DOE/NV/13609-LTR2005-003

Letter Report

Borehole Flow and Horizontal Hydraulic Conductivity with Depth at Well ER-12-4

prepared by

Phil L. Oberlander and Charles E. Russell
Division of Hydrologic Sciences
Desert Research Institute
Nevada System of Higher Education

submitted to

Nevada Site Office
National Nuclear Security Administration
U.S. Department of Energy
Las Vegas, Nevada

December 2005

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: order@ntis.gov
online ordering: http://www.ntis.gov/ordering.htm

Available electronically at http://www.doe.gov/bridge

Available for a processing fee to the U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

DOE/NV/13609-LTR2005-003

Letter Report

Borehole Flow and Horizontal Hydraulic Conductivity with Depth at Well ER-12-4

prepared by

Phil L. Oberlander and Charles E. Russell
Division of Hydrologic Sciences
Desert Research Institute
Nevada System of Higher Education

submitted to

Nevada Site Office
National Nuclear Security Administration
U.S. Department of Energy
Las Vegas, Nevada

December 2005

The work upon which this report is based was supported by the U.S. Department of Energy under Contract #DE-AC52-00NV13609; intended for limited distribution.

ABSTRACT

Borehole flow and fluid temperature during pumping were measured at well ER-12-4 at the Nevada Test Site in Nye County, Nevada. This well was constructed to characterize the carbonate aquifer. The well is cased from land surface to the total depth at 1,132 m (3,713 ft bgs) below ground surface (bgs). The screened section of the well consists of alternating sections of slotted well screen and blank casing from 948 to 1,132 m bgs (3,111 to 3,713 ft bgs).

Borehole flow velocity (LT^{-1}) with depth was measured with an impeller flowmeter from the top of the screened section to the maximum accessible depth while the well was pumped and under ambient conditions. A complicating factor to data interpretation is that the well was not filter packed and there is upward and downward vertical flow in the open annulus under ambient and pumping conditions. The open annulus in the well casing likely causes the calculated borehole flow rates being highly nonrepresentative of inflow from the formation. Hydraulic conductivities calculated under these conditions would require unsupportable assumptions and would be subject to very large uncertainties. Borehole hydraulic conductivities are not presented under these conditions.

ACKNOWLEDGEMENTS

Grateful acknowledgement is given to the following for their contributions to this report: U.S. Department of Energy, National Nuclear Security Administration, Nevada Site Office, for funding this project; Desert Research Institute staff, including Charles Russell (Project Manager), David Gillespie, Brad Lyles, and Scott Campbell, for data collection.

LIST OF ACRONYMS AND ABBREVIATIONS

bgs	below ground surface
cm	centimeters
d/m	degrees Celsius per meter
DRI	Desert Research Institute
EC	electrical conductivity
ER	Environmental Restoration
ft	feet
ft/d	feet per day
$ft^{2/}d$	feet squared per day
ft/min	feet per minute
gpm	gallons per minute
in	inches
kg	kilogram
L^3/T	length cubed per time
L/min	liters per minute
m	meters
m/d	meters per day
m^2/d	meters squared per day
m/min	meters per minute
NTS	Nevada Test Site
psi	pounds per square inch
UGTA	Underground Test Area
UTM	Universal Transverse Mercator grid

INTRODUCTION TO BOREHOLE FLOW LOGGING

Background

The U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office (NNSA/NSO) constructed a series of deep characterization and monitoring wells as part of the Underground Test Area (UGTA) project in southern Nevada. The Desert Research Institute (DRI) characterized borehole flow rates as a part of the UGTA project. Borehole flow rates (L^3T^{-1}) with depth were measured under ambient and pumping conditions. Two types of flowmeters were used for this project: a thermal pulse flowmeter constructed by DRI is used to characterize ambient conditions and can detect vertical borehole flow rates as low as 0.015 meters per minute (m/min) (e.g., 0.05 feet per minute [ft/min]) and an impeller flowmeter was used to characterize borehole flow during well pumping and can detect flow rates as low as 0.75 m/min (e.g., 2.5 ft/min).

Borehole temperature and flow rate measurements were recorded every 0.06 m (0.2 ft) of depth. Flow measurements were collected from above the well screen to the maximum accessible depth in the well. Flow logging did not include the lowest portion of the wells due to the probability of encountering rock detritus that would damage the borehole flowmeter.

Monitoring well ER-12-4 is located in Yucca Flat on the Nevada Test Site (NTS) at NAD 27; UTM (Zone 11) coordinates 4,119,346-m northing, 572,473-m easting. The land surface elevation is 2,098 m (6,883 ft). The well was flow logged in August 2005 by DRI staff. This letter report presents the interpretation of borehole flow, temperature, and hydraulic conductivity within the well. The location of the well with respect to the NTS is illustrated in Figure 1.

Borehole flow measurement was conducted under two conditions: 1) the logged well was under ambient conditions (i.e., not being pumped) and 2) the well was logged while being pumped. Logging under ambient conditions was conducted with two different types of flowmeter. A thermal pulse flowmeter was used to measure subtle vertical flow rates and an impeller flowmeter was used to measure more rapid vertical flow rates.

The selected pumping rate represents a balance between the minimum pumping rate that provides sufficient cooling water flow past the submersible electric motor and the maximum pumping rate that avoids excessive drawdown in the well. Because of the well's limitation in producing water and the flow requirement for cooling water, the only logs that could be repeated at differing line speeds were conducted while pumping at 59 L/min (15.7 gpm). Flow logging was conducted at nominal line speeds (the speed at which the geophysical tools are raised or lowered in the well) of 6, 9, and 12 m/min (20, 30, and 40 ft/min). The different combinations of logging speeds and pumping rates provide eight unique data sets for pumping conditions that aid in reducing measurement uncertainty and mechanical bias.

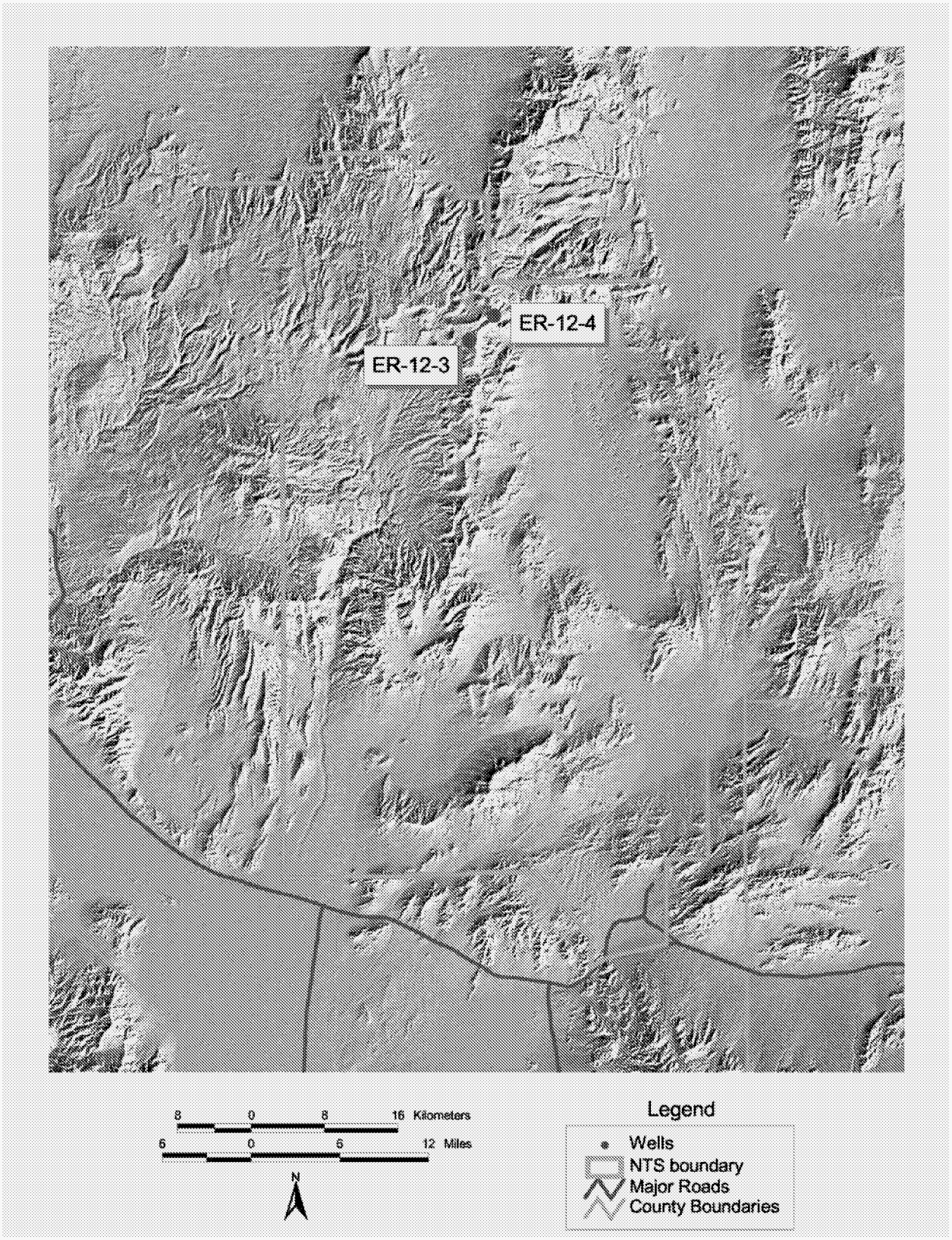

Figure 1. Location of UGTA wells ER-12-3 and ER-12-4 at the Nevada Test Site.

Flow Logging Equipment

The UGTA program uses a high-precision, wireline borehole flowmeter that can retract the impeller blades to enter 7-cm (2.75-inch) diameter access tubing that extends past the pump and submersible motor assembly. As the flowmeter exits the access tube at depth, the impellers unfold and extend to nearly 14 cm (5.5 inches). The borehole flowmeter uses lightweight impellers and minimal shaft seals to allow rotation at fluid velocities as low as 0.75 m/min. The flow rate logging equipment consists of Computalog® Flexstak tools arranged from top to bottom in the following order: telemetry cartridge, centralizer, temperature tool, centralizer, and the borehole flowmeter with a coaxial centralizer.

The temperature tool is rated for a maximum of 176°C and the tool string is rated to a maximum pressure of 117.2 megapascals (17,000 pounds per square inch [psi]). Three centralizers are used to ensure that the tool string is centered in the casing. Temperature measurements supplement the borehole flow rate information.

The borehole flow-logging computer records impeller rotation rate (revolutions per second), temperature, cable speed (LT^{-1}), and depth (L). An interface cable is connected between the flowmeter at land surface and the borehole flow-logging computer. The well discharge rate (L^3T^{-1}) at land surface and the downhole borehole flow rate (L^3T^{-1}) are recorded simultaneously. Borehole flow rates and fluid temperatures are measured every six centimeters while the borehole flowmeter is continuously lowered or raised (i.e., a trolling flowmeter). Recording borehole flow rate and temperature measurements every six centimeters is an UGTA data requirement to aid in accurately identifying the locations where there is groundwater inflow at fractures. In a 1,000-m-long water column, this measurement scheme produces about 16,000 depth-specific borehole flow measurements for each log. As a normal practice, the data are not interpreted at this spatial scale. The data are typically interpreted at a vertical scale of 1.5 m or greater to reduce the measurement noise in the calculated hydraulic conductivities. The 6-cm data spacing is used to accurately align the instrument measurements with cased sections, screen intervals (if any), and changes in bore diameter.

A second type of flowmeter used to characterize UGTA wells is a thermal pulse flowmeter (thermal flowmeter). This flowmeter electrically heats a wire element and detects the heated water that moves upward or downward with the vertical flow in the well. The thermal flowmeter is calibrated under laboratory conditions to account for buoyancy effects. This flowmeter was used to characterize ER-12-4 under ambient flow (i.e., nonpumping) conditions and can detect borehole flow rates much lower than the impeller flowmeter.

ANALYSIS METHODOLOGY

Hydraulic Conductivity Determined from Borehole Flow Rates and Pressures

Horizontal hydraulic conductivity with depth is calculated based on measurement of the borehole flow rate with depth while the well is pumped at a constant rate. The borehole flow rate data are interpreted using the methodology developed by Rehfeldt *et al.* (1989), in which the hydraulic conductivity of an interval is a function of the interval's groundwater contribution to the well discharge and the change in fluid pressure (i.e., water level drawdown) caused by pumping. The hydraulic conductivity over an interval under steady-state conditions is defined as

$$K_i = \frac{(q_o - q_n)}{(2 * \pi * (h_o - h_n))} \ln \frac{Ra}{ro} \qquad (1)$$

where K_i is the interval hydraulic conductivity (LT^{-1}),
q_o is the ambient flux through the aquifer for an interval (L^2T^{-1}),
q_n is the pumping flux through the aquifer for an interval (L^2T^{-1}),
h_o is the pressure at an interval at ambient conditions (L),
h_n is the pressure at an interval under pumping conditions (L),
Ra is the effective hydraulic radius during pumping (L), and
ro is the radius of the borehole (L).

The information necessary to apply Equation (1) is provided by aquifer testing and borehole flow logging. Groundwater inflow rates are taken as the difference between successive depth-dependent borehole flow rates. This assumes that all changes in borehole flow rate are caused by groundwater inflow from the formation. The effective hydraulic radius is estimated from aquifer test parameters and includes an adjustment for the deliberate changes in pumping rate between certain flow logs. The radius of the borehole within each calculation interval is taken from caliper log measurements of the bore before placing casing in the well.

Fluid pressure with depth necessary for Equation (1) was not measured directly during flow logging. This is because a pressure transducer capable of operating at a high level of precision over a very large pressure range was unavailable. Pressure with depth is estimated based on measured fluid temperature, height of the fluid column, and the well-known temperature dependencies of fluid density and fluid compressibility. Where the fluid in the well is flowing, the effects of temperature-dependent viscosity and friction loss (laminar and turbulent conditions) are used in the pressure calculation based on standard engineering equations for flow in pipes. The pressure estimations under nonpumping conditions have been compared to values measured by transducers set at depths of 235 to 1,101 m bgs (771 to 3,613 ft bgs) at other UGTA wells. Pressure estimation errors are generally between 6.9 and 27.6 kilopascals (1 and 3 psi).

Horizontal hydraulic conductivity calculated in Equation (1) is based on the *change* in pressure at a specific depth caused by pumping and not the absolute value of pressure. Therefore, a minor systematic inaccuracy in the estimate of ambient and pumping pressures becomes less important to the analysis.

The physical processes not included in the pressure calculation are:

- the amount of total dissolved and suspended solids, which increases pressure with increasing concentration, and
- dissolved and entrained gasses, which decrease fluid pressure.

Exclusion of these opposing processes does not appear to affect significantly the accuracy of the static fluid pressure prediction.

Pumping causes two major pressure effects within the well. The first effect is the pressure change caused by lessening the height of the fluid column by inducing water-level drawdown.

The second pumping effect is the typical replacement of the ambient borehole fluid with a fluid of a different temperature and density. When the replaced borehole fluid has lesser density (i.e., a warmer fluid), the fluid has less mass per unit volume than the more dense fluid initially in the well. If the borehole fluid temperature increased in a nonpumping well, the pressure at depth would remain constant and there would be a corresponding increase in water-level elevation.

In pumping wells, the effect of fluid density decrease functions in concert with the water-level drawdown to decrease pressure at depth. The density effect on fluid pressure is not uniform with depth and becomes more pronounced over longer fluid columns. This can be illustrated by considering the pressure change during pumping at two locations within the well, at the water surface and with increasing depth. The fluid pressure in a moving water column is described (Vennard and Street, 1975) as

$$P_t = (\rho * g * h) + (\tfrac{1}{2} \rho_p * V^2) + P_e \qquad (2)$$

where P_t is the total pressure at the measurement point ($ML^{-1}T^{-2}$),
ρ is the effective fluid density above the measurement point (ML^{-3}),
g is gravitational acceleration at the measurement point (LT^{-2}),
h is the height of the fluid column above the measurement point (L),
ρ_p is the fluid density at the measurement point (ML^{-3}),
V is the fluid velocity at the measurement point (L/T), and
P_e is the externally applied pressure ($ML^{-1}T^{-2}$).

There is no externally applied pressure in the case of boreholes except atmospheric pressure and aquifer matrix compression. The external pressure (P_e) is assumed zero. The borehole fluid near the water-level surface is many meters above the pump intake and the fluid velocity (V) is essentially zero. The hydraulic head pressure can then be calculated by the simplified equation

$$P = (\rho * g * h) \qquad (3)$$

where the terms are as above.

First, consider the fluid pressure change at the top of the water column during pumping. The fluid pressure change is determined with Equation (3) by subtracting the pressure under pumping conditions from the fluid pressure under nonpumping conditions. At the top of the water column during pumping, the height of the fluid column (h) is zero and the fluid pressure at the water surface is zero. Therefore, at the pumping water level, the change in fluid pressure is caused solely by the water-level drawdown (i.e., removal of the fluid above the pumping water level).

Secondly, consider pressure at increasing depth. At depth, the pressure change caused by pumping includes the constant pressure decrease caused by drawdown (i.e., the change in [h]) and the pressure change caused by the change in fluid density (ρ) between a specific depth and the top of the fluid column. With increasing depth, the relatively small changes in fluid density caused by pumping act over longer fluid columns and the effect on fluid pressure change becomes more pronounced. Therefore, when the fluid density changes with depth during

pumping, the resulting fluid pressure change with depth is not uniform. In most UGTA wells, there are notable variations in fluid temperature and fluid density with depth under nonpumping and pumping conditions. Therefore, the fluid pressure change caused by pumping is variable with depth and nonlinear. When fluid density varies significantly, drawdown during pumping does not represent the total pressure change at depth. In the deep UGTA wells such as ER-EC-1, the pressure change at the bottom of the well caused by replacement of cooler fluids with warmer fluids during pumping was equivalent to over 3 m (10 ft) of additional water-level drawdown. In UGTA well ER-12-4, the change in thermally induced density has an insignificant affect on fluid pressure.

The apparent radius of influence used in Equation (1) is calculated based on the Thiem equation (Driscoll, 1986) and calculated transmissivity, estimated storativity, pumping rate, well diameter, and period of pumping. An apparent radius of influence is calculated for each pumping rate. The well was not allowed to recover fully between the changes in pumping rates and the effective time of pumping is used to calculate the apparent radius of influence. This calculation is performed in a manner similar to interpreting a step drawdown test based on the Cooper-Jacob Step Pumping Method (Kruseman and de Ridder, 1970). These interpretive techniques assume that the flow field during well logging is:

- fully radial,
- strictly horizontal, and
- at steady state.

These assumptions are probably not fully met in the fractured carbonate aquifer underlying permeable tuff. The affects of these simplifying assumptions are not quantified.

Flow Log Specific Calibration

The borehole flowmeter records with depth the impeller revolution rate as counts per second. A separate thermistor measures fluid temperature. Borehole flow rates are plotted in the field based on a simple calibration scheme. However, the borehole flowmeter is subject to mechanical wear on the impeller shaft bearings and grease and grit adhering to the impeller blades. The source of this material is believed to be the grease used on casing threads and a combination of grit from the formation and scale from the mild steel access tubing. Therefore, the borehole flow logs are post-processed to calibrate each log individually to account for the time-varying instrument condition. Combining individual logs without accounting for changes in mechanical efficiency of the borehole flowmeter would result in information degradation.

The individual flow logs are downloaded from the geophysical logging computer as spreadsheet files. The impeller rotation rate and cable travel speed are post-processed along with well construction information to refine the borehole flow calculations. Specifically, the effects of pumping rate, well diameter, vertical travel speed and direction of the logging tool (cable line speed), and instrument calibration are considered in calculating the final borehole flow rate.

A consideration in flowmeter calibration is accounting for the apparent flow caused by moving the flowmeter through the water column while measuring borehole flow rates. The casing diameter and the travel speed of the flowmeter are used to calculate the apparent

volumetric borehole flow rate. The apparent flow is assumed to occur as slug flow without a velocity change across the well diameter. This assumption is slightly simplistic compared to the actual borehole conditions (i.e., nonlaminar pipe flow). Small changes in casing diameter or inaccuracy in cable travel speed would also affect the predicted borehole flow rate and flowmeter calibration.

Each borehole flow log includes logging about 12 m (40 ft) within the blank casing above the interval open to the aquifer. This portion of the log is important because within this cased interval the borehole flow rate is the same as the well discharge.

The borehole flowmeter is recalibrated for each logging run by comparing downhole flow rate above the open bore to the land surface flowmeter. The surface flowmeter used to control the pumping rate is magnetic and the installation has an appropriate length of straight pipe upgradient and downgradient of the flowmeter to limit turbulence. Typically, the surface flowmeter exhibits very steady readings with standard deviation of about five liters per minute (L/min). The geophysical logging computer is linked via a communications cable to the land surface flowmeter and simultaneously records readings by both the land surface flowmeter and the borehole flowmeter. When the borehole flowmeter is positioned in the casing above the open bore, the two meters should provide similar results. Knowing the actual borehole flow rate from the land surface flowmeter, the borehole flowmeter can be recalibrated for each log. Recalibration consists of calculating the slope and y-intercept of a linear equation relating impeller rotation rate to the known well discharge rate.

Recalibration occurs only in the upper portion of each flow log. Sometimes the calibration section is logged at the beginning of the log (e.g., when logging downward) and sometimes at the end of a log (e.g., when logging upward). Ideally, there would be a section of blank casing located at the bottom of the well so that the flowmeter could be calibrated at the top of the log to the known pumping rate and again at the bottom of the log under a no-flow condition. Calibration parameters are also adjusted for changes in borehole diameter based on a caliper log.

Flow rates in the cased well are reported only as measured within the 14-cm (5.5-inch) casing. Borehole flow rates outside the casing and in the annulus between the casing and the borehole wall are difficult to extrapolate because the flow velocity (LT^{-1}) outside the casing may not be the same as inside the casing. The calculated flow rates in the screened sections for upward logging and downward logging at the same line speed produced very different results. Additionally, the discrepancy between the upward and downward flow rates increased with logging line speed. This effect strongly indicates that the borehole flowmeter restricted flow in the casing and that water was being pushed through the well screen and into the open annulus (i.e., the space between the outside of the well casing and the formation). Typical well construction provides a filter pack that presents flow resistance and most of the fluid remains inside the screened interval. Averaging flow logs conducted at the same line speed in upward and downward directions removed most of the flow effect and determined representative values for flow at that pumping rate.

ABSTRACTION OF FLOW LOGGING INFORMATION

The borehole flowmeter impeller rotation rate is recorded every six centimeters of logging depth. The relatively short recording distance of just a few centimeters allows accurate depth identification of abrupt borehole flow features such as large groundwater inflow rates at discrete fractures. The six-centimeters recording distance also causes the logging system to base the impeller rotation rate on a limited number of rotations. The rotation rate is calculated by the logging computer based on four discrete "counts" per rotation. At the slowest logging line speed of about six meters per minute, there are 0.6 seconds of impeller rotations available to calculate the average rotation rate. Logging at higher travel speeds of 9.1 to 12.2 m/min reduces the recording interval to every 0.4 to 0.3 seconds, respectively. The short time period available for data collection limits the number of impeller rotations (or partial rotations) before data recording. Therefore, apparent short-term flow rate variations are imbedded in the data. It is important to reduce the small-scale flow rate variations caused by measurement noise so that they are not attributed to changes in borehole flow rate or hydraulic conductivity. The field measurements are post-processed using more sophisticated techniques than the field plot calibration to calculate hydraulic conductivity with depth and includes:

- averaging within and among the borehole flow logs,
- removing spurious data within a log by filtering,
- smoothing the small-scale instrument noise by averaging the higher quality data among logs at a common depth and pumping rate,
- reducing data volume for easier handling and smoothing data by averaging over vertical intervals within the composite log for a given pumping rate, and
- abstracting the essential flow data trends at an appropriate spatial scale within the open bores.

These processes are applied in a specific sequence and at appropriate scales to preserve hydrogeologic information as described in Oberlander and Russell (2003). A brief discussion of the major data processing steps is provided below.

Removing Impeller Stalls

Data filtering is used to remove spurious data within an individual flow log. At certain upward logging line speeds, the velocity of the fluid column and flowmeter are nearly the same. Under this condition, there is insufficient flow past the impeller to cause rotation (i.e., the impeller stalls). As the upward velocity of fluid in the borehole changes with the groundwater inflow, the impeller resumes rotation.

Impeller stalling is addressed by trolling the flowmeter at up to four different travel speeds and operating the well at up to three pumping rates. This causes stall locations (if any) to be over different depth intervals for each flow log. Under ideal conditions, the flowmeter rotates when the vertical flow velocity is greater than about 0.75 m/min. Impeller stalls are readily indicated by locations of a few meters to a few tens of meters in length where there was no impeller rotation. Impeller stalls are bracketed by the minimum upward and downward flow

velocity sufficient to cause rotation. Within this velocity range, it is not possible to calculate an accurate borehole flow rate, and the data for that portion of the flow log are omitted from the analysis.

Filtering and Compositing among Logs Collected at a Common Pumping Rate

More subjective is determining where the flowmeter was experiencing difficulty in freely rotating or had been perturbed mechanically or hydraulically, causing a spurious calculated flow rate. A comparison of borehole flow rates measured at the same pumping rate and depth indicates the consistency of calculated borehole flow rates. Ideally, borehole flow measurements collected at the same depth and the same pumping rate should be nearly the same value. Experience with these logs indicates that there can be significant differences in flowmeter values, even after individually calibrating the flow rate logs and removing impeller stalls. Some of the differences in the apparent flow rates are believed to be caused by sudden changes in flowmeter efficiency during logging. If grit or grease affects the impeller efficiency, suddenly or progressively during a log, then the calibration coefficients calculated at the beginning or end of a log can be somewhat inaccurate and produce anomalous values.

Variability among the borehole flow rates is evaluated by calculating the standard deviation of the three to six values collected at the same depth and pumping rate. The standard deviation of only a few values does not reflect the same statistic as if there were many borehole flow measurements at the same pumping rate at the same depth location. If there were many flow measurements at the same depth and pumping rate, an evaluation of statistical confidence and outliers could be performed according to standard statistical practices. The standard deviation used within this context is only to identify which log is causing the largest difference among values. The identification of anomalous data is performed at the spatial logging scale of six centimeters because irregular flow features often occur over small vertical distances.

The anomalous values are removed by a filter that evaluates the borehole flow rates at a constant depth and identifies which flow log's rate is most different from the other rates. If the difference is greater than a specified threshold value (i.e., the filter strength), that log's flow rate is removed from the analysis. The filter strength is adjusted based on judgment to account for the individual quality of each logging suite. The data are filtered at various levels to determine qualitatively when most of the anomalous data have been removed. Application of a filter to remove anomalous data also has the potential affect of smoothing the data and disrupting the calculated mass balance within the borehole, depending on the amount of filtering selected. The minimum amount of filtering necessary to remove the largest differences between flow rate measurements is used.

Compositing Flow Logs at a Constant Flow Rate

The individual flow logs at a common pumping rate are composited after removing anomalous values. By logging at various line speeds within a common pumping rate, information gained at one logging line speed may not be recognized at another line speed because of impeller stalling. By compositing the individual logs collected at a common pumping rate, data gaps are filled by information from other logs. This effectively combines the information collected at various logging speeds into a single representation of flow in the well for each pumping rate and smoothes the measurements. The flow rate measurements made at a common pumping rate and

depth are composited by averaging at the measurement scale of six centimeters. These values exhibit flow rate variations about the mean that can be reduced to better define borehole conditions and a more confident interpretation of hydraulic conductivity.

MONITORING WELL ER-12-4

Well Construction

Monitoring well ER-12-4 is located on Rainier Mesa at the NTS at NAD 27; UTM (Zone 11) coordinates 4,119,346-m northing, 572,473-m easting. The land surface elevation is 2,098 m (6,883 ft). The well construction and completion are summarized in Table 1. The well is cased and screened in the logged section. A factor that disturbed borehole flow during logging was the open annulus between the well screen and the well bore. This zone provided an open conduit for water to flow outside the well casing during well logging as discussed below.

Table 1. Summary of ER-12-4 well construction.

Depth Interval (m)	Depth Interval (ft)	Diameter (cm)	Diameter (in)	Comments
0 - 762	0 - 2,501	47.0	18.5	borehole diameter
762 - 1,132	2,501 - 3,715	31.1	12.25	borehole diameter
606 - 678	1,988 - 2,225	47.0	18.5	annulus cement
0 - 922	0 - 3,026	19.4	7.625	blank casing
922 - 948	3,026 - 3,111	14.0	5.5	blank casing
948 - 959	3,111 - 3,154	14.0	5.5	well screen
959 - 974	3,154 - 3,197	14.0	5.5	blank casing
974 - 987	3,197 - 3,239	14.0	5.5	well screen
987 -1,000	3,239 - 3,282	14.0	5.5	blank casing
1,000 - 1,013	3,282 - 3,325	14.0	5.5	well screen
1,013 - 1,027	3,325 - 3,368	14.0	5.5	blank casing
1,027 - 1,040	3,368 - 3,411	14.0	5.5	well screen
1,040 - 1,053	3,411 - 3,454	14.0	5.5	blank casing
1,053 - 1,066	3,454 - 3,497	14.0	5.5	well screen
1,066 - 1,079	3,497 - 3,540	14.0	5.5	blank casing
1,079 - 1,092	3,540 - 3,583	14.0	5.5	well screen
1,092 - 1,105	3,583 - 3,626	14.0	5.5	blank casing
1,105 - 1,118	3,626 - 3,669	14.0	5.5	well screen
1,118 -1,131	3,669 - 3,711	14.0	5.5	blank casing
1,131 - 1,132	3,711 - 3,713	14.0	5.5	bullnose

Ambient Flow in the Well Bore

The thermal pulse flowmeter was used to measure vertical flow in the well under unpumped conditions. The thermal flowmeter measurements are taken while the flowmeter is stationary in the well. The ambient flow measured in the uncased and cased well is presented in Tables 2a and 2b.

Table 2a. Ambient flow in the uncased bore for UGTA Monitoring Well ER-12-4.

Depth (m)	Depth (ft)	Flow Rate (L/m)	Flow Rate (gpm)
838	2,750	0.840	0.222
866	2,840	0.000	0.000
899	2,950	0.000	0.000
991	3,252	0.000	0.000
1,036	3,400	0.000	0.000
1,073	3,520	0.000	0.000
1,113	3,650	0.000	0.000

Table 2b. Ambient flow in the cased bore for UGTA Monitoring Well ER-12-4.

Depth (m)	Depth (ft)	Flow Rate (L/m)	Flow Rate (gpm)
0	3,030	0.000	0.000
945	3,100	0.000	0.000
968	3,175	0.606	0.160
994	3,260	0.477	0.126
1,018	3,340	0.416	0.110
1,047	3,435	0.000	0.000
1,074	3,525	-1.491	-0.394
1,097	3,600	-2.866	-0.757
1,128	3,700	0.000	0.000

These data indicate different flow conditions in the well following installation of well casing as illustrated in Figure 2. A consideration in the interpretation of thermal pulse flowmeter data is that the thermal flowmeter contains flexible flow diverters to force water in the casing past the thermal sensors. Under normal flow conditions, the diverters have minimal affect on flow in the well. In well ER-12-4, the flow diverters may have forced water out of the well screen and into the open annulus. Significant flow diversion out of the casing would invalidate the borehole flow measurements. Alternatively, the ambient flow in the well was not established until well development was completed.

This circumstance does not invalidate the findings of more detected flow in the well under cased conditions than under uncased conditions or the direction of borehole flow. The impeller flowmeter has an "open cage" design that allows water to more freely flow through the instrument than the thermal pulse flowmeter. The importance of this difference in instrument design will be noted later in this report.

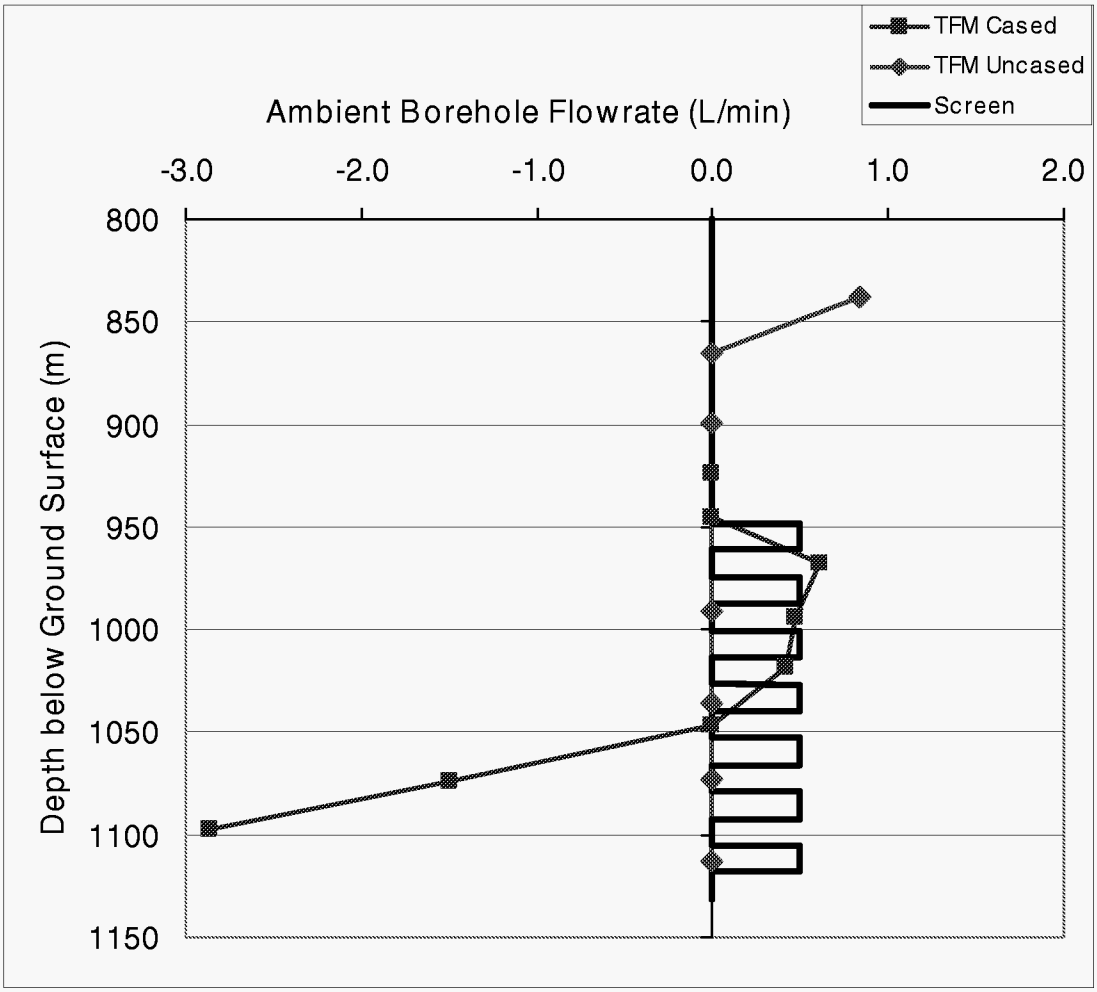

Figure 2. Ambient flow rates provided by the thermal pulse flowmeter for cased and uncased conditions.

Ambient flow under uncased conditions is upward at 838 m bgs (2,750 ft bgs). Under cased conditions the flow is upward between 968 and 1,018 m bgs (3,175 and 3,340 ft bgs) and downward between 1,074 and 1,097 m bgs (3,525 and 3,600 ft bgs).

To understand more fully the potential changes in borehole flow caused by installing casing, the Chemtool temperature logs for uncased and cased conditions were evaluated. Figure 3 illustrates the fluid temperature from the water table to total accessible depth. The temperature logs also indicate that there was a change in the ambient flow field after installation of well casing. The thermal profile before casing installation indicates a nearly uniform geothermal gradient with a very minor change in slope at about 1,014 m bgs (3,327 ft bgs). The thermal profile for cased conditions indicates significant changes to borehole flow with an apparent source of cool water entering at about 912 m bgs (2,992 ft bgs). At the top of the upper well screen there is a severe steepening of the thermal gradient to the bottom of the lower well screen. A steep thermal gradient is often associated with strong vertical fluid flow.

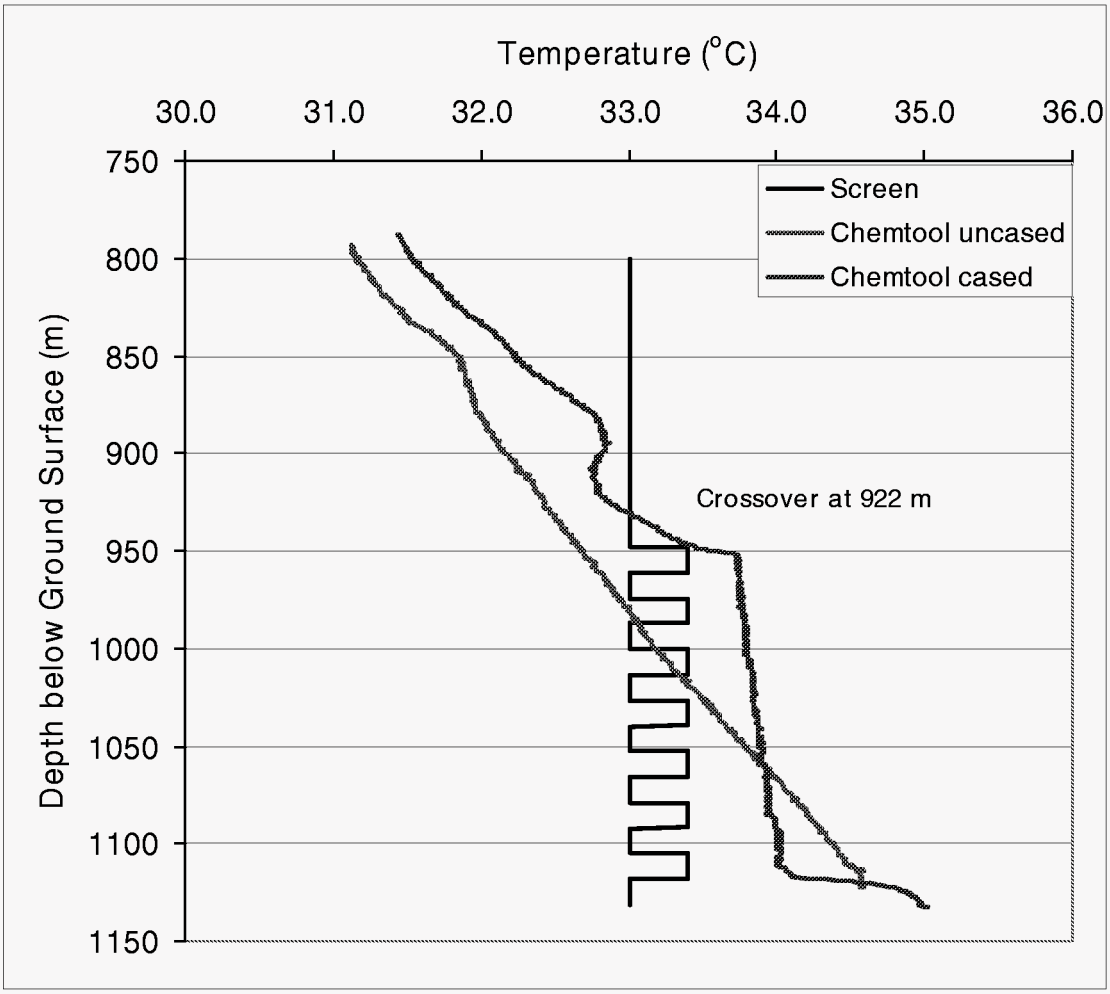

Figure 3. Chemtool fluid temperature logs.

The most likely explanation is there was a major change in groundwater flow rates and locations after casing installation and formation development. This would explain the greater variability in ambient borehole flow and fluid temperature once the well was allowed to flow freely along the open interval.

The water entering the well may be flowing rapidly in the screened section and thus causing the very steep thermal gradient. The abrupt change in the thermal profile above the well screen at about 912 m bgs (2,992 ft bgs) is not understood because this zone has an open annulus and water should be able to freely flow in the vertical direction. The thermal log for ER-12-4 has similarities to the log for ER-12-3 that may aid in future understanding of the underlying flow regime.

Water-producing Zones under Stressed Conditions

The well was borehole flow logged in August 2005 by DRI staff. The summary of each borehole flow log is presented in Table 3. The maximum accessible depth to the logging tools was about 1,119 m bgs (3,670 ft bgs).

Table 3. Impeller borehole flow logs for UGTA Monitoring Well ER-12-4 (August 2005). Downward logging is indicated by a negative sign.

Log Destination	Pumping Rate (L/min)	Pumping Rate (gpm)	Line Speed (m/min)	Line Speed (ft/min)
MOV 01	0.0	0.0	-6.3	-20.7
MOV 02	0.0	0.0	6.8	22.3
MOV 03	0.0	0.0	-12.8	-42.0
MOV 04	0.0	0.0	12.8	42.0
MOV 05	0.0	0.0	-9.5	-31.3
MOV 06	0.0	0.0	9.7	31.8
MOV 07	31.0	8.2	-6.3	-20.8
MOV 08	52.2	13.8	-13.2	-43.4
MOV 09	83.7	22.1	-10.0	-32.8
MOV 10	62.5	16.5	10.0	32.9
MOV 11	62.1	16.4	-13.1	-43.1
MOV 12	57.9	15.3	13.0	42.8
MOV 13	57.5	15.2	-6.5	-21.4
MOV 14	56.8	15.0	6.7	22.1

Vertical profiles of borehole flow were measured while pumping at nominal rates of 31, 59, and 84 L/min (8, 15, and 22 gpm). The single log conducted while pumping at 31 L/min was not sustainable because of the cooling water requirements for the submersible motor. That pumping rate was used for only one log. A single log conducted at a pumping rate of 84 L/min caused excessive water level drawdown in the well. The borehole flow interpretation is based on the logs conducted at a nominal pumping rate of 59 L/min (15.7 gpm) and under ambient conditions.

The processed flow logs were subject to wide variation in results depending on logging direction and line speed. This is interpreted as water inside the well screen being diverted into the open annulus by the moving borehole flowmeter. In filter-packed wells, the material outside the screen somewhat restricts flow and thus tends to keep water inside the well screen. There is no such limitation in a well with an open annulus and water freely exchanges between the annulus and inside the well screen. A minor flow restriction such as a borehole flowmeter therefore can cause large apparent changes in flow inside the well screen.

The individual flow logs for well ER-12-4 under ambient conditions are illustrated in Figure 4. The logs indicate an unrealistically wide variation in calculated borehole flow rates. The ambient flow logs were successfully calibrated in the cased section above the well screen as evidenced by the values approximate to zero above 950 m. The calculated flow rates below 950 m bgs (3,117 ft bgs) produce a range of results with apparent changes in the flow rate in the

blank casing. The calculated flow rates again demonstrate calibration in the blank casing below the deepest well screen, indicating the anomalous results are not caused by a mechanical problem or numerical error.

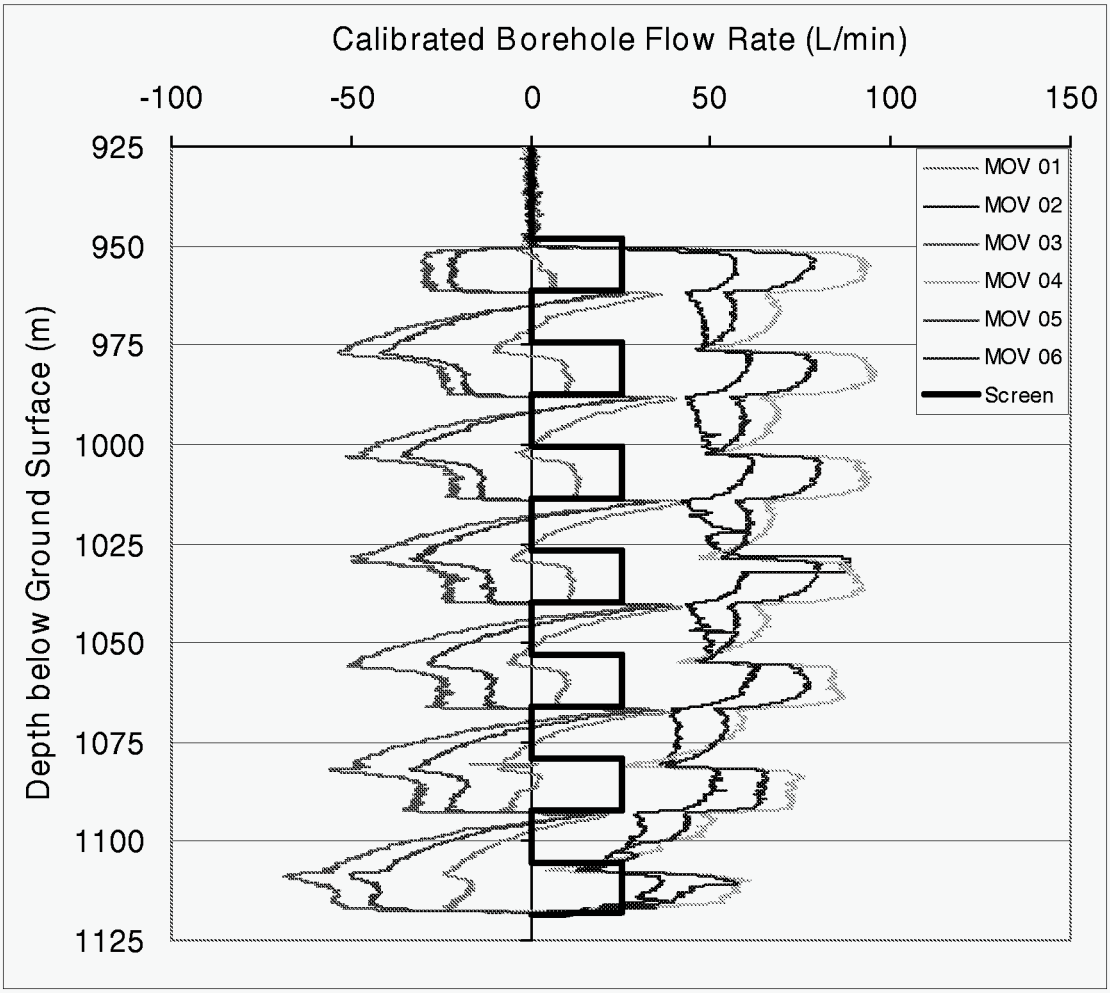

Figure 4. Calculated borehole flow rates under ambient conditions.

At first assessment, the logs appear to contain no usable information. Continued evaluation demonstrates several features that indicate the logs are accurately representing the conditions encountered inside the well casing. The log characteristics include:

- upward logs provide the highest values,
- downward logs provide the lowest values,
- upward logs tend to produce similar values when entering the bottom of a section of blank casing,
- downward logs tend to produce similar values when entering the top of a section of blank casing,

- calculated flow rates for individual logs vary from higher to lower values when transversing blank casing, and
- the higher flow values are related to the higher line speeds.

These log features are accentuated by illustrating the impeller rotation rates for two representative flow logs in Figure 5. Impeller rotation is clearly affected by the flowmeter entering and exiting well screen and blank casing. The features important to interpreting the impeller rotation data are provided on the figure.

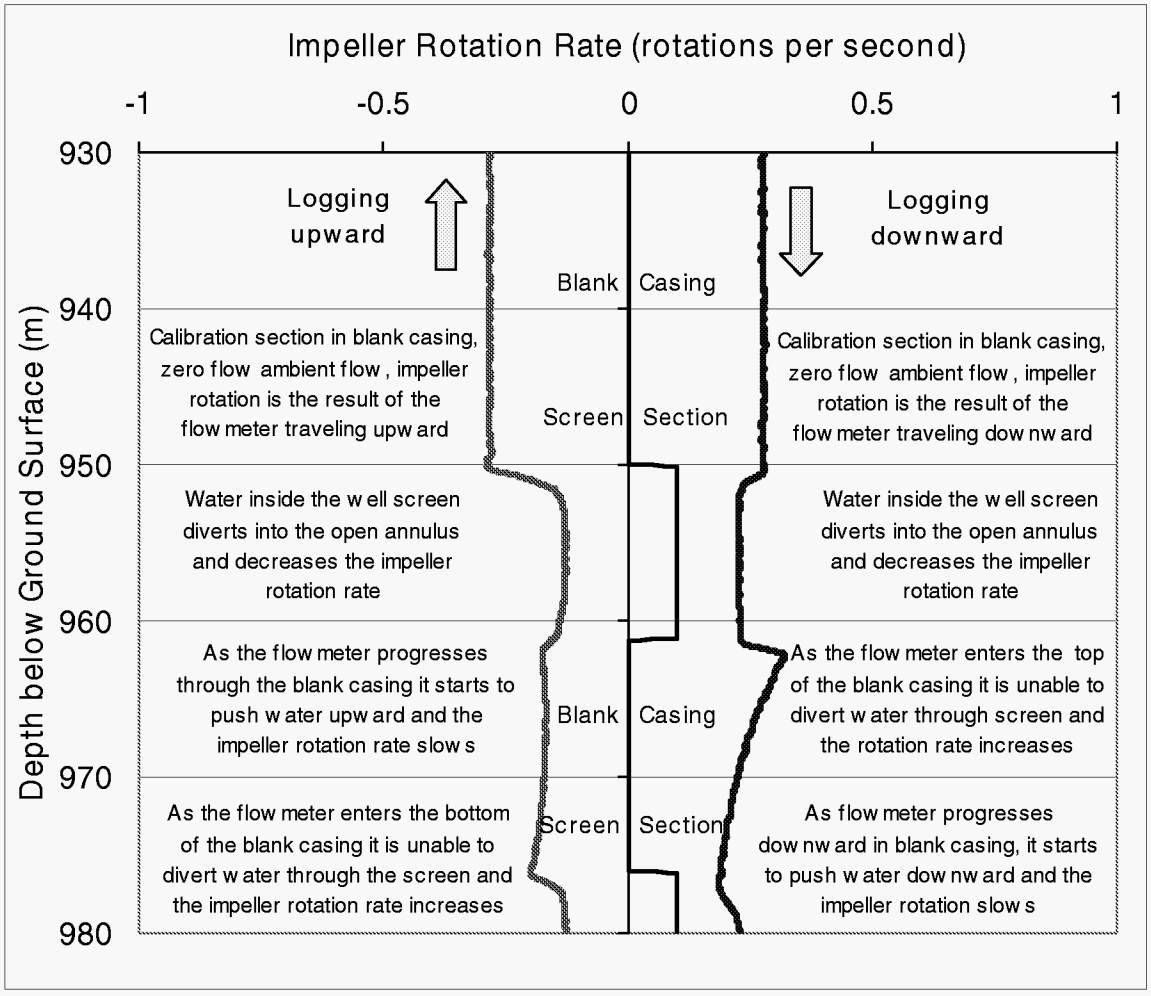

Figure 5. Impeller rotation rates for upward and downward logs.

The figure suggests that as the flowmeter enters blank casing (traveling either upward or downward), the flow rate is least affected by flow diversion through the well screen. As noted above, these locations have similar calculated flow rates when logging at various line speeds. The flowmeter entry locations into blank casing are illustrated on Figure 6. Comparing the calculated flow rate at the bottom of the blank casing when logging upward and the top of the blank casing when logging downward provided similar, but not identical, flow values at all line speeds.

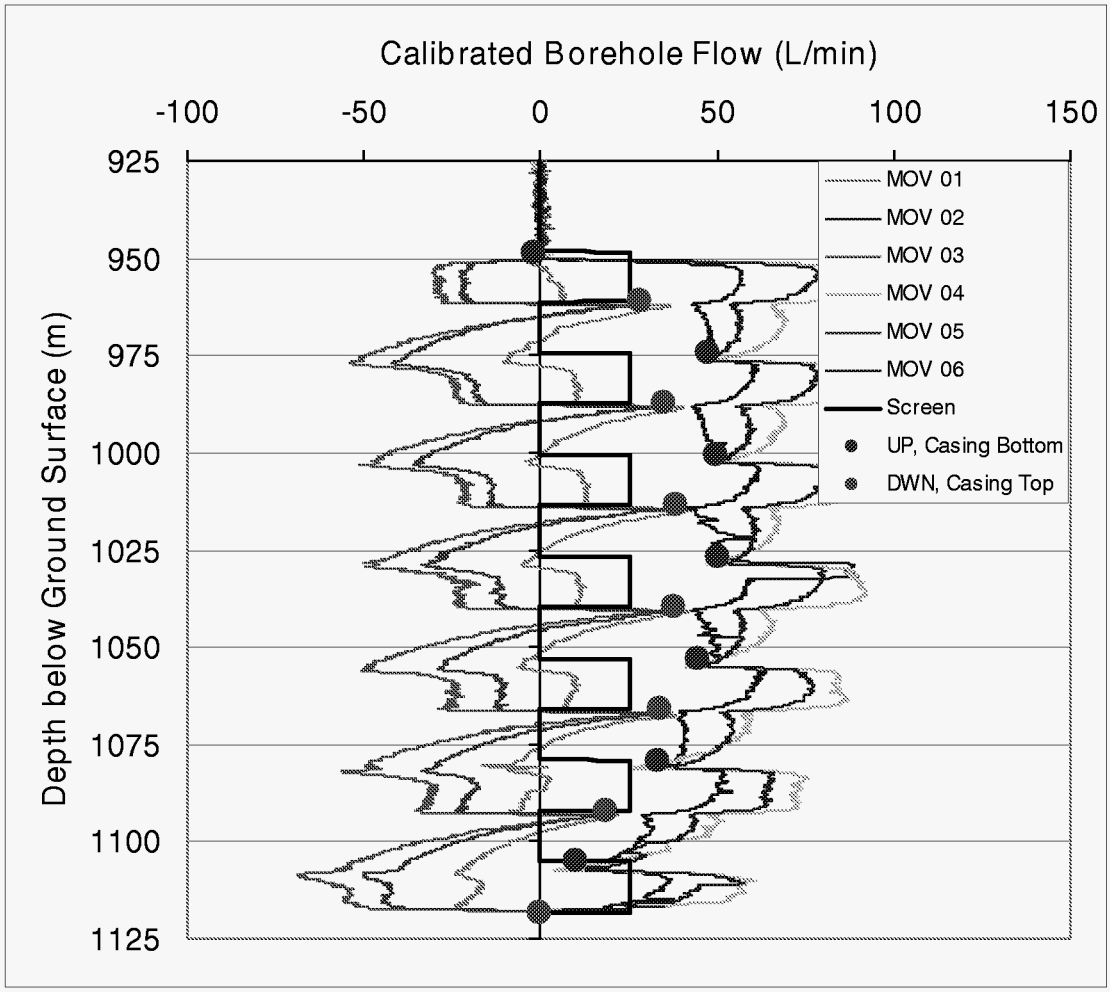

Figure 6. Entry locations into blank casing when logging upward and downward.

The analysis conducted thus far suggests the question: are the flow rates calculated at the top and bottoms of the blank casing approximate to overall conditions inside the well casing? It is not possible to prove this assertation with the available data. The values calculated at the entry locations to the blank casing are not rigorously quantitative representations of borehole flow, but they may be useful as qualitative representations of the relative changes in the well caused by pumping.

The analysis is continued by averaging the calculated flow rate values at the upper and lower entrance locations to blank casing to estimate the relative flow rate in the blank casing. These values for ambient and pumping conditions are provided in Figure 7. The continued analysis needs to be placed into the appropriate interpretative context. These flow values are the result of an extended interpretation process that includes unvalidated assumptions concerning flow in the screened and blank casing in the well.

The relative ambient and pumping rates are very similar at depths below 990 m bgs (3,248 ft bgs). The minor differences in ambient and pumping values are within the measurement precision of the impeller flowmeter at about 10 L/min. The figure suggests that most of the

change in borehole flow rate under pumping conditions was limited to the upper portion of the well screen. This feature is on the figure as the green line showing the difference in flow between pumping and ambient conditions. This information is somewhat nonspecific because there is an open annulus extending to the cement casing seal at 762 m bgs (2,501 ft bgs) that may be contributing water to the well.

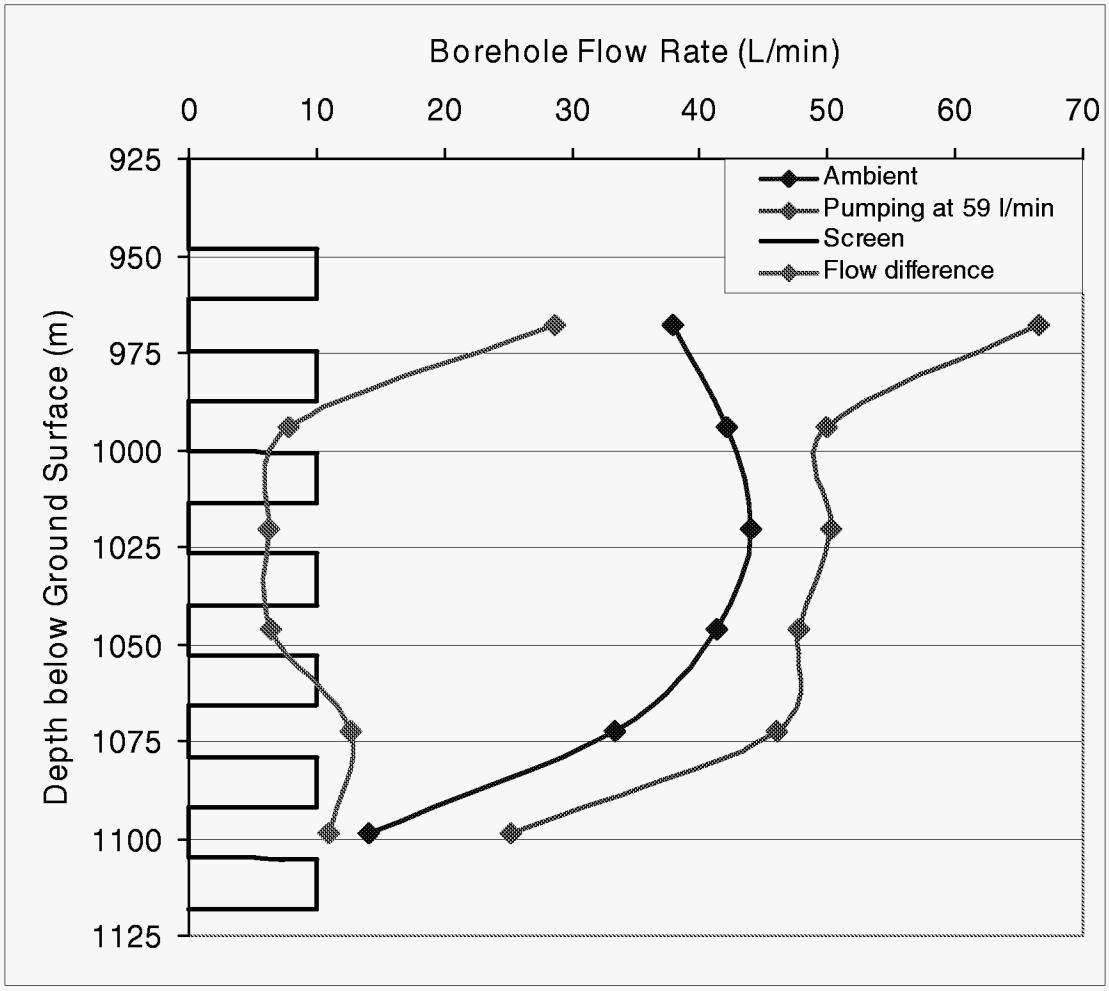

Figure 7. Relative borehole flow rates under pumping and ambient conditions.

Fluid Temperature in the Borehole

Fluid temperature data were collected at the same time as the borehole flow data. These data are examined to reveal additional aspects of the flow regime under pumping conditions. The well was essentially in thermal equilibrium with time under pumping conditions. It is also assumed that changes in thermal gradient are caused by fluid flow and not differing thermal conductivity of the rock. Fluid temperature while pumping was essentially the same at all discharge rates. The temperature log under ambient and pumping conditions is provided in Figure 8.

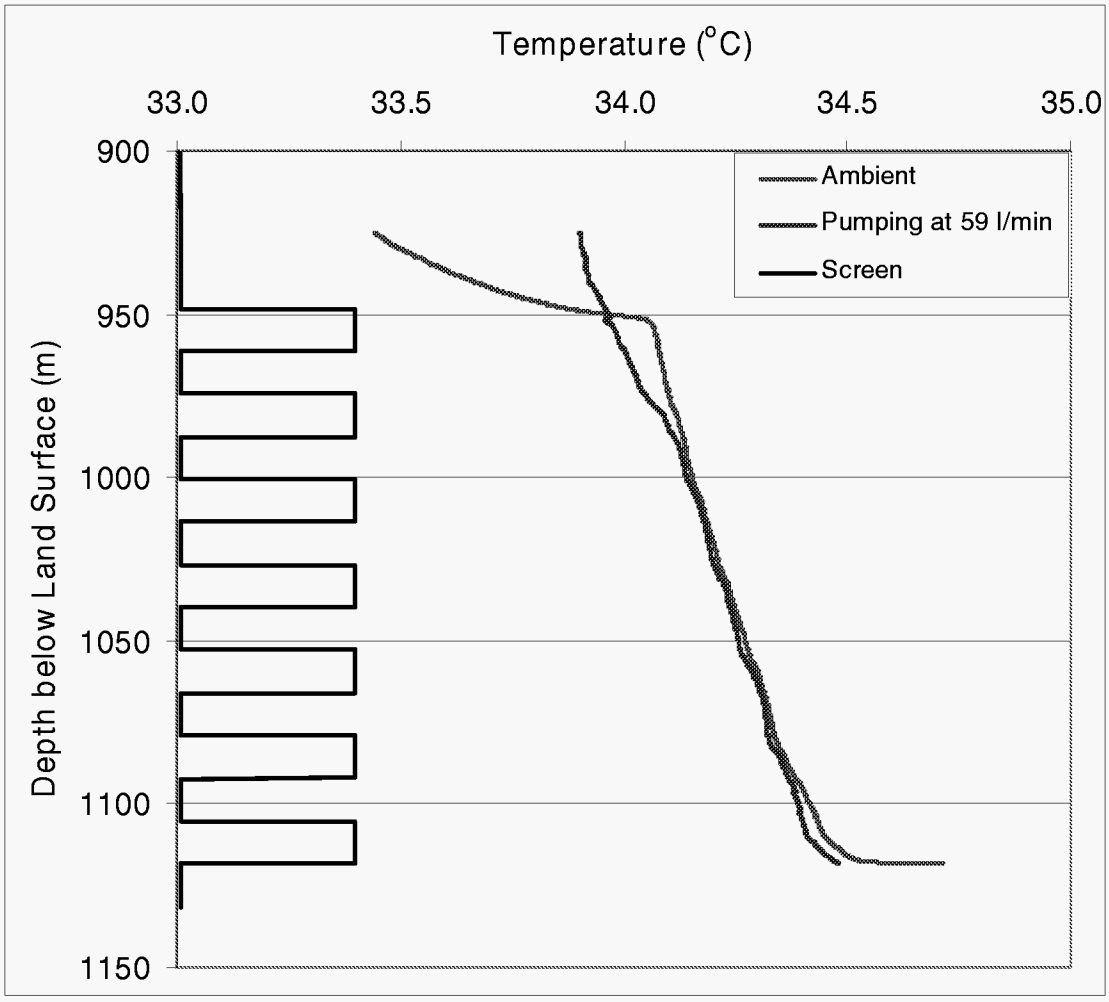

Figure 8. Fluid temperature under ambient and pumping conditions.

The figure indicates that the fluid temperature change was essentially limited to the zone above 1,000 m bgs (3,281 ft bgs). This information is very similar to the extended flow analysis that suggests the flow regime is minimally affected by pumping below about 1,000 m bgs.

Hydraulic Conductivity

Hydraulic conductivity values cannot be reliably calculated because it is not possible to quantify the total flow in the well at depth. The lack of a filter pack and an open annulus above the screened intervals results in nonspecific measurements of flow in the well.

SUMMARY

Well ER-12-4 was borehole flow logged under ambient conditions and while pumping at 59 L/min (15 gpm). A complicating factor to data interpretation is that the well was not filter packed. Flow rates in the well are a combination of flow inside the well casing and outside the well casing within the borehole annulus. The absence of a filter pack in the annulus provides an open conduit outside the casing that allows flow velocities (LT^{-1}) to be unequal inside the casing

and within the annulus. The presence of the borehole flowmeter in the well caused a flow restriction within the well screen that diverted an unknown portion of the borehole flow into the annulus. The amount of flow diversion is apparently a function of the restrictive force exerted by the flowmeter and dependent on the logging line speed, line speed direction, and the flow rates within the casing.

There are indications from the extended (and qualitative) flow analysis and the temperature log that the well was unaffected by pumping below about 1,000 m bgs (3,281 ft bgs).

The open annulus in the well casing resulted in the measured borehole flow rates in the casing being highly nonrepresentative of flow contributions from the formation. Hydraulic conductivities calculated under these conditions would require unsupportable assumptions concerning partitioning of flow inside and outside the casing. The flow values would also be subject to very large uncertainties. Borehole hydraulic conductivities are not quantified under these conditions.

REFERENCES

Driscoll, F.G., 1986, Groundwater and Wells, Second Edition, Johnson Division, St. Paul, Minnesota.

Hubbert, M.K., 1956, Darcy's Law and the field equations of the flow of underground fluids. *Transactions of the American Institute of Mining and Metallurgy Engineers*. 207:222-239.

Kruseman, G.P. and N.A. de Ridder, 1970, Analysis and evaluation of pumping test data, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

Oberlander, P.L. and C.E. Russell, 2003, Depth-specific Hydraulic Testing of Yucca Flat and Frenchman Flat Environmental Restoration Wells FY 2003, Desert Research Institute, Publication No. 45199.

Rehfeldt, K.R., P. Hufschmeid, L.W. Gelhar and M.E. Schaefer, 1989, Measuring hydraulic conductivity with the borehole flowmeter, Electric Power Research Institute, EN-6511, September 1989.

Vennard, J.K. and R.L. Street, 1975, Elementary Fluid Mechanics, John Wiley & Sons, Inc., New York.