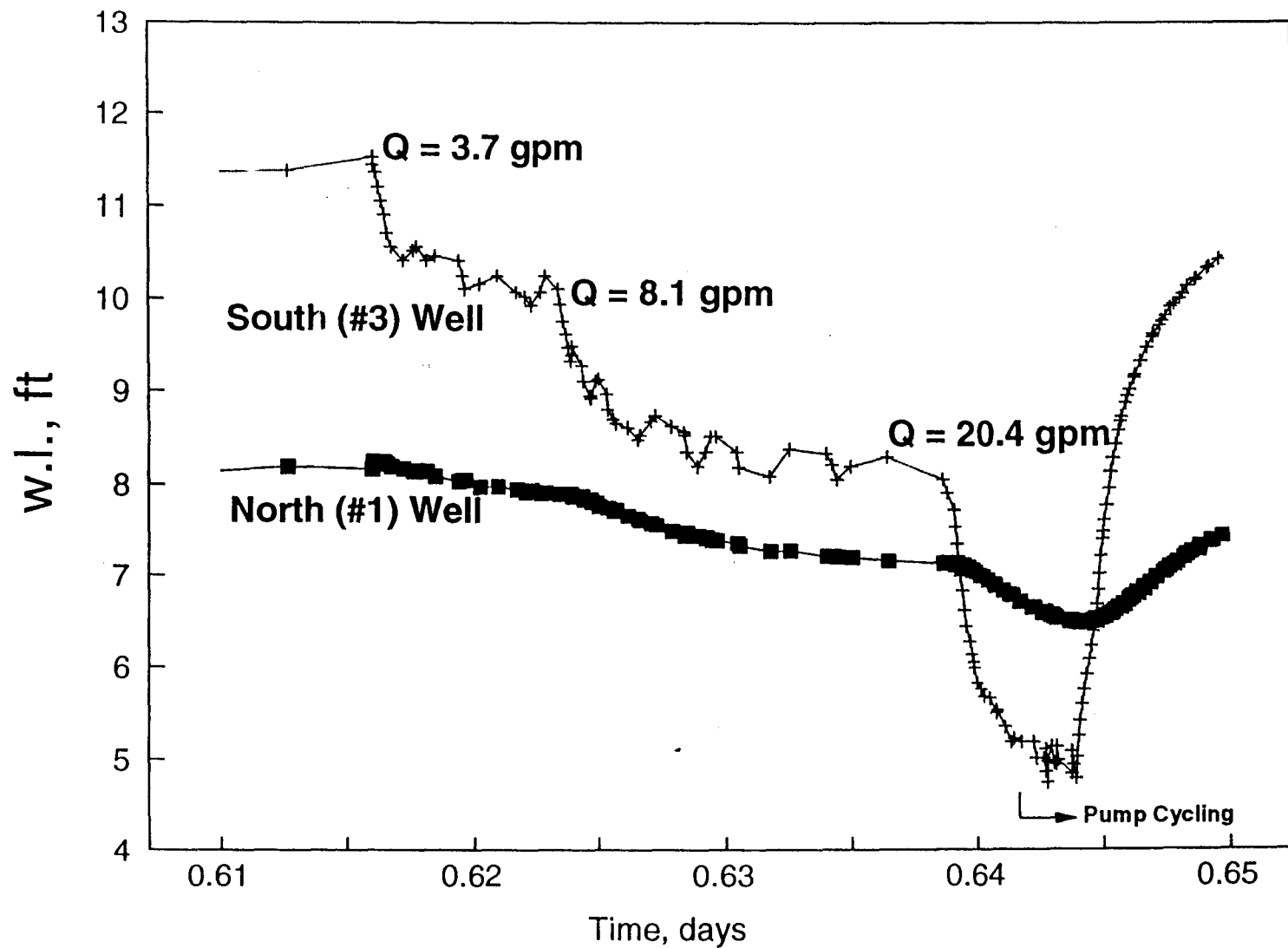


Figure 2a - Drawdown behavior observed in step-drawdown test on South Well, September 30, 1992. Water levels (in feet above an arbitrary datum for each well) are shown for the pumping well (#3; crosses) and for the observation well (#1; squares). Pumping rates shown were determined from multiple volumetric measurements.

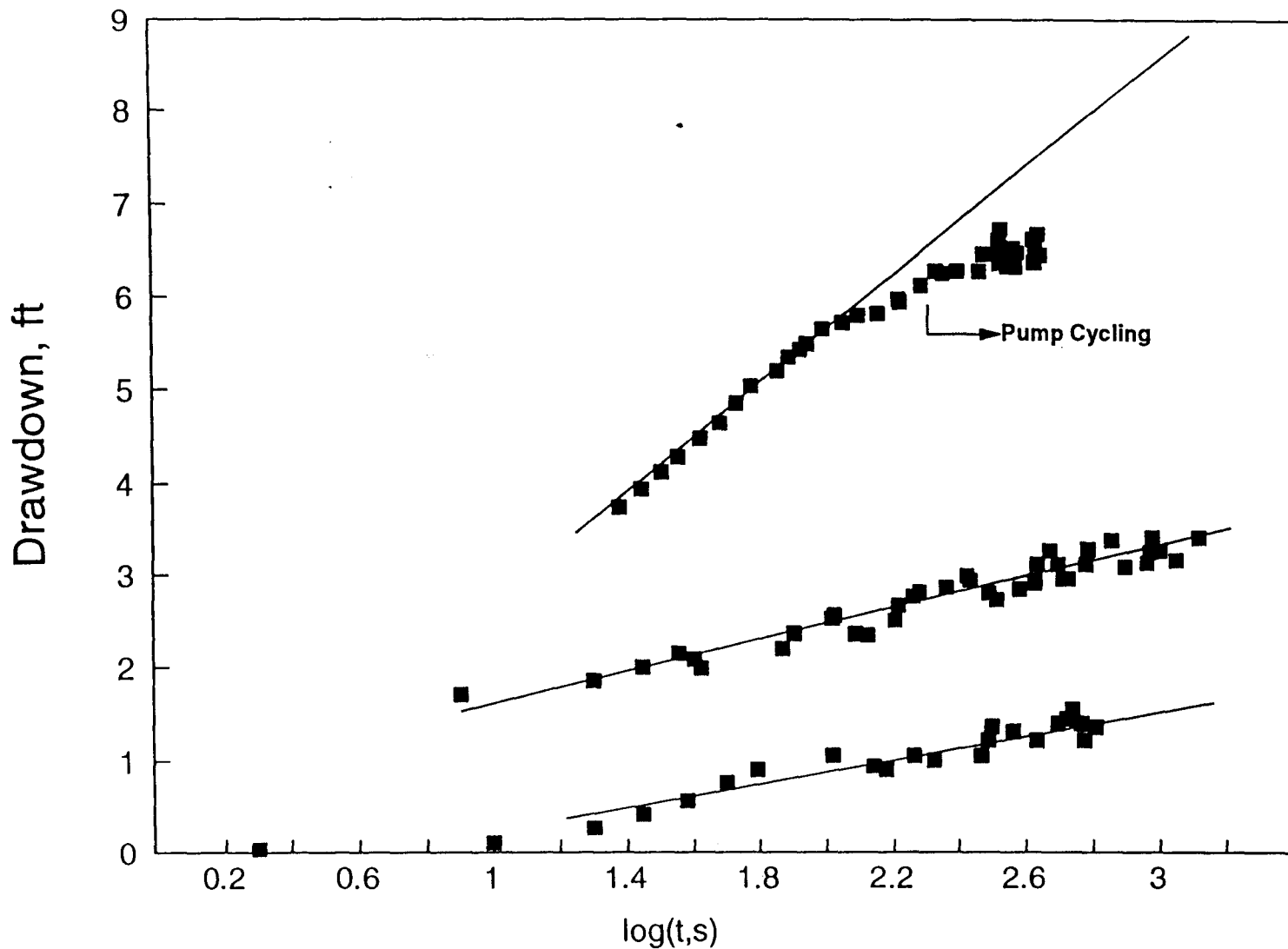


Figure 2b - Total drawdown vs logarithm of time (sec) since change in flow rate, for 9/30/92 step-drawdown test on South Well. Each drawdown trend was extrapolated to 1000 seconds to determine drawdown at each incremental discharge rate increase.

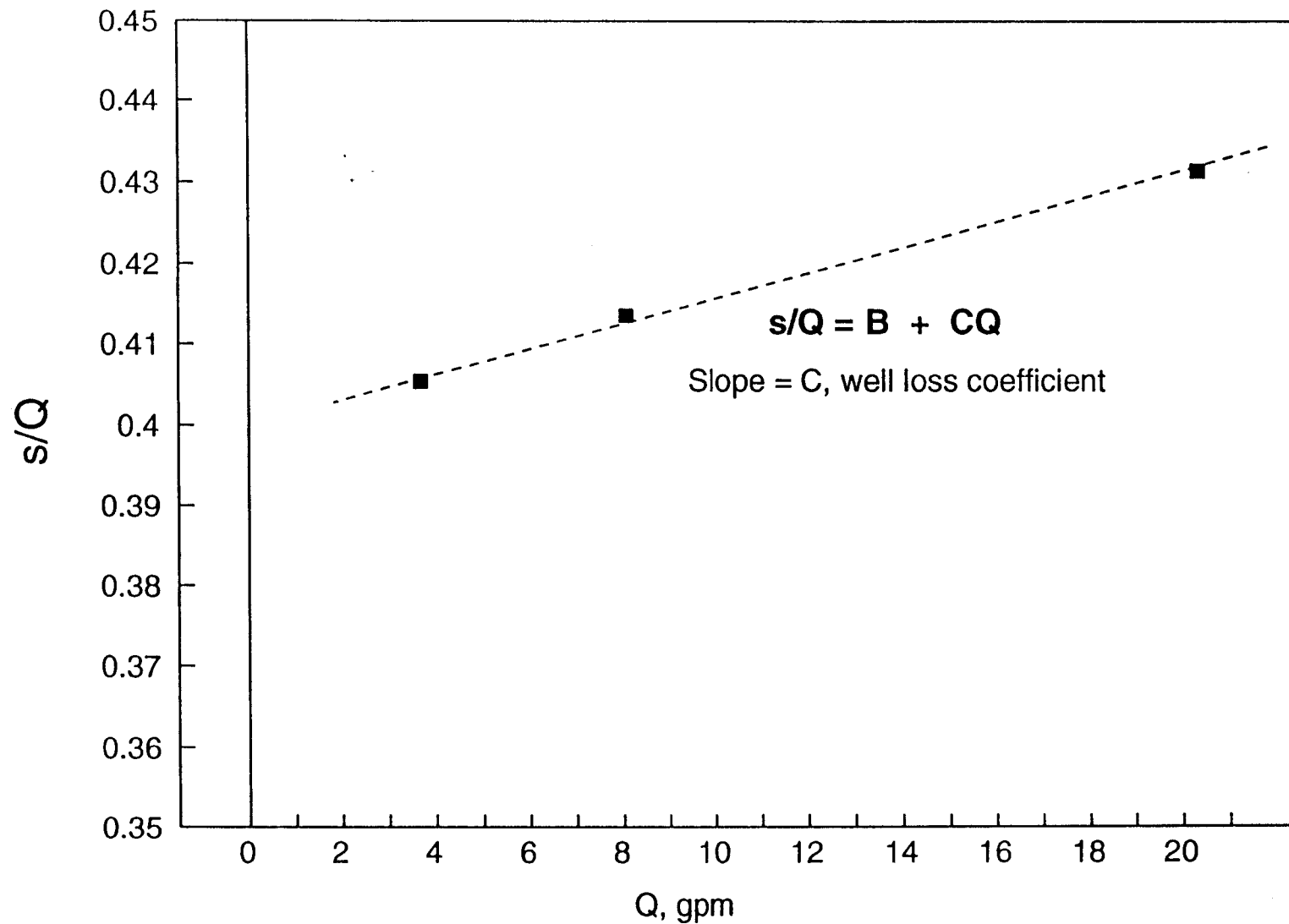


Figure 3 - Plot of specific drawdown (s/Q) vs discharge rate for the three discharge rate steps in Figure 2. The slope of the best-fit straight line through the points is the well loss coefficient, C . The higher the value of this coefficient, the less efficient the well is in delivering water from the aquifer to the pump.

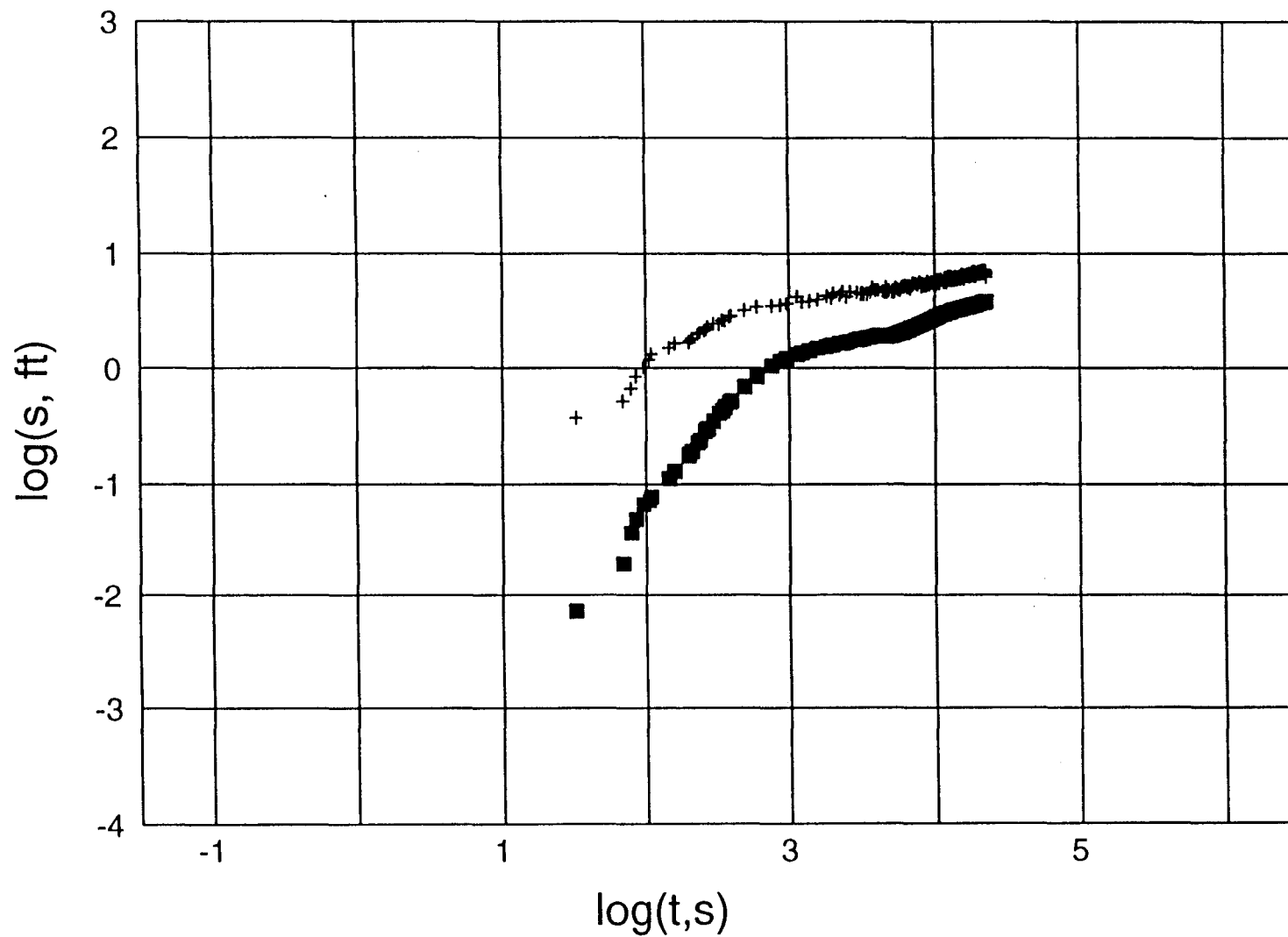


Figure 4 - Double logarithmic plot of drawdown vs time in the pumping well (#3; crosses) and the observation well (#1; squares) during the pumping test of October 1, 1992.

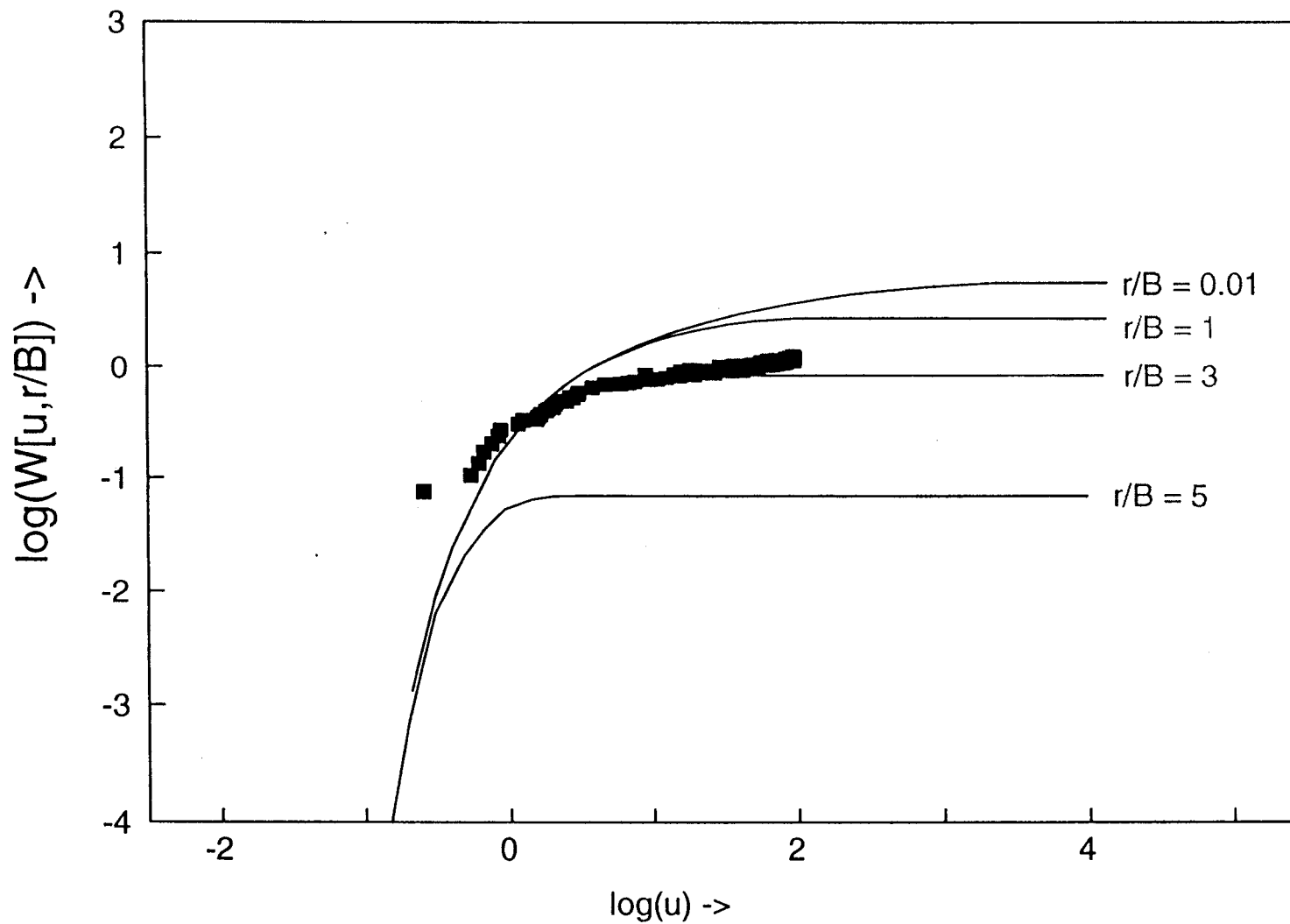


Figure 5a - Match of pumping well (#3) logarithmic drawdown vs logarithmic pumping time (squares) to type curves for a leaky aquifer model, with various vertical leakage coefficients (r/B). Transmissivity derived from the best match is $0.00055 \text{ ft}^2/\text{s}$, using a constant $W(u, r/B)$ offset for partial penetration effects of 0.63 units.

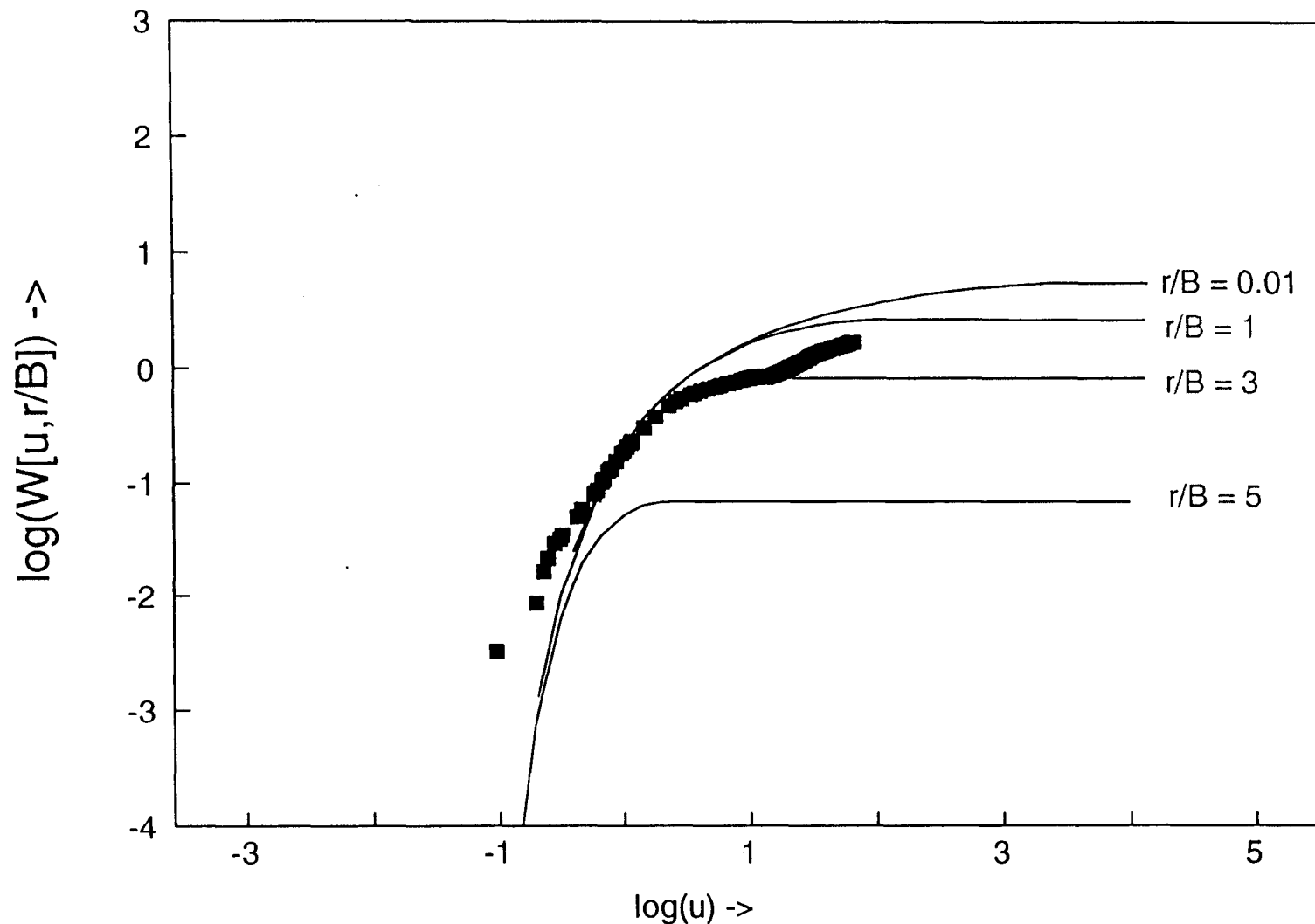


Figure 5b - Match of observation well (#1) logarithmic drawdown vs logarithmic pumping time (squares) to type curves for a leaky aquifer model, with various vertical leakage coefficients (r/B). Transmissivity derived from the best match is $0.00124 \text{ ft}^2/\text{s}$, using a constant $W(u, r/B)$ offset for partial penetration effects of 0.63 units; storativity for early-time response is 0.0020. The inflection point in observed drawdown-time data can be interpreted in terms of the distance to an

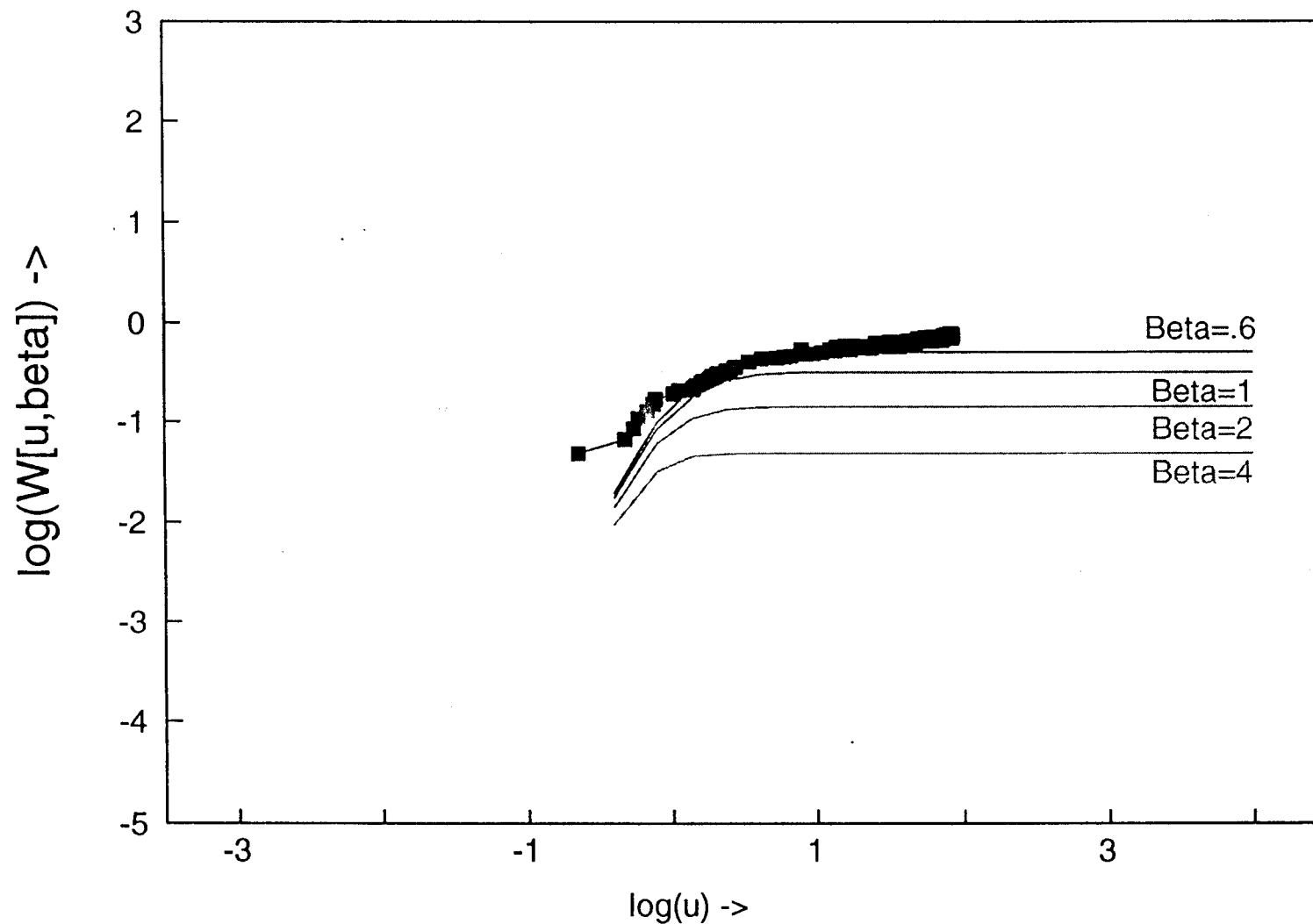


Figure 6a - Match of pumping well (#3) logarithmic drawdown vs logarithmic pumping time (squares) to early-time type curves for an unconfined aquifer model, with various delayed gravity drainage coefficients (β). Transmissivity derived from the best match is $0.00035 \text{ ft}^2/\text{s}$, using a constant $W(u,r/B)$ offset for partial penetration effects of 0.63 units.

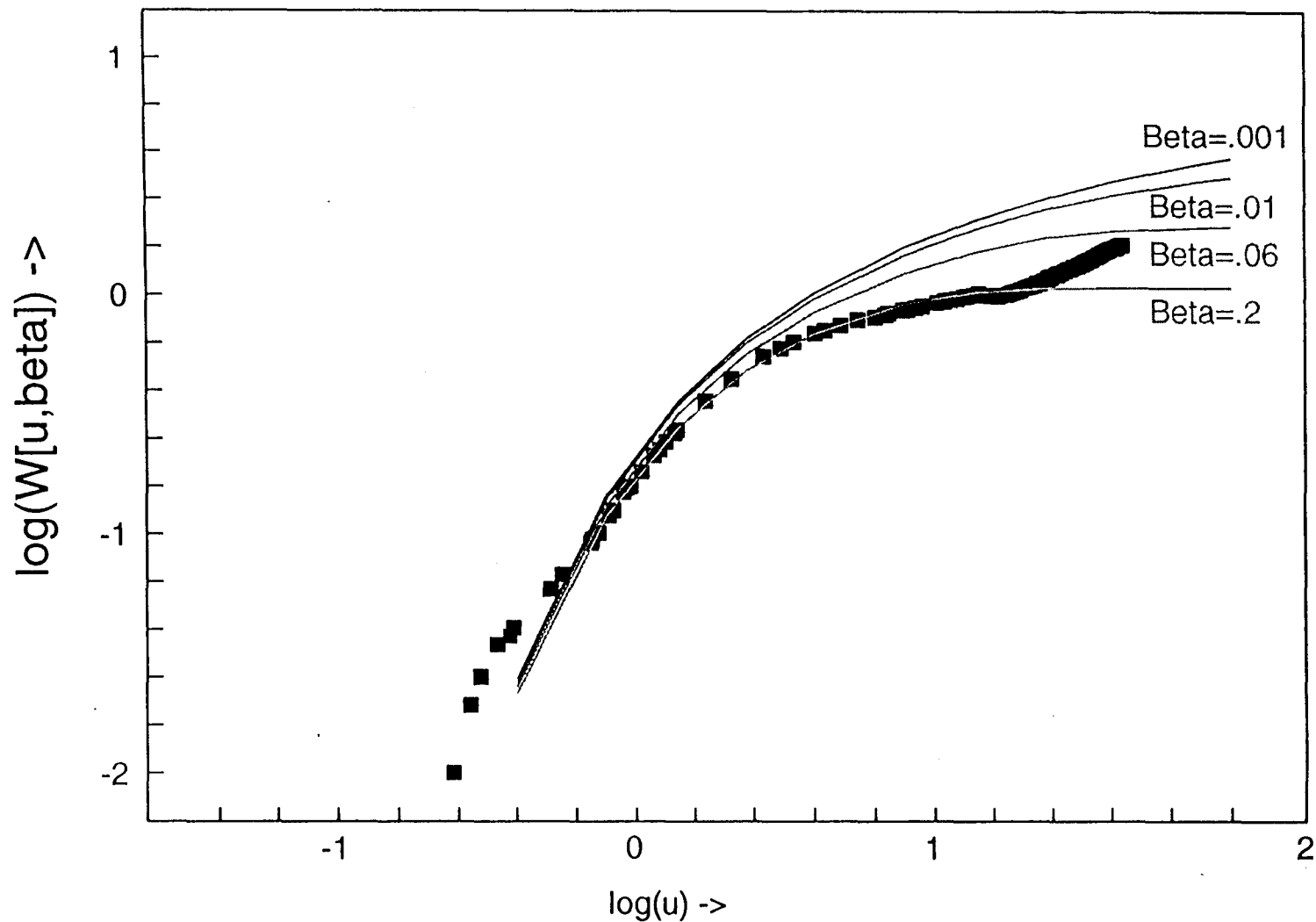


Figure 6b - Match of observation well (#1) logarithmic drawdown vs logarithmic pumping time (squares) to early-time type curves for an unconfined aquifer model, with various delayed gravity drainage coefficients (β). Transmissivity derived from the best match is 0.00145 ft²/s, using a constant $W(u, r/B)$ offset for partial penetration effects of 0.63 units; storativity for early-time response is 0.0020. The inflection point in observed drawdown-time data can be interpreted in terms of the distance to an impermeable boundary, which is of the

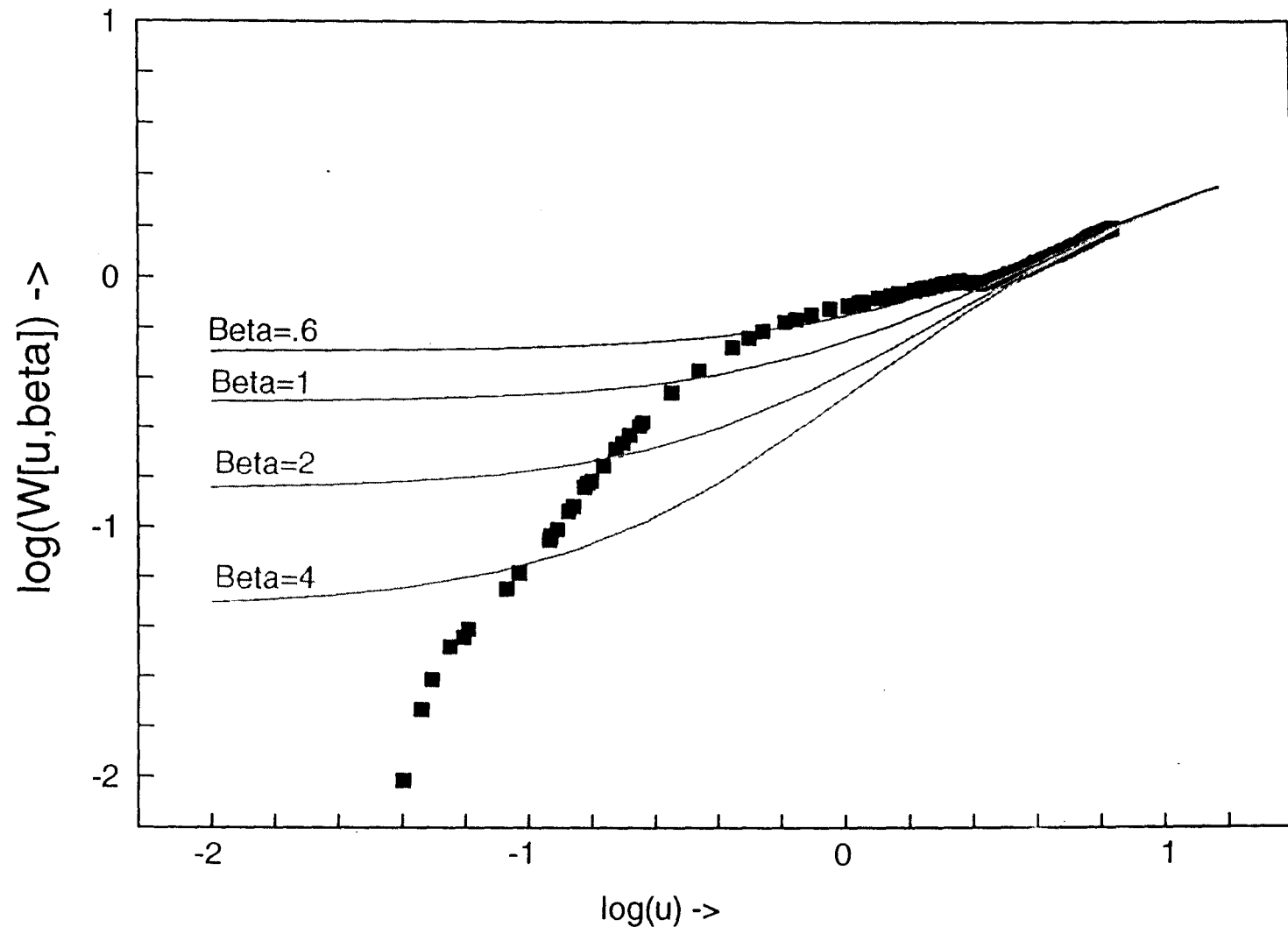


Figure 7 - Attempt to match the observation well (#1) drawdown-time data to a late-time unconfined aquifer type curve. The calculated specific yield in this case was 0.006, indicating that the inflection in the late drawdown data is not due to the cessation of gravity drainage, and supporting the hypothesis that a nearby barrier boundary is responsible for the late-time drawdown.

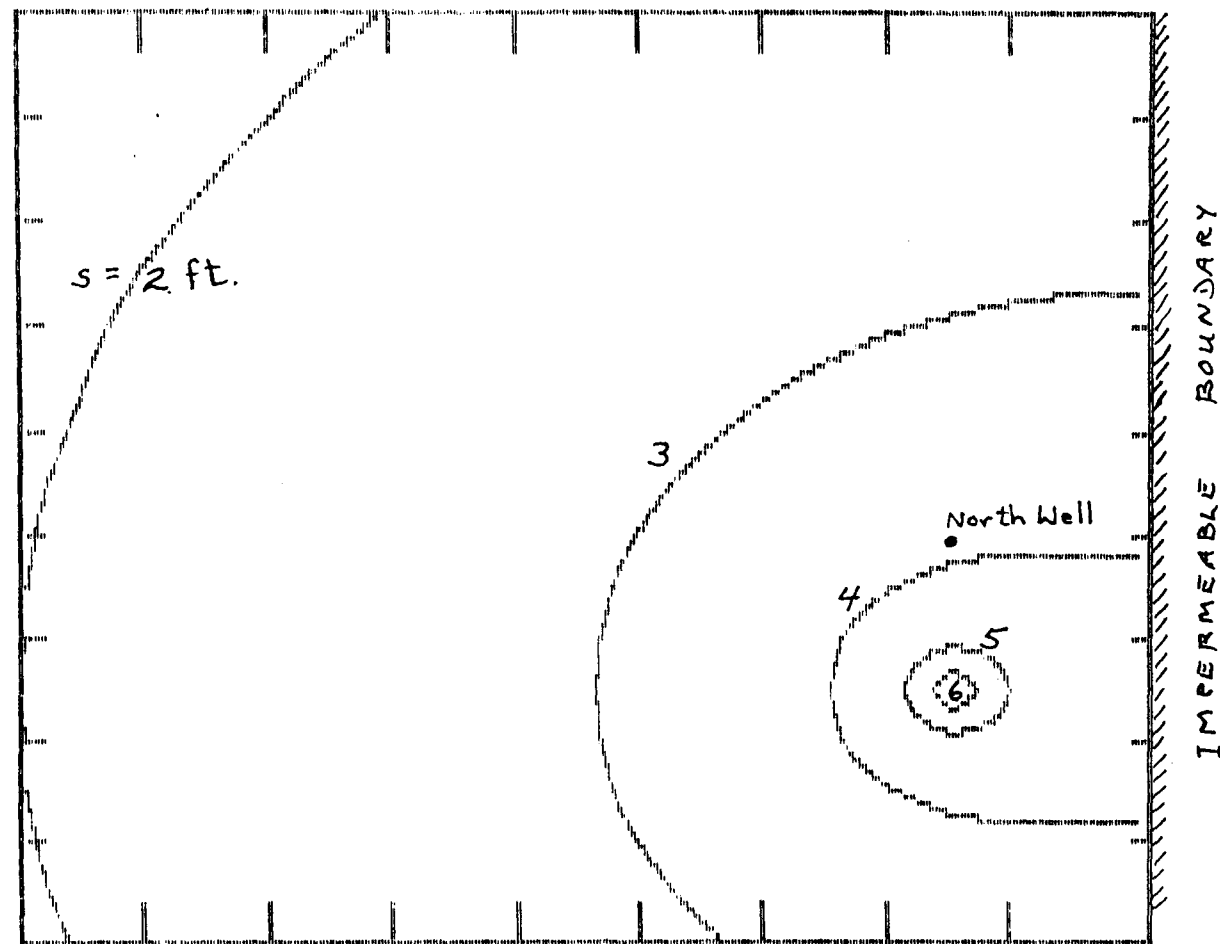


Figure 8a - Results of a simple analytical ground water flow model to describe the effects of well pumping on the areal distribution of early-time drawdowns in the aquifer, assuming an areally homogeneous Theis-type aquifer and a single impermeable boundary on the east margin of the grid (valley bedrock margin) 30 ft east of the production wells (cf Figure 1c). Grid marks are spaced at 20 ft intervals; pump discharge rate is 9.2 gpm and continuous. For a transmissivity of 0.0046 ft²/s and storativity of 0.002, drawdown in the pumping well (#3) was matched to that observed in the 10/1/92 test with partial penetration effects of the order of 0.5-1 ft. Drawdowns shown are computed after 0.25 days of

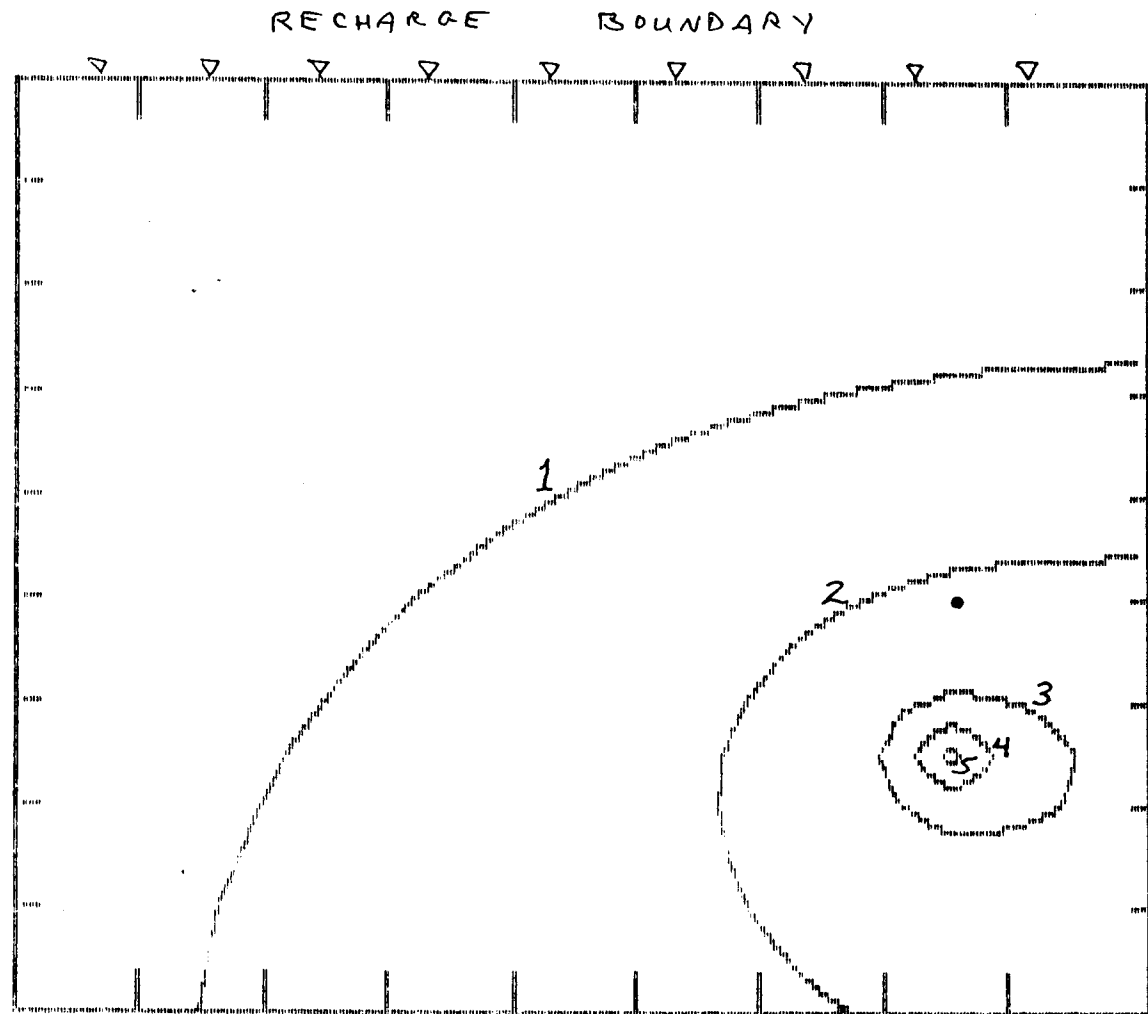


Figure 8b - Predicted effect on aquifer drawdowns under the influence of the same conditions as in 8a, but with a full-strength recharge boundary placed 100 ft north of the observation well (#1). Note that the effect of the recharge boundary is to substantially reduce drawdowns, such that after 7 days of pumping in the presence of recharge, Well #7 has less drawdown than if no recharge occurred (Figure 8a). Under the assumed boundary conditions, the model predicts that drawdowns would stabilize between 1 and 2 days after the start of pumping and remain unchanged thereafter.

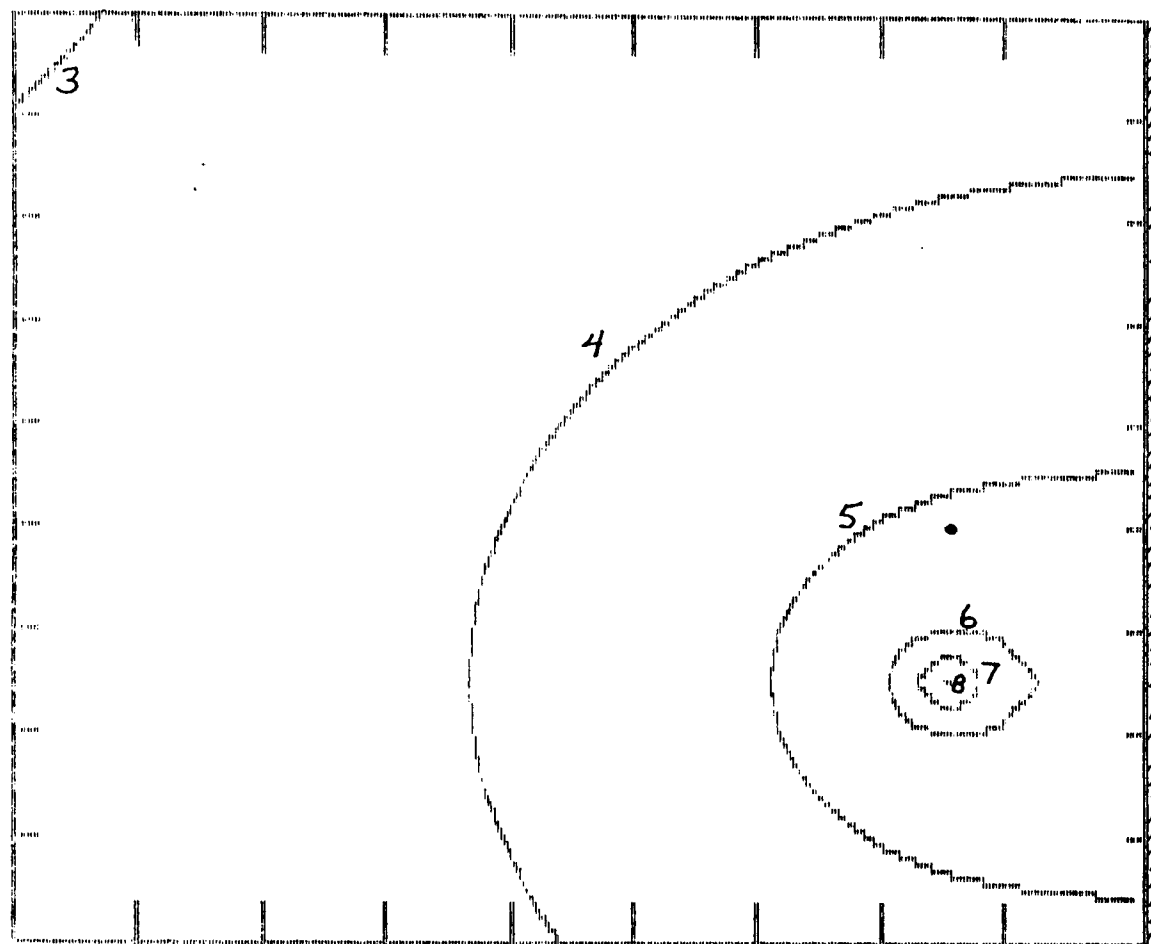


Figure 8c - For comparison with the drawdowns predicted after 7 days of pumping with a recharge source in 8b, the lack of recharge would be expected to lead to ever-increasing drawdowns in the aquifer as pumping continued, with more than 8 ft of drawdown possible in the pumping well after 8 days.

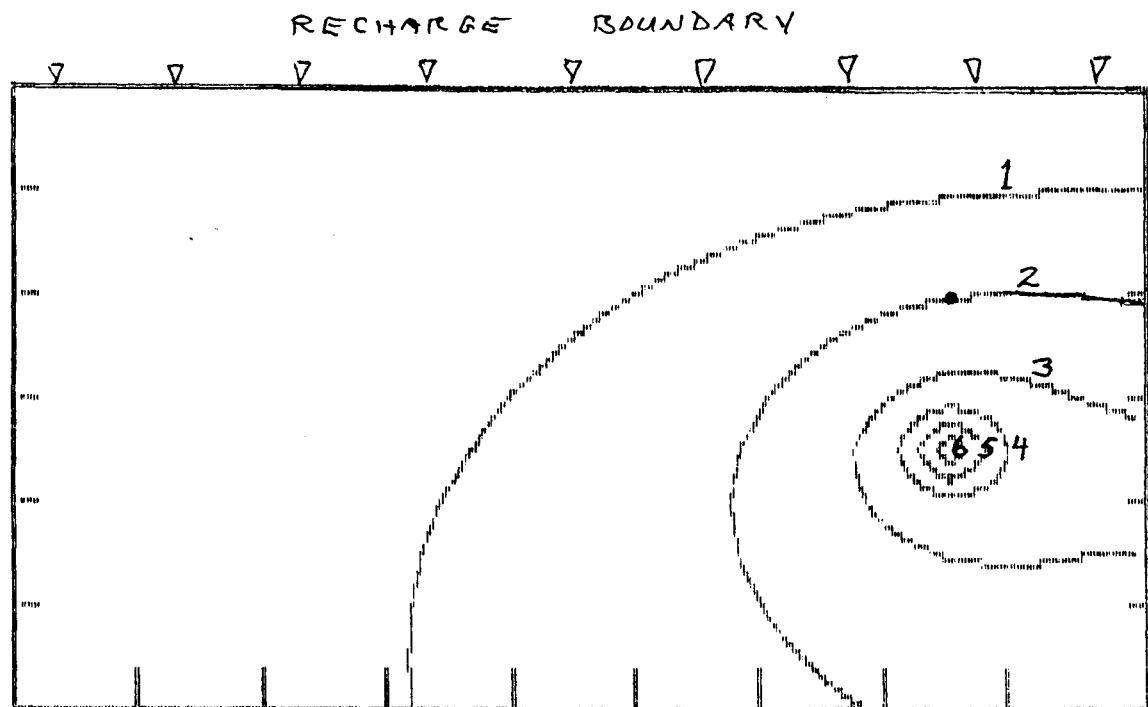


Figure 8d - If a recharge boundary exists, its influence on the aquifer is substantial and depends on its strength (how much water it freely supplies to the aquifer), position (where it exists at the level of the wells' intake zones), and the transmissivity and storativity of the aquifer (how readily its influence is felt by the wells). As an example of the difficulty of interpreting the information obtained from the short-term pumping test, the position of a full-strength recharge boundary has been changed in this simulation, with transmissivity adjusted until the measured drawdown in the pumping well matched the predicted value. Apparent aquifer transmissivity is now 33% lower, or .003 ft²/s. This underscores the need for long-term pumping test data, so that a unique interpretation of observed drawdowns can be made in terms of hydrologic boundaries and aquifer hydraulic properties.

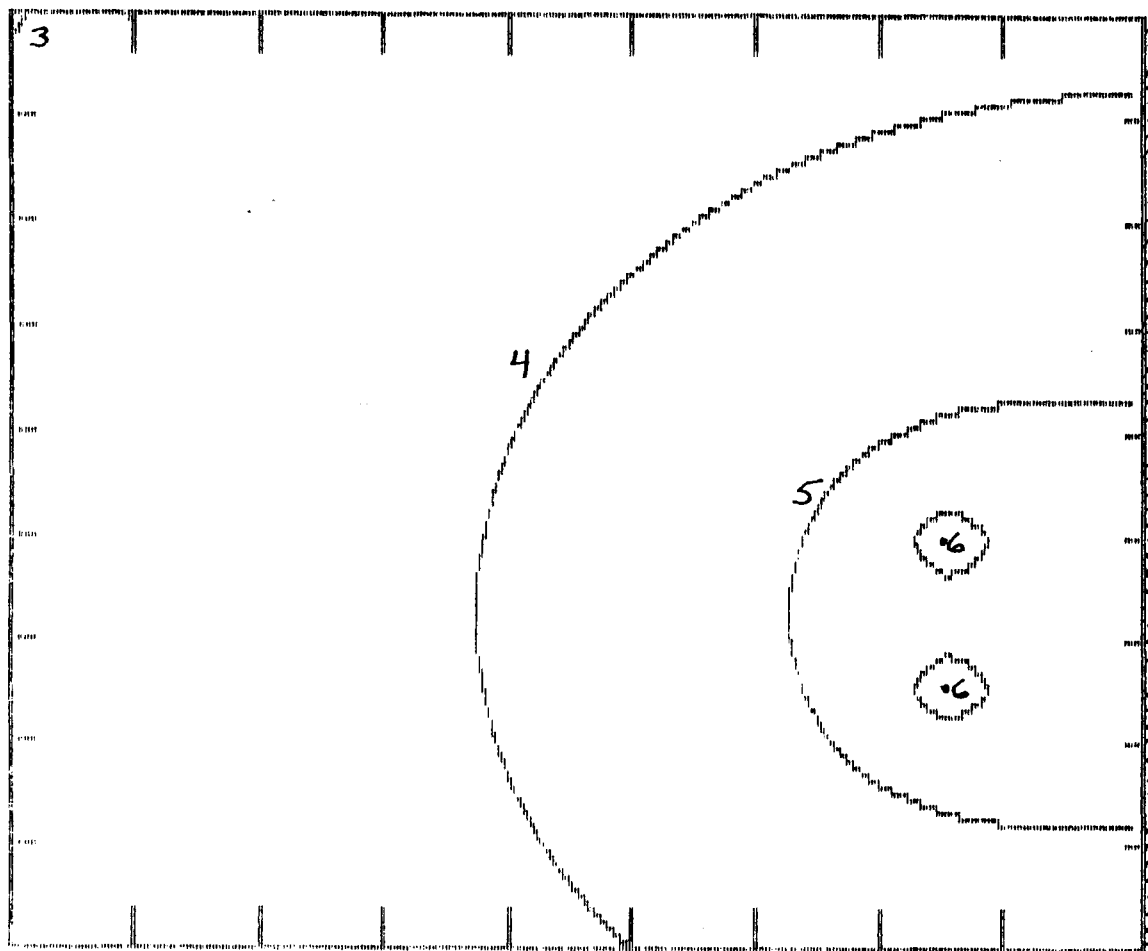


Figure 8e - A hypothetical example of the use of an aquifer model in management planning. In this case, the discharge rate of 9.2 gpm has been equally split between both wells, pumping continuously for 7 days in an aquifer without a recharge boundary. Note that although the drawdown at some distance from the wells is similar to the single well case (Figure 8c), drawdown in either well is substantially less than in a single well pumping continuously at 9.2 gpm.

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March 31, 1993

Mr. Jon Jarvis, Superintendant,
Craters of the Moon National Monument,
P.O. Box 29,
Arco, ID 83213

Dear Jon:

Enclosed is the long-overdue report on the results of the pump tests that were conducted in October, 1992 at the production wells near the mouth of Little Cottonwood Creek.

I didn't envision this report taking so long when we ran the tests, as I didn't expect the multitude of competing factors which made the test results very challenging to interpret. Although the analysis has been very rewarding, it has not been without its frustrations. As you probably know, the pumping test was terminated after only 6 hours due to excessive drawdown in the pumping well (even though it was pumped at only 9 gallons/minute); many of the report's conclusions are therefore tentative because of the multiple interpretations that are possible when a short test is conducted in a complex system. As you will see in the report, there, a number of factors which appear to strongly influence the behavior of the wells. I experimented with several possible aquifer models, in an attempt to learn more about the possible importance of these factors in developing a long-term pumping strategy for the aquifer. In short, it turned out to be a complex and intriguing hydrologic system, and I got carried away with the analysis!

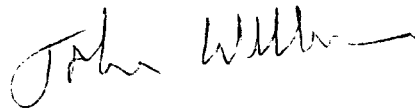
In particular, two different kinds of hydrologic boundaries appear to be very close to the wells (at distances of 30-100 ft), and which have very important implications for the sustainable, long-term production rate that can be derived from these wells: (1) the impermeable bedrock of the valley margin approximately 30 ft east of the wells at depth, whose presence serves to accelerate drawdown in the wells; and (2) a source of water - a so-called recharge boundary - possibly situated in high-permeability, fractured rock less than 100 ft north of the production wells (whose presence can only be inferred at this time based on geologic information and the wells' responses to pumping),

which would serve to reduce the amount of total drawdown in the wells and thereby increase the wells' capacity to provide a long-term, sustained yield.

Because of the short duration of the 10/92 pumping test, only the impermeable boundary has been located with any certainty, although even its existence can be questioned in light of the very short duration of the pump test. Because of the importance of the inferred recharge boundary on the ability of the wells to provide appreciable water, I've recommended that long-term (>72 hour) pump tests be conducted on both wells, together with long-term water level monitoring, and that these data be integrated in a simple computer model of the aquifer-well system to provide a management tool and a basis for future planning and development of this ground water resource. To this end, I've discussed some of the capabilities of such a model for management applications in the section on aquifer modelling in the report.

I'd be glad to discuss the results and implications of the report with you, at any time. Please call me if you have any questions about the report or its recommendations. If you should decide that a follow-up study to achieve these goals is warranted, I'd be happy to work with you and your staff on putting together a proposal.

Sincerely yours,

A handwritten signature in cursive script, appearing to read "John Welhan", followed by a horizontal line.

John Welhan
Supervisory Resident Geologist