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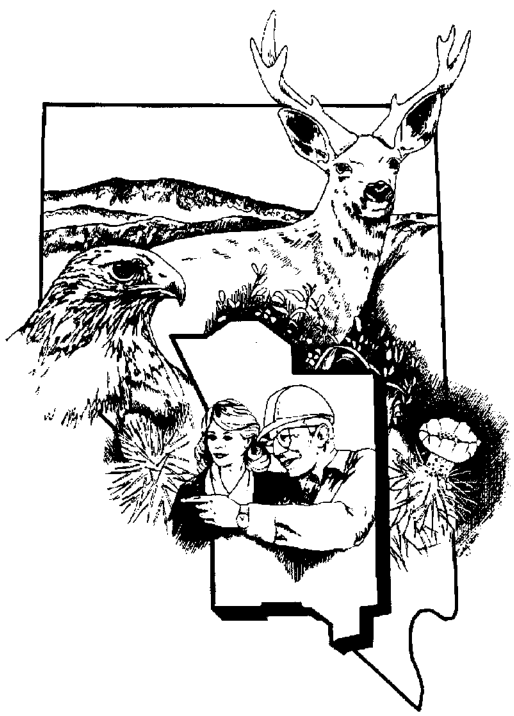
Summary of Well Testing and Analysis, Western Pahute Mesa-Oasis Valley FY 2000 Testing Program



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SUMMARY OF WELL TESTING AND ANALYSIS, WESTERN PAHUTE MESA-OASIS VALLEY FY 2000 TESTING PROGRAM

Revision No.: 0

September 2002

IT CORPORATION
P.O. Box 93838
Las Vegas, Nevada 89193

Prepared for U.S. Department of Energy under Contract No. DE-AC08-97NV13052.

**SUMMARY OF WELL TESTING AND ANALYSIS,
WESTERN PAHUTE MESA-OASIS VALLEY
FY 2000 TESTING PROGRAM**

Approved by: Signature Approved Date: 9-13-02

Janet N. Wille, UGTA Project Manager
IT Corporation, Las Vegas Office

Part I

Summary of Well Testing and Analysis, Western Pahute Mesa-Oasis Valley FY 2000 Testing Program

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List of Acronyms and Abbreviations

bgs	Below ground surface
CAU	Corrective Action Unit
cm	Centimeter
DRI	Desert Research Institute
ft	Foot (feet)
ft/d	Feet per day
fpm	Feet per minute
FY	Fiscal year
gpm	Gallons per minute
HSU	Hydrostratigraphic unit
in.	Inch(es)
ITLV	IT Corporation, Las Vegas
K	Hydraulic conductivity
m	Meters
m/d	Meters per day
m^3/m	Cubic meter per meter
psi	Pounds per square inch
PXD	Pressure transducer
rev/sec	Revolutions per second
T	Transmissivity
UGTA	Underground Test Area
WPM-OV	Western Pahute Mesa-Oasis Valley
°F	Degrees Fahrenheit

1.0 Introduction

This report summarizes the results of the analysis of the Western Pahute Mesa-Oasis Valley (WPM-OV) well development and testing program that was conducted during fiscal year (FY) 2000. This program included the testing of eight wells: ER-EC-1, ER-EC-6, ER-18-2, ER-EC-7, ER-EC-5, ER-EC-8, ER-EC-2a, and ER-EC-4. The locations of these wells are shown in Figure 1-1. The data collection for the program was documented in individual well development and testing reports. Drilling and well construction information has been documented in individual well completion reports. This summary report is based on the individual well analysis reports.

1.1 WPM-OV Wells, Completion Intervals and Geology

The WPM-OV wells were constructed with similar specifications, primarily differing in the overall depth, the number of completion intervals, and the configuration of the screens within the completion intervals. The completion intervals extend over substantial vertical distances and access different hydrostratigraphic units (HSUs) and/or lithologies. The individual well completion specifications and the lithology/stratigraphy for each well can be found in the individual well completion reports.

Table 1-1 presents the correlation of completion intervals for each well with stratigraphic unit(s) encountered in that interval and the lithologic units accessed in that interval. For each correlation category, there may be more than one stratigraphic unit or lithologic type. The relative amount of each unit or type is given. Table 1-2 provides a key to the stratigraphic abbreviations. This table will be the basis for synthesizing the results of the analyses by stratigraphic unit and lithology. Detailed specifications for the completion intervals are shown in the initial figures in Section 3.0 of the individual analysis reports, which show the well construction, and are summarized in Table 3-4 in Section 3.0 of this report.

1.2 WPM-OV Testing Program

A standardized testing program was conducted for each well with minor variations to accommodate the differences between wells. The differences were primarily related to the number of completion intervals and the productivity of the well. The testing program included:

1. Discrete pressure measurements for each completion interval

2. Well development and step-drawdown tests

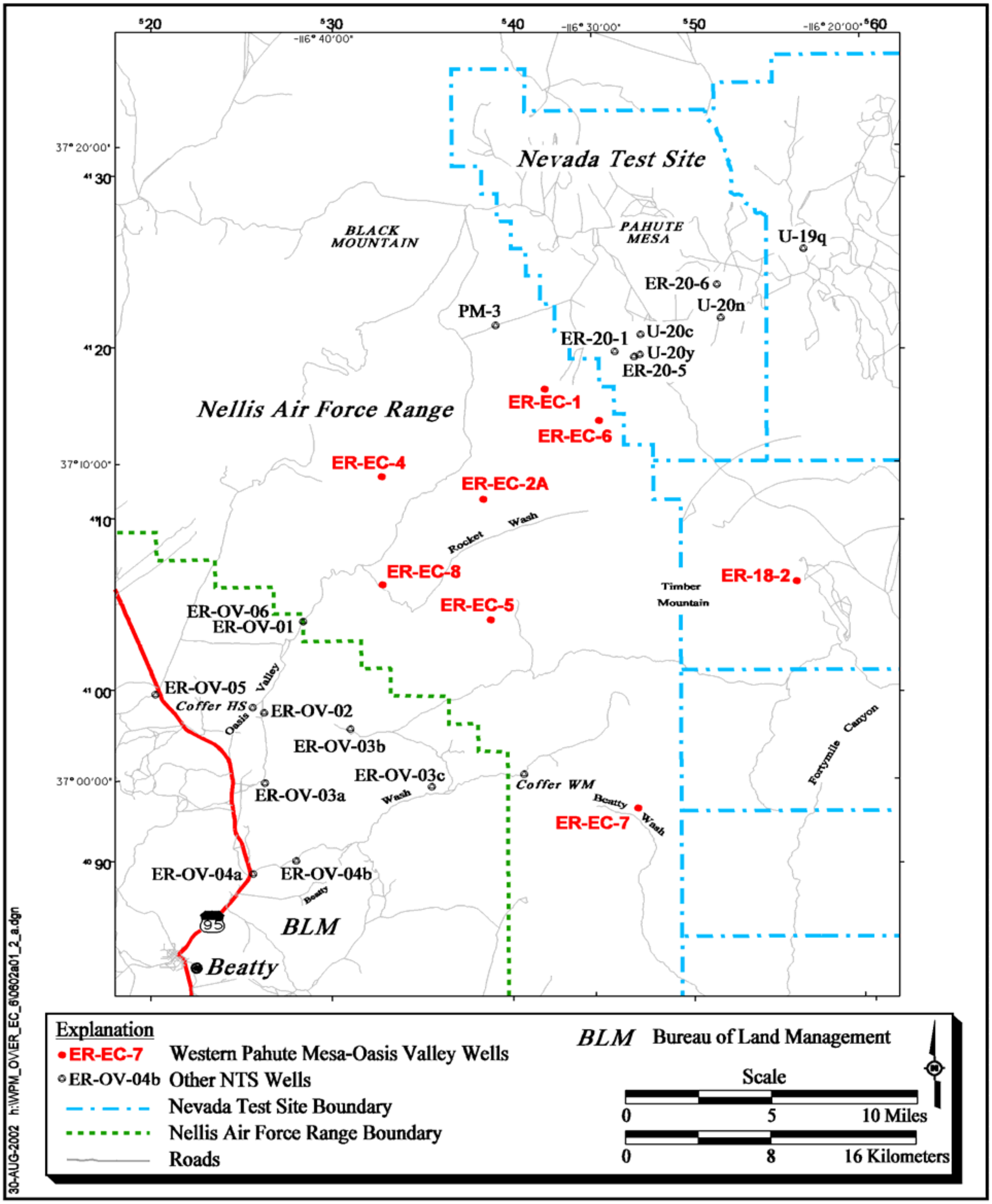

Figure 1-1
Location Map of WPM-OV Wells

Table 1-1
WPM-OV Wells Completion Intervals and Tested Geology

Well	Completion Interval	Stratigraphic Unit	% of Each Unit	Lithology	% of Each Lithology
ER-EC-1	upper	Tpb	100	Lava, Flow Breccia	100
	middle	Thr/Tptm	53/47	Bedded/Non-Welded to Partially Welded Tuff,Welded/Vitric Tuff	70/30
	lower	Tcpe	100	Lava/Flow Breccia, Bedded Tuff	89/11
ER-EC-6	upper	Tpb	100	Lava	100
	upper middle	Tpb/Tpcm	71/29	Non-Welded/Bedded Tuff, Welded Tuff	71/29
	lower middle	Tptm,Thr	36/64	Welded Tuff, Non-Welded Tuff	36/64
	lower	Tcpe/Tcpk	35/65	Lava, Non-Welded Tuff	77/23
ER-18-2		Tmar	100	Welded Tuff	100
ER-EC-5	upper	Tmar	100	Welded Tuff	100
	middle	Tmar	100	Welded Tuff	100
	lower	Tmap	100	Welded Tuff/Vitrified Tuff	100
ER-EC-7	upper	Tfbw	100	Lava, Flow Breccia	100
	lower	Tfbr,Tfb	30/70	Lava	100
ER-EC-8	upper	Tfb	100	Non-Welded Tuff	100
	middle	Tmaw	100	Non-Welded Tuff, Welded Tuff/Vitrified Tuff	18/82
	lower	Tmap	100	Non-Welded Tuff, Welded Tuff/Vitrified Tuff	37/63
ER-EC-2a	upper	Tfbw, Tfb	91/9	Bedded/Non-Welded Tuff	100
	middle-1	Tf,Tmaw	42/58	Non-Welded/Reworked/Bedded Tuff	100
	middle-2	Tmaw	100	Non-Welded Tuff	100
	lower	Tmaw,Tmar	60/40	Non-Welded Tuff, Welded Tuff	60/40
ER-EC-4	upper	Ttc	100	Lava, Colluvium	96/4
	middle	Tfbw,Tmay,Tmap	15/5/79	Reworked/Bedded Tuff/Non-Welded Tuff, Welded Tuff, Lava	27/70/3
	lower	Tmrp	100	Non-Welded Tuff, Welded Tuff/Vitrified Tuff	14/86

Table 1-2
Key to Stratigraphic Units

Stratigraphic Abbreviation	Stratigraphic Unit
Ttc	trachyte of Ribbon Cliff
Tf	Volcanics of Fortymile Canyon
Tfb	Beatty Wash Formation
Tfbw	rhyolite of Beatty Wash
Tfbr	rhyolite of Chukkar Canyon
Tmaw	Tuff of Buttonhook Wash
Tmay	trachyte of East Cat Canyon
Tmar	mafic-rich Ammonia Tanks Tuff
Tmap	mafic-poor Ammonia Tanks Tuff
Tmrp	mafic-poor Ranier Mesa Tuff
Tpb	rhyolite of Benham
Tpcm	Pahute Mesa lobe of Te'va Canyon Tuff
Tptm	Pahute-Mesa lobe of Topopah Spring Tuff
Thr	mafic-rich Calico Hills Formation
Tcpe	rhyolite of ER-EC-1
Tcpk	rhyolite of Kearsarge

3. Flow logging at three pumping rates
4. Collection of discrete groundwater sample(s) with a downhole sampler
5. Constant-rate pumping test and recovery monitoring
6. Collection of composite groundwater characterization samples
7. Flow measurements and water quality parameter logging under natural gradient flow

1.3 Analysis Objectives and Goals

The testing program was designed to provide information about local hydrologic conditions and HSU hydraulic parameters for use in the Corrective Action Unit (CAU)-scale flow and transport model. In addition, groundwater quality information from groundwater characterization samples collected was intended for use in geochemistry-based analyses of hydrologic conditions and groundwater flow, as well as to detect the presence of any radionuclides. The first objective for the analyses was to derive the maximum information about the hydrology from the data. The second objective was to evaluate the functionality of the well designs for use in future investigation and testing activities, and also evaluate the functionality of the wells for use in future monitoring. Timely evaluation of the data collected to determine the quality of the data and the effectiveness of the testing methodologies was important to guide ongoing and new testing activities.

Specific goals for the individual well analyses were to determine: the discrete head for each completion interval and the resultant vertical gradients between completion intervals, representative hydraulic parameter(s) for the formation(s) in each completion interval, and representative groundwater quality for the formation(s) in each completion interval. With regard to the well design, goals included determination of the well hydraulics of the multiple completion interval design under both natural gradient and pumping conditions, and the best application of development and testing methodologies to this design.

1.4 Objectives and Goals for This Summary

The primary objective for this summary is to bring together the results of the individual well analyses to derive an understanding of the range of hydrologic conditions encountered, determine the hydraulic behavior of this type of well design, evaluate the effectiveness of the testing methodologies for characterizing hydraulic parameter values, and evaluate the wells for long-term monitoring use.

The specific goals for these evaluations include:

- Evaluate the range of well hydraulics observed, both nonpumping and pumping, and determine how best to optimize various testing methods to determine parameter values.
- Evaluate the comparability of hydraulic parameters determined from various data and analysis methods.
- Evaluate development methods and the extent of development achievable to remediate effects of drilling and completion, and crossflow between completion intervals in order to produce representative results and samples.
- Evaluate the multiple completion well design for functionality, and determine protocols for future uses of these wells.
- Evaluate the resultant well behavior observed with respect to the information available when the well completions are specified, and identify correlations of productivity with features in that information set.

1.5 Structure of This Report

This report is divided into Part I and Part II. Part I is based on the individual well analysis reports published as IT reports. The organization generally follows the structure of the individual well reports, summarizing the results and presenting commentary under the same subject headings. Section 2.0 of this report discusses the analysis of the nonpumping natural-gradient well hydrology, and evaluates opportunities for deriving hydraulic parameters for the completion intervals. Section 3.0 discusses the well hydraulics during pumping and the flow logging results. Section 4.0 discusses the groundwater sampling and the analytical results, as well as how this information fits into characterizing the geochemistry of the groundwater in the different stratigraphic and lithologic units. Section 5.0 presents observations on well hydrology, well design, and the testing methodologies used. Section 6.0 presents conclusions and recommendations about testing and sampling wells of this construction.

Part II of this report is independent summary report of the Desert Research Institute (DRI) analysis of the flow logging conducted on these wells. This report was provided by the DRI and is presented verbatim. The analysis conducted by the DRI is an alternate approach to the analysis of the flow logging data, and characterizes the hydraulic conductivity of the formations at a different scale from the analysis presented by IT Corporation, Las Vegas (ITLV). These results cannot be directly equated to the ITLV results since the scales are different and several different decisions were made on the treatment of uncertainties. In addition, the analysis of the overall well transmissivity value which serves as the basic input to the flow logging analysis was determined using a different method. There are substantial differences in the well transmissivities, which correspond to differences in the hydraulic conductivity values as well as differences resulting from the different flow logging analysis method. The differences between these two approaches can be viewed as a measure of uncertainty in the analyses and indicate the variation in resultant parameter values that occurs at different scales of characterization.

2.0 Equilibrium Well Hydraulics

This section discusses many aspects of the equilibrium, nonpumping well hydraulics relating to the individual completion intervals. This includes the equilibrium composite water levels for each well, barometric efficiency of the composite water level barometric response, completion interval heads and head adjustments, and flow in the well between completion intervals under the natural gradients. The summaries and conclusions presented here are based on the data and analyses presented in Section 2.0 of the individual well analysis reports. This report summarizes the results of the other reports and further develops the concepts and concerns that were presented.

The WPM-OV wells are generally constructed with multiple completion intervals ranging from two to four in number except for Well ER-18-2, which has only one completion interval. The formation in the completion intervals is accessed through joints of slotted casing with blank casing interspersed. The slotted casing is installed as both single or multiple joints; each discrete interval of slotted casing is counted as one screen. The completion intervals are isolated from each other outside the well casing by cement annular seals. Within each completion interval, the annulus is filled with continuous filter pack extending above and below the screens. Downhole flow features are often discussed with reference to individual screens. The convention for referencing screens is by the consecutive number (e.g., first, second, third) of the screen from the top downward.

Table 2-1 presents a summary of the results of the various nonpumping measurements and analyses. These results will be discussed in the following sections.

2.1 Barometric Efficiency

The barometric efficiency of the well is used in the analyses of the hydraulic tests to refine the analysis and produce more accurate results. The importance of determining the correct value for barometric efficiency is somewhat dependent on the magnitude of the hydraulic response that is being analyzed. To accurately determine the head differences between the upper completion interval and the next lower interval, correction for barometric changes had to be incorporated into the analyses in many cases. Response of the lower completion intervals to barometric variation was not incorporated into the analysis because the barometric response of those intervals has not been appropriately quantified. However, with respect to the drawdown of the well during the constant-rate test, the greater the drawdown the less important the barometric correction. In case of the WPM-OV ER wells, the barometric correction of the drawdown record was not a significant factor in the test analysis. In circumstances requiring accurate knowledge of the status of a

Table 2-1
Summary of Nonpumping Measurements and Results

Well	Completion Interval	Barometric Efficiency	Head Change from Composite WL ft	Steady State Analysis T ft²/d/K ft/d	Transient Analysis T ft²/d/K ft/d	Equilibration Curve	Flow From/Into Completion Interval
ER-EC-1	upper	85%	0.08/0.14	NA	NA	No	No Flow Defined
	middle	NA	-1.32/-1.32	NA	NA	Yes	Flow Not Defined
	lower		-0.28/-0.26	NA	NA	Yes	Flow Not Defined
ER-EC-6	upper	83%	+0.12	NA	NA	No	Flow Quantified
	upper middle		-0.44	NA	NA	Yes	No Flow Defined
	lower middle		-1.79	NA	16.4/0.012	Yes	Flow Quantified
	lower		-5.45	NA	NA	Yes	Flow Not Defined
ER-18-2		90%	NA	NA	NA	NA	NA
ER-EC-5	upper	88%	+0.11	NA	NA	No	Exceeded Tool Limit
	middle		+0.08	NA	4900/18 Lower Limit	No	Exceeded Tool Limit
	lower		0.00	NA	4900/18 Lower Limit	No	Exceeded Tool Limit
ER-EC-7	upper	95%	+0.85/+1.21	690/6.2 Lower Limit	NA	No	Exceeded Tool Limit
	lower		+0.00/+0.25	NA	NA	No	Exceeded Tool Limit
ER-EC-8	upper	64%	+0.01/-0.09	29,900/56.4	NA	No	Questionable Measurement
	middle		-0.74/-0.49	125/1.0	NA	No	Questionable Measurement
	lower		-0.93/-0.93	133/0.4	NA	No	Quantified
ER-EC-2a	upper	80%	NA	NA	NA	No	Questionable Measurement
	middle		NA	NA	NA	No	Questionable Measurement
	lower		NA	NA	NA	No	No Flow Defined
ER-EC-4	upper	93%	+0.17/-0.05	NA	NA	No	Exceeded Tool Limit
	middle		-2.94/-2.17	3,460/12.5 Lower Limit	NA	No	Exceeded Tool Limit
	lower		-7.59/-8.22	78/.2 Lower Limit	108/.27 Lower Limit	Yes	Exceeded Tool Limit

T = Transmissivity
K = Hydraulic conductivity
ft = Feet
NA = Not available
d = Day

well relative to equilibrium with the natural state of the groundwater system, the refinement offered by correcting a water level monitoring record for barometric efficiency can be important. This was discussed in the report on Well ER-EC-2a, and is particularly important when analyzing ambient trends in water levels based on a short or sparse record and for completion intervals with low hydraulic conductivity.

The records used to determine barometric efficiency need to be long enough to readily allow separation of the barometric response of the well from the variety of periodic fluctuations that occur in the water level and barometric records. Daily atmospheric heating/cooling effects and earth tides obscured the barometric response in the short records. Several weeks to several months of records that include several large-scale barometric shifts that can be distinguished from short-term fluctuations are often required for accurate analysis. The methodology used for determining barometric efficiency allows very accurate analysis when this condition is met. In general, the records have often been insufficient to determine the barometric efficiency with a high degree of accuracy and confidence. This is a particular problem with respect to obtaining good records that are collected with the upper interval isolated from lower completions by a bridge plug. This is a situation in which the analysis is very sensitive to the correction for barometric response.

2.2 Completion-Interval Heads

Table 2-1 lists values for the head change from the composite water level for each completion interval in response to the isolation of the completion interval as change in head from the composite head. Two values are listed in cases where there appeared to be an initial equilibration and a long-term trend. The head difference between two completion intervals is the sum of the head changes for each of the intervals. The difference in heads between completion intervals does not appear to be a fixed value, but varies as head in the different intervals fluctuates with time.

2.2.1 Head Differences Between Completion Intervals

Revised head differences between completion intervals were reported in the well testing analysis reports from those presented in the well data reports (Appendix A of the analysis reports). This resulted from further interpretation of the responses of the completion intervals to isolation, as exhibited in the pressure records. The earlier interpretation used the change between the preset pressure (before the bridge plug isolated the interval) and the final pressure at the end of the monitoring period to calculate the head change for the completion interval. Upon further examination of the pressure records it was recognized that some intervals appeared to change rapidly and then trend slowly. Pressure changes in other intervals were long term only. Interpretation of the pressure record for each interval during monitoring identified the initial, more rapid changes as the equilibration of the interval head, and the latter part of each record as changes primarily due to trends in the formation head. These initial change values are reported first since they occurred earlier in time. The part of the record identified as initial equilibration probably accounts for most of the equilibration to the formation head, but may not fully include the effects of longer-term temperature equilibration of the completion interval following cessation of crossflow. This formation temperature equilibration effect is mixed in with the head trend, and there is no data to separate it. Head change values for the end of monitoring are listed second (after the slash), since they indicate the later head difference.

These two different interpretations did not produce qualitatively different results in the relationship between completion intervals; the reported head differences between the intervals generally changed only a small amount. Both interpretations represent the general head difference between completion intervals in a well, and the differences between them provide some sense of the short-term variations of the head differences. Trends in formation head explain the cases where all of the intervals in a well appear to have changed in one direction, such as in the later-time data for Wells ER-EC-5, ER-EC-7, ER-EC-8, and ER-EC-4. Since the composite head is an interval transmissivity-weighted average of the completion interval heads, the individual completion interval equilibration adjustments should cancel when weighted by the interval transmissivity. This implies that one of the changes should have an opposite sense from the others. However, since the reference head measurement was separated in time from the completion interval data points, a general head trend can shift all of the values in one direction.

The interpretation for Well ER-EC-2a was revised to reflect a different situation, and resulted in more substantial changes in the reported head differences than for the other wells. The pressure records for this well showed a behavior different from the other wells: an initial decline followed by a long-term rise, which had been interpreted to indicate failure of the isolation of the interval. The long-term rise was reinterpreted as continuing recovery of the completion interval heads from drawdown induced during drilling. Consequently, there were no measurements that represent equilibrium heads in the lower two completion intervals. Head relationships and differences for the completion intervals in Well ER-EC-2a cannot be determined from the bridge plug measurements. Later measurements for the upper completion interval indicate substantial changes from earlier measurements, perhaps indicative of long-term equilibration or seasonal changes. It now appears that the gradient is upwards, and that the head of the lower intervals is about 10 feet (ft) higher than the upper interval.

The ambiguous data record for Well ER-EC-2a may indicate that substantial seasonal changes can occur. One interpretation of the record suggests that head relationships may even change during the course of a year. The short time scale of the bridge plug data precludes determining these details. The present water level monitoring schedule for these wells probably would not provide enough data to observe such changes.

2.2.2 Measurement Methodology

The bridge plug measurement methodology worked fairly well to determine the magnitude of head differences between completion intervals. However, several refinements to the methodology would improve the quality of the data and the accuracy of the analyses. The refinements would mainly require additional time spent at various stages of the process to make additional measurements that would remove some of the uncertainty in the data. In particular, more time should be allowed for temperature equilibration of the PXDs whenever they are moved. The additional information collection should include more complete pressure transducer (PXD) calibration statistics, premeasurement water level monitoring, premeasurement temperature or pressure logging, bridge plug PXD pressure measurements at the ground surface, time-depth records to index the bridge plug pressure records, more calibration stations during installation, time allowance for temperature equilibration at each station, a higher data recording rate, and longer monitoring periods.

The bridge plug data were used in several analyses that would benefit from improved data collection. These include the determination of head differences between completion intervals, water density variation along the water column, and definition of the pressure equilibration curves for use in calculating interval transmissivities. The determination of head differences is dependent upon the conversion of pressure to head, and the variable density in the water column introduced uncertainty into that calculation. Improvement in the data would provide a better basis for determining the appropriate density to apply to the pressure adjustment for each completion interval. The improved data would be useful in understanding the natural flow between completion intervals. Improvement in the definition of the pressure equilibration curves could provide data for determining completion interval transmissivities, often for intervals for which no other data is available. Better temperature equilibration data following setting the bridge plugs may also provide information for refining the quantification of flows in the borehole.

2.3 Variable Density/Viscosity of Water in the Wellbore

Variation in density along the water column can have a significant effect on the pressure profile. The primary factor producing the variable density appears to be the temperature variation with depth. In the analysis reports, a calculated density profile as a function of the temperature profile was compared with the pressure measurements at various depths from the bridge plug work. The temperature profiles were typically not linear, and the temperature density relationship is also not linear. Consequently, it was necessary to integrate the density profiles to get more accurate predicted pressures at various depths. Compressibility of water was also included in the calculated composite water density, but this factor did not account for a significant part of the variation. A problem with this comparison is that the temperature logs used for the pressure-depth calculations were not run at the same time the bridge plug measurements were made, but after the pumping tests. Therefore, the temperature profiles in the wells may have been substantially different at the time the bridge plug measurements were made resulting in discrepancies. The differences between the calculated and measured pressures range from 0.05 to 0.61 percent of the total pressure. Discrepancies of this order add up to significant differences in the predicted head at the depths of the completion intervals, ranging up to 5.26 pounds per square inch (psi). These discrepancies were problematic in evaluating the accuracy of the bridge plug measurements.

The variation of temperature with depth appears to account for much of the variation in the density profile, as exhibited by the bridge plug pressure measurements. However, other factors such as dissolved gasses and suspended solids may also vary with depth and affect the density profile. No data was collected that would provide any information on these other factors. Since the density profile will change with pumping and natural-gradient flow, the density variation should be characterized at the same time as measurements are made that require interpretation based on the pressure-depth profile. A pressure log would be a more direct approach to characterizing this variation. Presently, temperature logs are the only available data to provide relevant information. A better dataset is required to evaluate the adequacy of temperature logs for this purpose.

Corrections for the density variation have not been included in the flow logging analysis as a correction factor for the drawdown (stress) that was applied to the formation as a function of depth during pumping. The potential magnitude of this correction has not been calculated, but would probably not significantly alter the result. The viscosity of the water also varies with temperature and perhaps other variables. Both the density and the viscosity variation may affect the flowmeter calibration and consistency of results. This refinement was not attempted in the flow log analyses since the effect of these factors on the flowmeter has not been defined.

2.4 Flow in the Well Under Natural Gradient

Flows in the wells under the natural gradients were evaluated using two different data sources, thermal flow logs and temperature logs. Definition of natural gradient driven flows in the wells were valuable for a variety of analyses. Natural gradient driven flows were found to be a significant factor in understanding the observed temperature profiles. The flow rate into or from each completion interval was used with other data to calculate hydraulic parameters for the intervals. When evaluating the representativeness of discrete bailer samples and the composite characterization sample relative to the origin of the water from the different completion intervals, it was found to be important to account for previous crossflow.

The best data for characterizing crossflows are direct measurements. Calculation of crossflow rates requires knowledge of the head differences between completion intervals and the hydraulic conductivity of the completion intervals. Flow between productive intervals at significant rates may occur under low gradients, which are difficult to measure accurately. The experience in this testing program was that head differences in the range of tenths of a foot probably could not be accurately characterized. Consequently, there would be considerable uncertainty in any prediction of flow based on those measurements.

2.4.1 Temperature Logs

Temperature logs run under nonpumping conditions provide information on flow in the well, indicating locations of entry and exit of groundwater and direction of flow. The interpretation of the temperature logs is used in conjunction with the flow measurements, providing guidance for locating and interpreting discrete measurements. Temperature logs were found to be very useful in interpreting and corroborating apparent flows, and were likewise interpreted in conjunction with the flow logging to understand the temperature profile. The flow and temperature logs used in the natural gradient analyses were run after development and testing, and represented conditions at that time. However, they were combined with head gradient measurements from many months earlier, prior to pumping and when the temperature regime may have been somewhat different. As mentioned, the temperature profile has a significant affect on the head (pressure) distribution in the well, so this combination produces only an approximate analysis. Future data collection programs should include all logs that are required for a particular analysis to be run under the same borehole conditions to improve the accuracy of the results. In particular, bridge plug measurements should include a temperature log close in time and before the borehole is disturbed by pumping.

In wells that produce from deep completion intervals, the change in temperature profile that occurs during pumping can have a substantial effect upon the head change as measured by a PXD high in the well. The drawdown and recovery records may need to be corrected for the temperature profile change. This effect was clearly observed in Well ER-EC-7, although the effect did not make a substantial difference in this case because the length of the water column was not great and the temperature shift was not great. To make such a correction accurately, temperature logs run just before the start of the test and just before cessation of pumping would be required, at a minimum.

2.4.2 Flow Measurements (Thermal Flowmeter and Spinner Meter)

Measurement of low-rate flow under nonpumping conditions was generally done with the DRI thermal flowmeter. Flow measurements were made prior to completion and following the pumping testing. Significant differences were noted between the two datasets. Evaluating the thermal flowmeter measurements made prior to completion in conjunction with later information on changes in water level and changes in the temperature regime suggests that these measurements do not necessarily represent the natural system very well. Completion of the well with discrete completion intervals also alters the downhole regime. Consequently, the precompletion flow measurements are not applicable and were not used in any analyses.

The measurements made after testing were used for the quantitative analyses, and are discussed in the following sections. These measurements support one method used to determine hydraulic parameters of completion intervals in conjunction with the head change measurements. However, the extent of the measurements made did not always provide definition of the flows for all of the completion intervals in a well. Also, the measurements did not always present a consistent flow profile, suggesting some problem with measurement.

The upper limit of the thermal flowmeter is about 2.2 gallons per minute (gpm). Downward flows in Wells ER-EC-5, ER-EC-7, and ER-EC-4 exceeded the upper limit of this tool and could not be measured. The spinner tool was run in Well ER-EC-4 in trolling mode to attempt to quantify the flow. The flow log analyses had found that the lower quantitation limit of the spinner log is on the order of 2 gpm, so the spinner tool should be able to quantify low-rate flow starting at the upper limit of the thermal flowmeter and greater. However, the ER-EC-4 nonpumping spinner log was run at a very high trolling rate, which resulted in very noisy data and poor low-rate quantitation.

Recognizing the difficulties in making thermal flowmeter measurements, these problems would have taken more time to resolve than was scheduled. Considering the value of the measurements for use in the analyses, additional time spent to collect complete datasets would be very worthwhile. The datasets should include stations between every adjacent pair of completion intervals, and duplicate measurements at each station. In cases where the impeller tool is used to measure higher flow rates, logging should be done at a low trolling rate to minimize the noise level. Again, duplicate logs would help reduce the uncertainty in the results.

2.5 Derived Hydraulic Properties

Measurement of flow in the well between completion intervals under the natural gradient can be used in conjunction with the bridge plug pressure data to calculate a transmissivity (T) value for the individual completion intervals. There are two types of analysis that can be conducted: a steady-state analysis using the measurement of the head differences between the completion intervals and measured flow between intervals, and a transient analysis using the pressure adjustment curve that occurred after the bridge plug was set and measured flow prior to shut-in. The result of these analyses is a T value for the completion interval, from which an average hydraulic conductivity (K) can be computed using the length of the entire completion interval. If more detailed flow measurements for a completion interval were available, the K could be refined. This would probably be most appropriate in cases in which two or more substantially different lithologies are present in one interval.

The results of these analyses are shown on Table 2-1. In several cases, the results are presented as lower limits for the value since the flow measurement was a minimum value due to the flow rate exceeding the tool upper limit. These analyses provided results for completion intervals in four cases where the pumping test/flow logging did not yield results, as well corroborative results for five intervals for which there were pumping/flow logging results. These are only general estimates for the various reasons mentioned in this section, but they appear to provide values that are much better than order-of-magnitude. In one case (the lowest completion interval for Well ER-EC-4), there were results for both types of analyses and they agree fairly well. While these estimates are less specific and less accurate than pumping/flow logging information, they can provide estimates of T and K values where higher level information was not or could not be collected.

This approach to determining hydraulic parameters is not without problems and there is uncertainty in the results due to a variety of circumstances. The measurements used for these analyses are generally quantitatively small and are subject to significant levels of measurement uncertainty. In general, these problems can be dealt with through refinement of the measurement process to yield fairly representative results. The measurement equipment is generally capable of making adequately precise measurements. The measurement process is generally not expensive, but the refinements in methodology required to produce more complete and defensible results will require additional time. The results of these analyses agreed well in three of five cases where there were overlapping results from the flow logging analyses. The corresponding results from flow logging are shown in Table 3-7 and discussed in Section 3.5. Many potential opportunities for determining hydraulic conductivity of completion intervals that did not produce results from the pumping testing could not be exploited for lack of suitable data. In general, the required data for such analyses could probably have been obtained from a more complete set of measurements.

One of the major flaws in these analyses for the WPM-OV wells involved having to combine the flow logging data from after testing with gradient information derived from measurements made many months before development during a different time of year. Previous discussions about long-term trends, seasonal changes, and changes resulting from pumping indicate problems with the accuracy of results from combining the two data sources used. However, the results are generally reasonable, and, as mentioned, correlated fairly well with the pumping/flow logging analyses results.

2.5.1 Steady-State Analysis

Values for the transmissivity of the completion intervals were derived from information on the steady-state flow into or from the completion intervals and the hydraulic gradients associated with the flow. The calculations used the empirical equation $T=2000Q/s_w$ (Driscoll, 1986), where Q is the flow rate in gpm and s_w is the drawdown in feet. The head difference data and the flow data both have substantial relative uncertainty, but the data appear to be good enough to derive order-of-magnitude estimates. The changes in head of the isolated completion interval from the composite head of the well were used as the head differences associated with flow into or from each interval. It is assumed that the well was in a representative steady state at the time of measurement. The flows attributed to each interval are derived from the thermal flowlog measurements, which, as mentioned, were made at a different time when the well may not have been in the same hydraulic balance.

2.5.2 Transient Analysis

The pressure equilibration records for completion intervals following setting the bridge plugs were also used to calculate transmissivities. Such records were only captured for lower intervals with the bridge plug PXDs/dataloggers. For the upper completion interval, the initial equilibration records could not be captured with the methodology used because of the time required to install the monitoring equipment. There may be equipment solutions to this problem that would provide this data. One approach would be a bridge plug with PXDs/data loggers to monitor both above and below the packer.

Analysis of the pressure equilibration data for the lower completion intervals used a pressure fall-off model following cessation of injection (Earlougher, 1977). This methodology is probably more accurate than steady-state analysis because the pressure-change response is characteristic of just the completion interval being measured, and is somewhat independent of the interaction between intervals. The pressure-change response is easier to characterize than head differences between intervals where the difference is very small. This method also requires data for steady-state flow into or from the completion interval, and is dependent on the availability and quality of that data.

3.0 Pumping Well Hydraulics

The pumping test data collected from the WPM-OV wells were analyzed to provide both transmissivity for the well and discrete hydraulic conductivity for the completion intervals. The hydraulic conductivity analysis is based on flow logging that was conducted during pumping and incorporates corrections for calculated well losses.

3.1 Measured Discrete Production

The WPM-OV wells typically penetrate a number of different formations and have multiple completions, often in different lithologies. Pumping tests and composite sampling provide general, composite results that are not specific to the different completion intervals within a well. Interpretation of such data can only attribute the composite results to all of the completion intervals. To provide information specific to individual completion intervals, the WPM-OV testing program included downhole flow logging to determine the distribution of water production in the well and discrete downhole sampling. This information was used to evaluate well hydraulics and water chemistry results specific to the different completion intervals.

As discussed later in this section, the flowmeter results show that production was generally distributed unevenly between completion intervals. Even after accounting for the different lengths of the completion intervals, there were substantial differences in the productivity of the different completion intervals. Consequently, derived hydraulic conductivities of different sections of formation and different lithologies varied over a wide range. Without flow logging, all of the completion intervals could only have been assigned one average value. In many cases, substantial variation in production was found within completion intervals. This can sometimes be equated to changes in lithology within the completion interval, or may be due to varying characteristics of the formation such as fracturing.

Flow logging was conducted for all of the WPM-OV wells except Well ER-18-2. Well ER-18-2 has only one completion interval with very limited screen coverage, and flow logging would not have provided representative information. The flow logging equipment and process, data types and quality, and derived producing interval flow rates are summarized in this section. The results of the flow logging are also used in the groundwater chemistry interpretation discussed in Section 5.0.

3.1.1 Flow Logging Equipment and Process

Brief descriptions of the equipment and process used during the flow logging of the WPM-OV wells are provided in this section. All flow logging for the WPM-OV wells was conducted by the DRI. More details about the equipment and process may be found in the DRI report provided in Part II.

The flow logging equipment consists of Compulog® Flexstak tools including a telemetry cartridge, a temperature tool, and a borehole flowmeter. Several centralizers keep the tool centered within the well. The borehole flowmeter measures the velocity of water movement via an impeller that spins in response to water moving past it and has a mechanical resolution of 0.1 percent of the indicated response. The flowmeter has a collapsible impeller that opens inside of the casing. The flowmeter may be used in both trolling and stationary modes. The rate at which the flowmeter is trolled in the borehole is measured by the logging line speed. Limitations of the flowmeter include the following: (1) the well casing diameter must be greater than 4 inches; (2) at low speeds (5 to 15 feet per minute [fpm]), the flowmeter may stall depending on bearing wear and the amount of foreign material adhering to the impeller; and (3) at high line speeds, the flowmeter's response becomes very noisy.

Prior to the initiation of a flow logging run, the well is pumped at a constant discharge long enough for the well to approach steady-state, if possible. This is desirable for the accurate interpretation of the flow logs. When the rate of drawdown has declined to a low level, the flow is logged at a steady line speed. Each of the WPM-OV wells was pumped at three different constant rates representing the range of production potential of the well. Logging runs were made at several different trolling speeds for each pumping rate for each well. Trolling the flowmeter at logging line speeds of 20 to 60 feet per minute (fpm) provided continuous data and generally avoids the low relative flow rate below which the flowmeter would stall. Note that when trolling in the same direction as the flow, there is a point at which the flowmeter rotation reverses, and a period around this point in which the relative flow rate does drop below the stall speed. In addition, stationary measurements between completion intervals were taken while the well was pumping and the flowmeter held stationary. A summary of these different logging runs is presented in Table 3-1.

Table 3-1
Summary of Flow Logging Runs Conducted at the WPM-OV Wells

Well Name	Number of Upward Trolling Flow Logs	Number of Downward Trolling Flow Logs	No. of Stationary Logs
ER-EC-1	6	5	9
ER-EC-6	3	3	6
ER-EC-5	5	3	9
ER-EC-7	0	6	6
ER-EC-8	3	6	9
ER-EC-2a	1	6	9
ER-EC-4	4	6	9

3.1.2 Description of Collected Data

In this section, the data types that were collected during the flow logging of the WPM-OV wells are described. The quality of the data used to derive the borehole production distribution is then discussed.

Data Types

Data types collected during a given flow logging run include the following parameters:

- Depth (feet below ground surface)
- Flowmeter Response (counts per second)
- Temperature (degrees Fahrenheit [°F])
- Differential Temperature (°F)
- Line Speed (fpm)
- Tension (pounds)
- Discharge at the well head (gpm)

Depths were recorded every 0.2 ft below ground surface (bgs). All other parameters were recorded for each depth increment. At any given depth, the flowmeter response is related to water velocity in the borehole and to the line speed. Thus, data types needed to derive interval flow rates are depth, flowmeter response, and line speed. In addition, the discharge at the well head measured when the well is being pumped is also needed for the calibration of the flowmeter. The temperature logging data were not used in the analysis of the flow logs. They were, however, used in the overall interpretation of well hydraulics and are discussed in Section 3.1.6. All other measured parameters were not used in the analyses and will not be discussed further in this section.

To evaluate the flowmeter response record, visual representation of the flow logs were generated by plotting the flowmeter response (number of revolutions per second [rev/sec]) versus depth. The lithologic log were also included in the visualization of flow logs to facilitate the evaluation. A typical flow log shows inflow to the well starting from the bottom of the lower completion interval. Increases in flow generally correspond with the locations of the screens, with relatively steady flow in the blank casing between the screens and completion intervals.

Data Quality

The quality of the data collected during flow logging and needed to calculate interval flow rates was assessed by a visual examination of the flow logs. Some of the problems encountered during the logging were visible on the logs. These problems include inaccuracies or errors in the records of depth, and pairs of line speed and flowmeter response.

Inaccuracies in depth records are due to differences in depth reporting equipment. In most cases, a visual comparison of the flow log and the lithologic log revealed that the logging depths did not exactly match the official well construction diagrams. Consequently, the flowmeter depths were adjusted so that the flowmeter responses corresponded to the well construction logs for each of the tested wells. The top and bottom of blank and screened intervals were identified in the flowmeter logs by plotting the rate of change of flow rate versus depth, and recording the locations where flow rate was changing. These depths were compared with the top and bottom of pipe sections in the construction log. Then, the depth of the center of each section was calculated and compared between the two logs. The depth correction to match the flowmeter and construction logs of a given well was determined from the average difference in the center depth of blank and screened sections. The difference was calculated as the center depth from the flow log, minus the center depth from the lithologic log. Correction factors ranged from -2.07 to +5.98 ft.

Most of the flow logs exhibit the expected pattern of flow increasing from bottom to top. However, a few flow logs exhibit an unexpected pattern in the upper part of the upper completion intervals. The flow rate decreases upwards across the lower part of screens, and then increases suddenly at the top of the screens. This was observed in Well ER-EC-7, for example. These flow profiles probably indicate that some fraction of the flow in the casing is exiting the screen in the lower part and reentering in the upper part of the screen. This could occur if such a flow pattern resulted in lower overall flow losses. In another case, the flow log for Well ER-EC 4 indicates that water was moving upwards from only the upper completion interval, and that there was flow downwards from the lower part of the upper completion interval to the bottom of the well.

The flow log records for the WPM-OV wells include large line-speed variations, negative flowmeter responses, and “zero” flowmeter responses. It was apparent from the flow logs that the impeller stalled in some cases and produced “zero” flowmeter responses. The reason for these problems are not known and should be determined so that the methodology can be improved to overcome or avoid the problems if possible.

3.1.3 Flow Rate Calculations

For each well, the process of deriving interval flow rates for a given well included two steps. First, the flowmeter record was calibrated. Second, interval flow rates were derived from the individual flow rates. A summary of the steps and results is presented.

3.1.3.1 Calibration of the Flowmeter Record

Calibration of the flowmeter record provides an equation for converting the flowmeter responses into flow rates. Basic calibration of the flowmeter is conducted in a calibration facility under controlled conditions to establish the relationship between the flowmeter response and flow rate. The calibration is specific to a variety of flow conditions related to casing size and wall roughness, fluid properties, and flow direction. The variation of these conditions downhole in the wells cannot be readily accounted for in the calibration facility. In order to deal with the apparent variation in flowmeter response observed between wells, the flowmeter records for each well were calibrated using well specific data. This variation is probably due to: (1) changes in the condition of the bearings that support the impeller; (2) differences in the physical characteristics of the fluid (density and viscosity) in the well as a function of temperature, dissolved gasses, and suspended solids content; (3) variations in the diameter, roundness, and roughness (especially in the slotted sections) of the casing; (4) variations in the centering of the flowmeter in the casing; and (5) variations in the flow rate and the trolling speed of the flowmeter, which vary between logging runs. The calibration approach and results are summarized in this section.

Calibration Approach

The flowmeter calibration process includes preparation of the calibration datasets, and identification of calibration equations and associated estimates of uncertainty. This calibration was accomplished using flowmeter data collected above the uppermost screen but below the crossover to the nominal 5.5-inch (in.) pipe. In this section of the well, the amount of water flowing upward to the pump should equal the discharge at the land surface. The calibration dataset was defined as a series of data points consisting of the flow rate as measured at the surface, the flowmeter response, and the line speed recorded along the blank section above the uppermost screen. The flow rate in the upper blank section should be the same as the discharge from the well (recorded at the surface). To avoid end effects, the data observed from an interval centered between the ends of the blank section were included in the calibration dataset. Also, the effect of logging direction on the flowmeter calibration was evaluated for one of the wells (Well ER-EC-1) and was found to be negligible. As a result, recorded values from all moving flow logs were included in the calibration datasets. Inadequate records were removed from the calibration datasets. Flow log records were judged to be inadequate if they exhibited large line speed variations or “zero” flowmeter responses. In the case of Well ER-EC-5, all records extracted from a logging run were omitted from the calibration dataset because the flowmeter responses were all equal to zero.

The calibration equations were derived in two steps. In the first step, multiple linear regressions were applied to the well-specific full calibration datasets by defining the flowmeter response as the dependent variable, and the borehole flow rate (as recorded at the surface) and the line speed as the two independent variables. In the second step, the equations resulting from the multiple linear regressions were rearranged to express the borehole flow rate as a function of the flowmeter response and the line speed. The rearranged equations form the calibration equations which were used to calculate flow rates using pairs of flowmeter response and line speed values recorded during the flow logging.

When using the full calibration dataset, discharge measured at the land surface at a given time is implicitly assumed to represent the instantaneous conditions recorded downhole by the flowmeter at that same time. To test this assumption, the calibration dataset of Well ER-EC-1 was reduced to average values. The surface discharge, line speed, and flowmeter response were averaged over the length of the blank section, or over time in the case of the stationary measurements. The resulting dataset was then used to derive a second calibration equation for comparison with the first one.

One important aspect of the calibration procedure described above is that its results may be used to calculate a confidence interval for any value of flow rate calculated using the calibration equation. A flow rate value may be calculated for any pair of measured flowmeter response and line speed. An 1-sided 95 percent confidence interval was calculated for each well using the well-specific flowmeter calibration results and a statistical formula described by Hayter (1996).

Calibration Results

A summary of the flowmeter calibration results is presented in Table 3-2. The datasets (1,260 to 2,898 data points) were large enough to yield reliable results. As shown in Table 3-2, the calibration results were satisfactory overall. The values of the multiple regression coefficients were greater than 99 percent for all wells, indicating good fits. The residuals were approximately normally-distributed. The standard errors ranged between 0.87 and 1.46 gpm. In general, the larger flow rate residuals occurred in association with the higher logging line speeds.

Table 3-2
Summary of Flowmeter Calibration Results

Well Name	Number of Data Points	Multiple Regression Coefficient	Standard Error (gpm)	Confidence Interval (gpm)
ER-EC-1	2,569	0.9998	0.95	1.87
ER-EC-6	1,569	0.9995	0.98	2.16
ER-EC-5	1,698	0.9998	0.90	1.62
ER-EC-7	1,260	0.9999	0.87	1.72
ER-EC-8	2,706	0.9999	0.87	1.72
ER-EC-2a	2,898	0.9998	1.30	2.56
ER-EC-4	2,649	0.9998	1.46	2.88
Minimum	1,260	0.9997	0.87	1.62
Maximum	2,898	0.9999	1.46	2.88

The regression coefficients derived from the full and reduced datasets of Well ER-EC-1 were nearly identical. The calculated flow rates using the coefficients from the two methods differed by less than 0.2 gpm over the entire range of values. The primary difference was that the confidence interval near the zero discharge prediction was narrower for the full dataset than when average values were used. Based on the case of Well ER-EC-1, it was be assumed that the time lag between the discharge measured at the land surface and the flow recorded by the flowmeter for all other wells has a negligible impact on the flowmeter calibration.

Well-specific confidence intervals were calculated for each well for low flow rates (near-zero when available) using pairs of flowmeter response and line speed. These one-sided 95 percent confidence intervals ranged between 1.6 and 2.9 gpm (Table 3-2). These values served as detection limits of flow and were used to identify screened intervals that produced statistically significant flow during flow logging.

3.1.4 Interval Flow Contributions

For each flow log, flow rates at different locations in the well were calculated using the well-specific flowmeter calibration equation and pairs of flowmeter response and line speed. Flow rates through the blank casing sections were then calculated as averages of the flow rates measured along the blank casing section. The average discharges were derived from a portion of a given blank section of pipe centered between the ends of the blank section to avoid end effects. If flow was not recorded along the deepest blank casing section of a given well during flow logging, it was assumed to be zero. The quantity of inflow from a given screened interval was then calculated as the difference between the flow rates in the well measured in the blank sections of pipe above and below the screened interval.

The interval flow contributions were calculated by dividing the interval flow rates derived from the flow logs by the total well discharge (Table 3-3). Only intervals that produced statistically significant flow are shown in Table 3-3. The confidence intervals associated with the calibration equation suggest that the interval discharge should be greater than about 1.5 to 2.9 gpm (depending on the well) to be statistically significant. These flow detection limits correspond to the 95 percent confidence intervals discussed in Section 3.1.3.

Table 3-3 shows the water production distribution among the screens for each well. Only those screens that produced water are listed. Table 3-4 shows the proportion of each well that produced water. These tables show that the distribution of production varied widely.

3.1.5 Resolution Effects of Well Construction

The physical construction of the completion intervals results in limitations for resolving the distribution of inflow across the completion intervals. While the annulus of completion intervals provides continuous connection to the formation, the screen casing joints do not provide continuous access to the annulus. The slotting of the casing is not continuous across joints. The slotting for each screen starts 2.5 ft on-center from the end of the casing joint, leaving 5 ft of unslotted casing at each joint of slotted casing. Second, the screens are interspersed with unslotted casing. Third, the screens do not extend to the ends of the completion intervals. The completion intervals (as defined by the filter packs) typically extend about 15 ft beyond the top end of the top screen and bottom end of the bottom screen in each completion interval.

Table 3-3
Summary of Interval Contributions to Borehole Flow for WPM-OV Wells

Screen	Depth to Top (ft)	Depth to Bottom (ft)	Screen Length (ft)	Stratigraphic Unit	Lithologic Unit(s)	Interval Contribution (% of Total Production)
Well ER-EC-1						
Screen 1	2,297.9	2,328.1	30.2	Tpb	Lava	51
Screen 2	2,368.6	2,398.7	30.1	Tpb	Lava	13
Screen 3	2,439.1	2,469.2	30.1	Tpb	Lava	30
Screen 4	2,509.7	2,539.2	29.5	Tpb	Flow Breccia	4
Well ER-EC-6						
Screen 1	1,628.4	1,658.6	30.2	Tpb	Lava	87
Screen 2	1,699.1	1,729.2	30.1	Tpb	Lava	9
Well ER-EC-5						
Screen 1	1,196.6	1,257.6	61.0	Tmar	Welded Tuff	9
Screen 2	1,298.0	1,328.1	30.1	Tmar	Welded Tuff	7
Screen 4	1,892.4	1,952.7	60.3	Tmar	Welded Tuff	27
Screen 5	1,993.3	2,023.4	30.2	Tmar	Welded Tuff	30
Screen 6	2,063.8	2,094.0	30.1	Tmar	Welded Tuff	12
Screen 7	2,245.7	2,275.9	30.2	Tmap	Welded Tuff	5
Screen 8	2,316.4	2,346.6	30.2	Tmap	Welded Tuff	5
Screen 9	2,387.1	2,417.2	30.25	Tmap	Welded Tuff	6
Well ER-EC-7						
Screen 1	920.0	979.0	59.0	Tfbw	Lava/Flow Breccia	15
Screen 2	1,215.1	1,304.0	88.9	Tfbr,Tfb	Lava	85
Well ER-EC-8						
Screen 1	682.6	742.9	60.3	Tfb	Non-Welded Tuff	58
Screen 2	773.0	803.1	30.1	Tfb	Non-Welded Tuff	32
Screen 3	833.3	863.4	30.1	Tfb	Non-Welded Tuff	4
Screen 5	953.6	983.7	30.1	Tfb	Non-Welded Tuff	1
Screen 9	1,807.1	1,837.2	30.1	Tmap	Welded Tuff	2
Screen 10	1,877.7	1,907.8	30.1	Tmap	Welded Tuff	2
Well ER-EC-2a						
Screen 1	1,707.1	2,178.8	471.7	Tfbw, Tfb	Bedded/Non-Welded Tuff	34
Screen 2-1	3,076.7	3,291.3	214.65	Tf,Tmaw	Reworked/Bedded/Non-Welded Tuff	57
Screen 2-2	3,291.3	3,500.0	208.7	Tmaw	Non-Welded Tuff	8
Well ER-EC-4						
Screen 1	992.1	1,052.3	60.2	Ttc	Lava	60
Screen 2	1,092.8	1,123.0	30.2	Ttc	Lava	33
Screen 3-1	1,163.6	1,173.1	9.5	Ttc	Lava	7

Table 3-4
Summary of Flow Losses Analysis

Well	Completion Interval	Top-Bottom Depth (ft)	Pumping Rate (Flow Logging, Constant-Rate Test) (gpm)	Distribution of Water Production	Proportion of Completion Intervals Producing Water	Constant-Rate Test Drawdown (ft)	Calculated Total Well Losses (ft)	Calculated Flow Loss in Casing (ft)	Well Losses/ Total Drawdown	Head Difference from Upper Interval (ft)
ER-EC-1	upper	2,270.0-2,867.0	126.0, 120.5	100.0%	24%	3.9	2.2	0.73	0.56	--
	middle	3,307.0-3,776.0								-1.46
	lower	4,424.0-4,790.9								-0.26
ER-EC-6	upper	1,608.0-1,948.0	68.4, 68.4	93.2%	32%	62.0	NA		NA	--
	upper middle	2,161.0-2,510.0		6.8%						-0.56
	lower middle	3,412.5-3,820.0								-1.91
	lower	4,394.0-5,000.0								-5.57
ER-18-2		1,351.4-2,240.0	NA, 10.2	100.0%	NA	190.0	NA		NA	NA
ER-EC-5	upper	1,177.0-1,443.0	161.4, 160.2	17.7%	84%	5.7	3.8	1.65	0.67	--
	middle	1,845.0-2,146.0		63.6%				3.69		-0.03
	lower	2,215.0-2,447.4		18.7%				3.75		-0.11
ER-EC-7	upper	904.0-1,024.0	177.7, 176.0	15.9%	82%	18.5	12.4	1.29	0.67	0
	lower	1,171.0-1,306.0		84.1%				3.21		-0.96
ER-EC-8	upper	654.0-1,050.0	177.1, 176.4	96.1%	77%	16.0	9.3	1.20	0.58	--
	middle	1,416.0-1,558.0		0.4%				1.21		-0.40
	lower	1,650.0-1,990.0		3.5%				1.21		-1.02
ER-EC-2a	upper	1,656.0-2,236.0	121.8, 120.8	32.6%	62%	271.0	NA	3.06	NA	--
	middle-1	3,047.0-3,291.3		56.8%				4.41		+10
	middle-2	3,291.3-3,500		9.2%				4.44		Unknown
	lower	4,442.0-4,974.3		1.4%				4.44		Unknown
ER-EC-4	upper	962.0-1,240.0	182.2, 180.8	100.0%	19%	4.7	2.8	1.12	0.61	--
	middle	1,856.0-2,295.0								-2.12
	lower	3,050.0-3,447.0								-8.17

The stress (drawdown) imposed by pumping acts throughout the filter pack and stresses the formation behind the blank casing. However, there is no way to determine the distribution of inflow behind the blank casing. Some qualitative interpretation could be made by evaluating increases in production at the ends of each screen and attributing such increases to formation behind the blank casing, but this is not necessarily accurate. Production behind blank casing was evident in many of the wells as very abrupt increases in flow at the ends of screens. The hydraulics of vertical flow in the filter pack and end effects for the screens are undefined. The impact of this situation is uncertainty in correlating increases in flow with the appropriate thickness of formation for use in discrete calculations of hydraulic conductivity. This uncertainty is analyzed in Section 3.4.4, and proved to be substantial in some cases. This problem may explain some of the variability in the discrete hydraulic conductivity values. However, determining hydraulic conductivity across entire completion intervals or long sections of completion intervals averages out much of this uncertainty.

3.1.6 Temperature Logs

Temperature logs were run in the WPM-OV wells during pumping in conjunction with the flow logging. These logs provide additional information on the origin and movement of water in the well. Of particular interest is a comparison of the temperature logs during pumping with nonpumping logs. The primary weakness of this comparison was that the only nonpumping logs for these wells were run shortly after the constant-rate test. At that time the well may not have reestablished an equilibrium temperature regime. Temperature logs run just before the start of development, or in conjunction with the bridge plug measurements, would have provided a baseline for interpreting the temperature profile changes during the testing program.

3.2 Well Losses

The drawdown observed in a well is comprised of aquifer drawdown and well losses associated with the flow of water into the well and up to the pump. Aquifer drawdown can be observed directly in observation wells near a pumping well, but observation wells were not available near any of the WPM-OV wells. The analyses of the constant-rate tests used the drawdown in the production well to determine hydraulic parameters. Analyses of the step-drawdown test, where they were run, were used to estimate the well losses. The derived hydraulic conductivities can then be corrected to reflect just the aquifer drawdown.

Well losses were divided into entrance losses from the formation into the well and flow losses in the casing. The well loss analyses were structured to calculate losses on a screen-by-screen basis for use in the analyses of hydraulic conductivity for each screen. The flow loss distributions in casing were based on the flow logging information. These calculations should provide representative values for the magnitude of the losses in the well, and consequently should produce more accurate results for the formation hydraulic conductivity. In many cases, the flow losses were found to be substantial fractions of the total drawdown. In those cases, accounting for flow losses in the analysis resulted in substantial adjustments to the derived hydraulic parameters. The analyses of the hydraulics of these wells provided more complete explanations for the restricted producing intervals that were observed. These analyses provide better understanding of the hydraulics of water production in these wells, and the results are used to evaluate this type of well construction for future testing and monitoring purposes.

3.2.1 Well Losses Methodology

The methodology used the step-drawdown test results, when available, to separate laminar and turbulent loss components of the drawdown. The laminar loss component was attributed to aquifer drawdown and the turbulent loss component to total well losses. Flow losses inside the well were calculated independently and subtracted from the turbulent losses to yield flow losses from the formation into the well.

Assignment of the total turbulent (nonlinear) component of the drawdown to well losses may not be entirely accurate, but was used as a best estimate for the well losses. The turbulent losses can be identified and quantified fairly well for flow in the casing, but the other components are much less certain. These components include flow through the screen slots, flow through the filter pack, flow through the formation/borehole interface, and fracture flow. These components may be turbulent or laminar, but are generally turbulent where production rates, and consequently velocities, are high. The nature of flow through screen slots can be characterized in theory, but is uncertain due to lack of information on the in-place condition of flow through the slots due to clogging. The nature of local flow through the filter pack, formation/borehole interface, and in fractures is not characterized independently. The latter may include turbulent flow that properly belongs to formation drawdown. The well skin factor from the constant-rate test analysis may also provide some information on the combined effect of these factors, but the quantitative relationship of the well loss components to this factor has not been investigated.

3.2.2 Results and Discussion

Table 3-4 presents a general summary of the well completions, production distribution during testing, and information on drawdown, calculated flow losses, and the vertical gradient. Only a portion of the completion intervals in each well produced water during pumping, as shown in the column labeled *Distribution of Water Production*. The column *Proportion of Completion Intervals Producing Water* gives the percent of the total length of the completion intervals for each well that produced water. These data show the varying distribution of production during pumping, and the varying percentages of the completion interval length for each well that produced water during pumping. The substantial differences between wells illustrate that a wide range of water production hydraulics can occur. Flow logging information was required to determine the representativeness of the testing data and samples from these long completion intervals/multiple-completion wells.

The next column gives the maximum *Constant-Rate Test Drawdown*, followed by columns containing the *Calculated Total Well Losses* and *Calculated Flow Loss in Casing*. The well loss calculations were done in support of the flow logging analysis, and the losses were calculated for the flow logging pumping rates. The constant-rate test pumping rate was very close to the flow logging rate for which data are presented, and the magnitude of the flow losses listed is representative for the constant-rate test drawdown. The calculated flow loss in casing gives the loss calculated for the flow from the bottom of the completion interval up the casing to the pump. It can be seen that the losses go up with the increasing percentage of production and with the distance the water travels to the pump. The pump was typically located several hundred feet below the static water level. These losses are a function of moving water through the well, and are not related to the efficiency of the connection of the well to the formation. It can be seen that, in some cases, these losses are large with respect to the drawdown. The variation of the flow losses in the casing with depth results in reduced applied stress to the formation with depth, which can have a great affect on the distribution of production with depth.

The difference between the total well loss and the flow loss in casing is attributed to losses from the formation to the casing. These losses were apportioned to the screens in the completion intervals according to the square of the production from each screen for the discrete hydraulic conductivity analyses.

The column labeled *Well Losses/Total Drawdown* shows the ratio of the predicted well losses to the total drawdown derived from the step-drawdown test analysis. For the wells with small to moderate drawdown, the well losses are typically more than half of the drawdown. These were very productive wells with high production rates. For the wells with large drawdowns, step-drawdown tests could not be run and there was no analysis to determine the proportion of turbulent losses. However, the well losses for these wells would probably be a much lower proportion of the drawdown since the well losses are related to the square of velocity, and the production rates (and consequently, velocities) were lower for these wells. In these cases, there was no basis for estimating total well losses, and only flow losses in the casing were subtracted from the total drawdown. For five wells, less than half of the measured drawdown represented formation drawdown.

The column *Head Difference from Upper Interval* repeats information shown in Table 2-1 as *Bridge Plug Response* in a slightly different format, and incorporates additional information on Well ER-EC-2a. These are representative values for the vertical gradient between completion intervals. Subtracting the vertical gradient from the well drawdown (constant-rate test drawdown less the flow loss in casing) indicates the effective drawdown applied to each completion interval. In one case (i.e., Well ER-EC-4), the drawdown imposed by pumping did not overcome the vertical gradient in the well, and, consequently there was no effective drawdown in the lower two completion intervals. Rather, the drawdown from pumping just reduced the vertical gradient to the lower intervals, and the downward flow rate from upper interval was correspondingly reduced. In another case (i.e., Well ER-EC-1), the vertical gradient was a large fraction of the imposed drawdown, and after accounting for flow losses the stress (drawdown) on the lower intervals was minimal. This situation accounts in great part for the lack of production from those intervals.

The combination of the results for the independent determinations of total well losses and flow losses in casing appear to be consistent. The calculated total well loss component is larger than the calculated flow losses in casing, as it should be since the flow loss in casing is only part of the turbulent losses. Factoring in the vertical gradient information with the drawdown and flow loss values provides a picture of the hydraulics consistent with the measured flow distribution.

3.2.3 Step-Drawdown Tests

The step-drawdown tests that were conducted produced data that yielded trendlines with high correlation coefficients. However, only three steps (pumping rates) were conducted for these tests, and the three data points that resulted from each test does not provide much refinement and only moderate confidence. The pumping rates that were used did span the entire range characterized by flow logging and included the rate used for the constant-rate test, so the results of the step-drawdown analysis are appropriate for use in the other analyses. An important improvement in the methodology would be to add several more intermediate flow rates to the step-drawdown tests to improve confidence in the result.

3.2.4 In-Casing Flow Losses

The methodology that was employed has some uncertainty for a variety of reasons; mostly, the major reason related to the appropriate friction factors to be used for the screen sections. In those sections, the losses are not only the result of friction but of the hydrodynamic effects of the inflow on the boundary layer. The losses in the screens were calculated with a friction factor double that of nonperforated casing, based on a generalization found in literature. Another factor in the uncertainty is that the flow rate increases through the screen sections. This was approximated in the calculation by using the root mean square of the velocities below and above the individual screen sections to calculate the loss for each length of screen, recognizing that the loss is proportional to the square of the velocity. However, for the wells with substantial calculated losses in-casing, the losses were dominated by the losses in the long lengths of nonslotted casing between the completion intervals. The calculated in-casing flow loss distributions are probably fairly representative. Another approach to this problem would be to determine flow losses directly by conducting pressure surveys during pumping in conjunction with the flow logging. This data would provide the basis for characterizing in-casing flow losses with depth, especially along the screen sections.

3.3 Constant-Rate Test Analysis

Analysis of the constant-rate tests were conducted using the software package AQTESOLV® (HydroSOLVE, 1996-2000). The implementations of the various models discussed below are described in the Users Guide. Confined aquifer solutions were most appropriate based on the general hydrogeologic situation of the wells. The completion intervals were located large distances below the water table, and generally were placed in more permeable lithologies bounded above and below by less permeable lithologies. The assumption was made that there was substantial vertical to horizontal anisotropy and that the response to pumping stress primarily propagated horizontally. This assumption was applied to defining the appropriate aquifer thickness in the analysis, and considering the wells to be fully penetrating.

The Moench 1984 (AQTESOLV®) model for dual porosity in a fractured aquifer was found to be the best model for matching the aquifer response. The Papadopoulous-Cooper 1967 (AQTESOLV®) confined aquifer model for large diameter wells was also used in cases where dual-porosity behavior was not clear. Both of these models incorporate casing storage, which can be important in the early-time. In both cases where the Papadopoulous-Cooper model was applied it could not produce solutions that matched the later-time data as well as the dual-porosity model. An alternative approach that could be used to simulate the midterm reduced rate of drawdown period would be a recharge boundary. Recharge boundaries could probably have been tailored to mimic the responses. However, the use of the dual-porosity model for all of the wells was thought to be more appropriate and less arbitrary than postulating recharge boundaries for each well without a physical basis for them.

The Moench dual-porosity model is consistent with the known geology, and produced generally good solution fits, better than the other models. The midterm reduced rate of drawdown period was reproduced very well with dual porosity, including late-term resumption of drawdown. The primary hydraulic conductivity was the main parameter of interest, and the values derived for this parameter using the dual-porosity model were not substantially different from values derived using other models. The other fitting parameters generally appeared to be reasonable and consistent, but there was no additional information available to constrain the solutions with regard to these parameters. The specific storage values, especially for the matrix, are somewhat questionable. However, data from a production well will not necessarily yield accurate values for storage.

The implementation of the Moench solution produces a primary hydraulic conductivity value rather than a transmissivity. The hydraulic conductivity is computed internally as a function of the aquifer thickness. The most appropriate value for aquifer thickness was identified as the length of the completion intervals that actually produced water, as quantified from the flow logging. There are two different considerations for assigning aquifer thickness. The first consideration was to only include completion intervals that produced water, and in several cases the aquifer thickness was limited to only the producing part of a completion interval. The reasoning was that the resultant hydraulic conductivity would be used in the discrete analysis using the flow logging to determine the variation in the sections of each well that produced resolvable flow. The characteristics of nonproducing intervals are generally not reflected in the drawdown response, but simply serve to define the length over which parameters are averaged. As can be seen in Table 3-4, the part of the total length of completion intervals in any well that produced water varied from 19 to 84 percent.

The second consideration was the uncertainty about the length of formation that produced water due to well construction features preventing direct measurement. This is discussed in detail in the section on flow logging analysis, and was handled as an uncertainty in the aquifer thickness. Alternate hydraulic conductivity values were determined for each well based on two values for aquifer thickness. This will be discussed further in Section 3.4.4. Briefly, the larger value allowed for production behind unslotted casing, and used the distance from the top of the completion interval, as defined by the top of the 6/9 sand, to the bottom of the quantified production. The smaller value included only the length of screen in which production was actually quantified.

Table 3-5 presents the hydraulic conductivity values that were determined from the Moench dual-porosity model. The K values are fracture hydraulic conductivity, which represents the primary permeability and is used to compute the transmissivity of the well. The adjusted K value is the K value from the aquifer analysis divided by the proportion of drawdown that was determined to be actual aquifer losses (see Table 3-4), which should better reflect the hydraulic conductivity of the formation.

The storage parameters produced from the analyses are not reported here since they were not the objective of the analysis and the quality of the values is not clear. The values that were determined for these parameters can be found in the individual well analysis reports. Although the solutions were generally sensitive to the parameter values, storage parameters cannot be reliably determined from single well tests. As described in the individual well reports, the storage parameters were constrained as much as possible to values consistent with other information. In general, storage parameter values that provided the best fit were higher than potential values calculated from general information on porosity and compressibility of rocks of similar general lithology. However, in the analysis the storage parameters values are interdependent with the specified well radius. The appropriate value for the well radius is somewhat uncertain since it would be an integrated function of the actual hole diameter, related proportional production, and local fracture characteristics.

Included on the table is identification of the lithologies that were characterized by the constant-rate tests. The results for each well are composites of the varying formation characteristics in the producing length of the completion intervals. However, production in each well is generally dominated by one lithology to which the hydraulic conductivity can be attributed. Two wells, ER-18-2 and ER-EC-2a, exhibited substantially lower hydraulic conductivities, resulting in large drawdowns. The low productivity of the formations in these wells is probably associated with less fracturing of the formations, but this has not been checked against any fracture data that might be available.

Table 3-5
Constant-Rate Test Analysis Results

Well	Completion Interval	Lithology	Percent of Lithology	Percent Production	K (Filter Pack/Screens)[1] ft/d	Adjusted K (Filter Pack/Screens) ft/d
ER-EC-1	upper	Lava, Flow Breccia	100%	100%	19.8/56.8	45.0/129.1
ER-EC-6	upper	Lava	100%	93%	1.8/5.2	NA
	upper middle	Non-Welded/Bedded Tuff, Welded Tuff	71/29%	7%		
ER-18-2		Welded Tuff	100%	100%	0.002/NA	NA
ER-EC-5	upper	Welded Tuff	100%	18%	9.5/27.1	28.8/82.1
	middle	Welded Tuff	100%	64%		
	lower	Welded Tuff/Vitrified Tuff	100%	19%		
ER-EC-7	upper	Lava, Flow Breccia	100%	16%	9.3/16.0	28.2/48.5
	lower	Lava	100%	84%		
ER-EC-8	upper	Non-Welded Tuff	100%	96%	2.9/8.2	6.9/19.5
	lower	Non-Welded Tuff, Welded Tuff/Vitrified Tuff	37/63%	4%		
ER-EC-2a	upper	Bedded/Non-Welded Tuff	100%	33%	0.06/0.06	NA
	middle-1	Non-Welded/Reworked/Bedded Tuff	100%	57%		
	middle-2	Non-Welded Tuff	100%	9%		
	lower	Non-Welded Tuff, Welded Tuff	60/40%	1%		
ER-EC-4	upper	Lava, Colluvium	96/4%	100%	59.9/155.1	153.6/397.7

[1]Determined for aquifer thickness equal to the filter pack length/determined for aquifer thickness equal to producing length of screens

ft/d - Feet per day
NA - Not applicable
K - Fracture hydraulic conductivity
Adjusted K - K divided by the proportion of drawdown that was determined to be actual aquifer losses

3.4 Interval Transmissivities/Conductivities

Ranges of hydraulic conductivities were calculated for producing screened intervals using the flow rates derived from the flow logs. Calculation of ranges rather than single values of hydraulic conductivity for a given screened interval are provided to account for major sources of uncertainties. Uncertainty in the interval hydraulic conductivity values comes from both uncertainty in the calculation method and uncertainty in parameters. Brief descriptions of the calculation methods, needed parameters, sources of uncertainties, and calculation process are presented, followed by a summary and discussion of the results.

3.4.1 Calculation Methods and Associated Uncertainty

A summary of the calculation methods and associated uncertainties is presented. More detailed descriptions may be found in the individual well reports**.**

Several methods are available for deriving hydraulic conductivities from flow rates derived from flow logs (Molz et al., 1989; Molz and Young (1993); Rehfeldt et al., 1989). These methods are, however, all based on the Cooper and Jacob (1946) equation. Assumptions underlying the Cooper-Jacob equations are as follows:

- The aquifer has infinite areal extent.
- The aquifer is homogeneous, isotropic, and of uniform thickness.
- The pumping well is fully-penetrating.
- The flow to the pumping well is horizontal.
- The aquifer is confined.
- The flow is unsteady.
- Water is released instantaneously from storage with decline of the hydraulic head.
- The diameter of the pumping well is very small so that storage in the well can be neglected.
- The values of u are small (i.e., the well radius is small and the time is large).

The differences between the various methods stem from assumptions about the storage coefficients and the flow losses. Two methods encompassing the range of uncertainties were used to calculate the interval transmissivities.

In the first method, the specific storage is assumed to be constant in the aquifer as considered by Molz et al. (1989) and Molz and Young (1993). This method accounts for the well losses. In the second method (Molz et al., 1989), the layer storage coefficient is assumed to be a portion of the full storage coefficient. This assumption amounts to a statement that the hydraulic diffusivity (the ratio of transmissivity to storage coefficient) of the aquifer is constant with depth. Also, in this method, the well losses are assumed to be zero. Both methods yield values of transmissivities for each of the screened intervals considered. Values of hydraulic conductivities are then calculated by dividing the transmissivities by the screened interval thicknesses.

Sources of method uncertainty evaluated in this analysis include the assumed form of the interval storage coefficient and whether the methods accounts for flow losses or not. However, method uncertainty due to violations of key model assumptions of the Cooper-Jacob equation was not evaluated. One of these key assumptions is that flow to the well is horizontal. As Ruud and Kabala (1997a and b), Cassiani and Kabala (1998), and Ruud et al. (1999) note, vertical flow may occur in the vicinity of the well due to heterogeneity, head losses, well skin effects, and partially penetrating screens. Each of these can lead to errors in the calculated interval hydraulic conductivity when using the horizontal flow assumption.

3.4.2 Required Parameters and Associated Uncertainty

Parameters required to calculate the interval hydraulic conductivities are discussed, along with the associated uncertainties. Some types of required parameters were not measured directly during flow logging but were rather estimated from the step-drawdown and constant-rate tests.

Required Parameters

The two methods used to calculate interval hydraulic conductivities require the following parameters:

- Well discharge rate during pumping
- Screened interval flow rates
- Water-level drawdown and associated time, adjusted for flow losses
- Aquifer transmissivity
- Aquifer storage term: product of effective radius squared and storage coefficient ($r_w^2 S$)
- Interval contributing thickness

The average of the recorded values of surface discharge was used to represent the well discharge rate in the calculations. The screened interval flow rates were those derived from the flow logs as described in Section 3.1.4. The water level drawdown of interest is that in effect during the conduct of a given flow log. The water level drawdowns were estimated using the step-drawdown, constant-rate test results, and time information recorded during the flow logging. The aquifer transmissivity was calculated by multiplying the transmissivity derived from the constant-rate pumping test by the ratio of the formation drawdown to the well drawdown at a given time. The formation drawdown was calculated as the drawdown observed in the well adjusted for the well-flow losses. Well-flow losses were calculated as averages of the screen-flow losses weighted by the flow rates. The aquifer storage term was assumed to be constant and was calculated using the Cooper-Jacob equation. The interval contributing thicknesses are derived from the well construction diagrams.

Parameter Uncertainty

Uncertainty in the transmissivity values calculated using the first calculation method comes from uncertainty in the flow rate, drawdown, and parameters within the logarithm of the equation used (well thickness, time and storage term). The major sources of parameter uncertainty in the calculation of interval hydraulic conductivities are the flow rate, drawdown, and interval thickness. The impact of the time, drawdown, and interval thickness uncertainty were assessed using ranges of values for these parameters, rather than single values.

The time at which flowmeter measurements are taken relative to the total time of pumping influence calculated hydraulic conductivity. If the time of measurement is long after pumping began, the change in drawdown and well hydraulic condition will be small both during the logging run and between logging runs. If one logging run is made too close to the start of pumping, it seems likely that parameters from that run could differ from later runs. Timing information that is relevant to the analysis of flow logging data includes the following times: start of pumping at a given rate, start of a logging run, and end of a logging run. This type of information was available from the morning reports. The start of pumping was available for all logging runs. However, the start and end times of logging were not available for each individual run. As a result, the start and end times of all flow logging of a given well were used to define the range of uncertainty of the time variable. The time reference was the start of pumping.

Drawdowns that occur during the well flow logging are unknown because they are not measured simultaneously. For each well, a range of drawdowns were estimated using information on the well response to pumping derived from the constant-rate or step-drawdown tests. The range of drawdowns was calculated to approximately correspond to the time period during which the flow logging was conducted. This time interval is as defined in the previous paragraph. The estimated values of minimum and maximum drawdown values were then adjusted for flow losses, if significant. These drawdowns were calculated using the Cooper and Jacob (1946) equation applied to the whole well, the average well transmissivity value and the product $r_w^2 S$. The calculated range of drawdowns includes flow losses discussed in Section 3.2. The corrections for well losses, both inside and outside the well, are an additional source of uncertainty.

To determine the hydraulic conductivity of an interval, the contributing portion of the well must be defined by top and bottom depths. For the WPM-OV wells, the screened interval thicknesses are not precisely known because flow to the screen may be derived, in part, from behind the blank section of pipe above or below the screen. A range of interval thickness was defined for each screened interval that produced a statistically-significant amount of flow. The minimum contributing thickness was assumed to be the length of the screened interval. Each screened interval is composed of one or more slotted sections of pipe. The minimum length did not include the nonslotted parts of the sections located at both ends of a given continuous string of slotted sections. The maximum contributing thickness was assumed to be equal to the length of the filter pack including the 6/9 sand where present. Hydraulic conductivity values averaged over intervals corresponding to the producing screened intervals are expected to provide adequate vertical resolution for the CAU-scale and sub CAU-scale models.

3.4.3 Calculation of Interval Hydraulic Conductivities

For each well, the transmissivity of each interval was calculated using the two methods described above. Hydraulic conductivities were calculated for two pairs of time/drawdown values and two values of interval thickness. These calculations led to several estimates of hydraulic conductivity for each screened interval.

3.4.4 Results and Discussion

A range of hydraulic conductivity values were derived from the flow logs of the WPM-OV wells. A summary of the results is presented, followed by a discussion of the sources of uncertainty. Major sources of uncertainties that were directly evaluated include the method, time variable, drawdown, and interval thickness. Other sources of uncertainty are also discussed.

Table 3-6 presents a summary of the calculated hydraulic conductivities in the form of average, minimum and maximum values for each screened interval. Overall, these values cover a wide range from 0.02 to 2225.84 feet per day (ft/d). The lowest value corresponds to an interval open to a tuff unit and the highest value corresponds to an interval screened in a lava unit. The average range of uncertainty was a factor of about 8, but could be as high as 40. The range of uncertainty was the smallest for Well ER-EC-2a, where drawdown and interval thickness uncertainties were very small for all three producing intervals. The range of uncertainty was the largest for Screen 3-1 of Well ER-EC-4 (a factor of 40). The uncertainty in the hydraulic conductivity of this interval is largely due to the uncertainty in the interval thickness (a factor of 17). The water enters the borehole from a small portion of Screen 3 (1.6 ft) but is believed to originate from a fracture behind the casing section located above. The maximum thickness of the producing interval is assumed to be the thickness of the corresponding filter pack (28.1 ft).

Method uncertainty was evaluated using two extreme methods to cover the full range. In the first method, the specific storage was assumed to be constant in the aquifer and the well losses were accounted for. In the second method, the layer storage coefficient was assumed to be a portion of the full storage coefficient and the well losses were assumed to be zero. The results show that the two methods used yield hydraulic conductivities that may be different by a factor of about four. Both methods are, however, based on the applicability of the Cooper-Jacob equation describing horizontal flow to the well. Method uncertainty resulting from violations of key model assumptions, such as the applicability of the Cooper-Jacob equation describing horizontal flow to the well, was not evaluated.

Table 3-6
Summary of Interval Hydraulic Conductivities Calculated for the WPM-OV Wells
(Page 1 of 2)

Screen	Depth to Top (ft)	Depth to Bottom (ft)	Slotted Screen Length (ft)	Filter Pack Length (ft)	Stratigraphic Unit	Lithologic Type	Average Hydraulic Conductivity (ft/d)	Minimum Hydraulic Conductivity (ft/d)	Maximum Hydraulic Conductivity (ft/d)
Well ER-EC-1									
Screen 1	2,297.9	2,328.18	25.4	78.3	TPB	Lava	114.71	49.05	194.79
Screen 2	2,368.6	2,398.7	25.4	70.6	TPB	Lava	23.87	9.71	47.04
Screen 3	2,439.1	2,469.2	25.4	70.6	TPB	Lava	63.69	31.51	101.57
Screen 4	2,509.7	2,539.2	24.8	70.0	TPB	Flow Breccia	6.85	2.30	14.12
Well ER-EC-6									
Screen 1	1,628.4	1,658.6	25.4	72.8	TPB	Lava	5.84	2.81	9.07
Screen 2	1,699.1	1,729.2	25.4	70.7	TPB	Lava	0.55	0.25	0.98
Well ER-EC-5									
Screen 1	1,196.6	1,257.6	56.3	90.8	TMAR	Welded Tuff	16.02	4.01	35.85
Screen 2	1,298.0	1,328.1	25.4	70.6	TMAR	Welded Tuff	23.53	7.32	74.28
Screen 4	1,892.4	1,952.7	55.6	118.0	TMAR	Welded Tuff	70.16	36.58	113.86
Screen 5	1,993.3	2,023.4	25.4	70.7	TMAR	Welded Tuff	170.47	55.35	318.00
Screen 6	2,063.8	2,094.0	25.4	102.4	TMAR	Welded Tuff	74.73	23.12	156.96
Screen 7	2,245.7	2,275.9	25.4	73.2	TMAP	Welded Tuff	27.07	7.61	111.78
Screen 8	2,316.4	2,346.6	25.4	70.7	TMAP	Welded Tuff	29.38	7.77	93.69
Screen 9	2,387.1	2,417.2	25.4	113.2	TMAP	Welded Tuff	31.62	4.40	111.44
Well ER-EC-7									
Screen 1	920.0	979.0	54.3	112.0	TFBW	Lava/Flow Breccia	6.55	2.67	14.17
Screen 2	1,215.1	1,304.0	84.2	126.0	TFBR,TFB	Lava	46.51	31.89	63.23
Well ER-EC-8									
Screen 1	682.6	742.9	55.6	104.0	TFB	Non-Welded Tuff	31.43	19.92	43.48
Screen 2	773.0	803.1	25.4	60.3	TFB	Non-Welded Tuff	37.28	18.88	62.72
Screen 3	833.3	863.4	25.4	60.3	TFB	Non-Welded Tuff	3.81	1.89	6.88
Screen 5	953.6	983.7	25.4	111.5	TFB	Non-Welded Tuff	1.10	0.28	2.53
Screen 9	1,807.1	1,837.2	25.4	70.6	TMAP	Welded Tuff	1.55	0.33	4.19
Screen 10	1,877.7	1,907.8	25.4	132.6	TMAP	Welded Tuff	1.25	0.10	3.91
Well ER-EC-2a									
Screen 1	1,707.1	2,178.8	467.0	580.0	TFBW, TFB	Bedded/ Non-Welded Tuff	0.034	0.026	0.043
Screen 2-1	3,076.7	3,291.3	209.8	244.3	TF, TMAW	Reworked/ Bedded/ Non-Welded Tuff	0.159	0.134	0.211

Table 3-6
Summary of Interval Hydraulic Conductivities Calculated for the WPM-OV Wells
(Page 2 of 2)

Screen	Depth to Top (ft)	Depth to Bottom (ft)	Slotted Screen Length (ft)	Filter Pack Length (ft)	Stratigraphic Unit	Lithologic Type	Average Hydraulic Conductivity (ft/d)	Minimum Hydraulic Conductivity (ft/d)	Maximum Hydraulic Conductivity (ft/d)
Screen 2-2	3,291.3	3,500.0	204.0	208.7	TMAW	Non-Welded Tuff	0.021	0.016	0.028
Well ER-EC-4									
Screen 1	992.1	1,052.3	58.4	110.5	TTC	Lava	142.68	90.90	209.14
Screen 2	1,092.8	1,123.0	25.4	70.8	TTC	Lava	175.22	75.25	317.44
Screen 3-1	1,163.6	1,173.1	1.6	28.1	TTC	Lava	849.21	55.78	2225.84

However, many of the errors due to small-scale vertical flow have been minimized in this work by integrating flowmeter responses over the length of each screened section.

The uncertainty on drawdown was a significant source of error for some of the wells. The maximum range of uncertainty due to drawdown uncertainty was a factor of two. Drawdown uncertainty comes from two sources: unknown time and corrections for flow losses. The well loss corrections are similar down the well, but the impact of the uncertainty will be larger for screened intervals that have lower flow rates. In addition, for a given screened interval, the differences between logging runs was relatively small, considering that the logging runs were made at different times after pumping began. Therefore, the time of measurement was not a significant source of error in the interpretation. This is consistent with the expectation that the effect of this parameter is not too large because the logarithm has the effect of moderating the impact.

In general, the biggest source of uncertainty was the length of the contributing interval for each screened interval. The uncertainty in the contributing thickness produced a maximum uncertainty in interval hydraulic conductivity that is about a factor of 17.

Other sources of parameter uncertainty come from uncertainty in the flow rate, and parameters within the logarithm of the equation used (other than time). In general, the flow rate determined from the flowmeter and line speed measurements is accurate to within plus or minus 3 gpm. Flow uncertainty is, therefore, a small factor for screened intervals which produced the most water, but could be a significant factor for intervals that produced small amounts of water. The estimate for the effective radius-storage coefficient product influences the calculated hydraulic conductivity values. This term was assumed to be a constant in the calculations but was found to actually vary depending on the time/ drawdown pair of values used.

In summary, the interval hydraulic conductivity values derived from the flow logging information are uncertain, with greater uncertainty associated with the small hydraulic conductivity intervals. The uncertainty of the interval hydraulic conductivity values varies depending on the well. The overall range of uncertainty ranges between factors of 1.5 to about 40. This range is quite good when compared with the range of hydraulic conductivity values presented in the regional groundwater model report (DOE/NV, 1997), where values of hydraulic conductivity for volcanic units ranged over more than seven orders of magnitude.

3.5 Comparison of Transmissivity Values Derived from Different Datasets

In several cases, transmissivity values were determined for completion intervals using both the constant-rate data/flow log analysis and the nonpumping bridge plug head change data and thermal flow measurements. Table 3-7 presents the range of values for T for comparison. Details on the determination of these various values can be found in the individual well analysis reports. The T Minimum from the pumping test is based on the length of the filter pack, and the T Maximum is based on the length of the screens. In most cases, the values are similar. There is a substantial discrepancy in the values for Well ER-EC-8 upper interval. In this case, the value computed for the steady-state, nonpumping analysis is based on a head change value of 0.01 ft, which is much less than the reasonable accuracy of the measurement. Consequently, this value is very uncertain.

Table 3-7
Comparison of T Values Derived from Different Datasets

Well	Completion Interval	T Minimum ft^2/d, Pumping Test	T Maximum ft^2/d, Pumping Test	T Steady State Analysis ft^2/d, Nonpumping	T Transient Analysis ft^2/d, Nonpumping
ER-EC-5	middle	10,597	18,395		4,900 (lower limit)
	lower	1,604	8,050		4,900 (lower limit)
ER-EC-7	upper	299	769	690 (lower limit)	
ER-EC-8	upper	3,355	4,250	29,900	
	lower	37	206	133	

4.0 Groundwater Chemistry

As part of the WPM-OV well development and hydraulic testing program for Fiscal Year 2000, groundwater characterization samples were collected at eight investigation wells. Generally, both discrete bailer and wellhead composite groundwater characterization samples were collected at each site. The discrete bailer samples were collected in order to represent the characteristics of the groundwater at a specific depth or in a corresponding completion interval. They are also used to collect a sample that represents a combination of the characteristics of the groundwater for all of the production below the depth of collection. The purpose of the well-head composite groundwater characterization sample, on the other hand, is to obtain a groundwater sample that represents as much of the open completion intervals as possible. The analytical results of the groundwater characterization samples were discussed in detail in previous reports. This discussion summarizes various aspects of both the sampling of the eight wells and the overall geochemistry of the eight wells. For example, the overall effectiveness of the development of these wells and the representativeness of the groundwater characterization samples as it applies to the groundwater chemistry is examined. In addition, the major ion chemistry and stable isotope data are examined to investigate similarities or differences between the eight wells.

4.1 Effectiveness of Well Developments

For each of the eight wells, water quality monitoring of the well discharge was conducted during pumping to provide information on water chemistry and to indicate when natural groundwater conditions predominate in the pumping discharge. The values of certain geochemical parameters (e.g., pH, turbidity, and dissolved oxygen) were expected to decline and stabilize as well development progressed. This decline and stabilization indicates the restoration of natural groundwater quality as opposed to water affected by drilling and completion activities. The results of the water quality monitoring during well development were examined in earlier reports.

The analytical results from the groundwater characterization samples also helped to address the effectiveness of each well's development. For example, during drilling of each well, the make-up water was tagged with a lithium bromide tracer to help determine such things as the water production during drilling through reference to the dilution of the tracer. This injection of tracer-tagged water into the well bore provides another means to gauge the effectiveness of each well's development. If any of the samples from the eight wells had either bromide or lithium concentrations that were significantly higher than the background concentration of either ion, it would tend to suggest that the well had not undergone sufficient development. The analytical results from the groundwater characterization samples for each well showed that none of the eight wells had concentrations of bromide that were significantly higher than the background concentrations in surrounding wells or springs. This likely indicates that all eight wells were sufficiently developed to remove residual drilling fluids and resultant chemistry changes in the formations resulting from drilling activities. This conclusion, of course, only pertains to the lithologic formations that were supplying water during pumping. In addition, there was no apparent difference in the water chemistry between the two types of characterizations samples due to sampling at different times.

In addition to the potential contamination of the groundwater characterization samples with residual drilling fluids, it was also important to assess the potential for cross-contamination of groundwater from one lithologic unit to another. For example, groundwater might flow from a screened interval completed in one lithologic unit to a screened interval completed in another lithologic unit that is at a lower hydraulic head. Unless this groundwater was completely removed from the impacted screened interval by sufficient pumping, a discrete bailer sample attempting to collect groundwater from this interval would in effect be sampling only the groundwater from the screened interval at a higher hydraulic head. This might result in the reporting of erroneous values for a given interval. For this reason, the individual completion intervals in each well were evaluated in order to determine if any of the completion intervals were impacted by groundwater from other completion intervals within the same well. This was based on whether there was flow into the interval from another interval, and whether the estimated volume of flow into the interval was removed from the interval during pumping before the sample was collected.

Section 4-1 contains a summary of the situation regarding the representativeness of the water quality for the samples. Inspection of Table 4-1 reveals that essentially all of the investigation wells have lower completion intervals that have been impacted by crossflow from completion intervals at higher hydraulic heads. It can also be seen from the table that for half of the investigation wells it was difficult to determine whether a given completion interval was impacted by crossflow. For example, the table shows that there was some uncertainty in determining if there was crossflow for Wells ER-EC-1, ER-EC-6, ER-EC-2A, and ER-EC-8. The table also shows that three of the wells had completion intervals that were not developed during the well development and testing phase. Specifically, it can be seen that Wells ER-EC-1, ER-EC-6, and ER-EC-4 had completion intervals that were not developed. It is not surprising that the crossflow into the lower completion intervals for those wells was not removed during the well development and testing phase of those wells. Unfortunately, the table also shows that for those wells that did have developed completion intervals not all of the crossflow was removed from those intervals. For example, it can be seen in the table that Well ER-EC-8 had crossflow into the lower completion interval that was not removed during the well development and testing phase even though that completion interval was developed.

Table 4-1
Summary of Information Relating to Representativeness of the Water Quality Samples

Well	Completion Interval	Crossflow into Interval From Other Interval(s)	Interval Developed by Pumping?	Volume of Crossflow Removed?	Interval(s) Contributing to Discrete Bailer Sample(s)[1]	Interval(s) Contributing to Composite Sample
ER-EC-1	upper	no	yes	NA	1	X
	middle	probably	no	no		
	lower	probably	no	no		
ER-EC-6	upper	no	yes	NA	1	X
	upper middle	?	?	?		X
	lower middle	yes	no	no		
	lower	no	no	no		
ER-18-2	NA	NA	Yes	NA	1	X
ER-EC-5	upper	no	yes	NA		X
	middle	yes	yes	yes - probably	1	X
	lower	yes	yes	no	1,2	X
ER-EC-7	upper	no	yes	NA		X
	lower	yes	yes	yes - probably	1	X
ER-EC-8	upper	no	yes	NA	1	X
	middle	maybe	?	?	1,2	X
	lower	yes	yes	no	1,2	X
ER-EC-2a	upper	yes?	yes	? - probably		X
	middle-1	?	yes	? - probably		X
	middle-2	?	yes	?	1	X
	lower	?	?	?		X
ER-EC-4	upper	no	yes	NA	1	X
	middle	yes	no	no		
	lower	yes	no	no		

[1]Denotes the shallowest discrete bailer sample or the only sample, 2 denotes the deeper sample when two were taken.

NA - Not Applicable
? = Unknown

4.2 Representativeness of the Characterization Samples

Despite the apparent crossflow and development issues, it can be concluded from Table 4-1 that most of the discrete bailer characterization samples from the investigation wells are representative of nonimpacted formation groundwater. This can be concluded by taking into account the fact that none of the groundwater characterization samples appear to be impacted by residual contamination of drilling fluids, and that most of the discrete bailer samples were not composed of groundwater from cross-contaminated screened intervals. For example, the table shows that for Wells ER-EC-1, ER-EC-6, and ER-EC-4 the discrete bailers were only sampling the upper completion intervals which were not impacted by crossflow and which were developed. It can also be seen from the table that for Well ER-EC-7 the discrete bailer was sampling the lower completion interval which was developed and, likely, had all of the crossflow into that interval removed during the well development and testing phase. The table also shows that Well ER-EC-5 had two discrete bailer samples. One discrete bailer contained groundwater from both the middle and lower completion intervals, while the other contained groundwater from only the lower completion interval. It appears from the table that both discrete bailers likely contained crossflow from the upper completion interval. For this well, however, all three completion intervals were completed within the same lithologic unit and crossflow should not pose a significant problem. Unfortunately, it appears likely that the discrete bailers from Wells ER-EC-2A and ER-EC-8 contained groundwater from screened intervals that were impacted by crossflow and not fully remediated during development and testing. As a result, it is difficult to determine exactly what those groundwater characterization samples represent.

It is more difficult to determine exactly what the composite groundwater characterization samples represent. None of the groundwater characterization samples showed substantial residual contamination from drilling. This suggests that the composite groundwater characterization samples that draw groundwater from only one completion interval are fairly representative of that formation's groundwater. These completion intervals were all judged to be developed. This pertains to Wells ER-EC-1, ER-EC-6, and ER-EC-4, which only produced groundwater from the upper completion interval. These samples should represent nonimpacted formation groundwater. Some of the composite groundwater characterization samples, however, contain crossflow groundwater. It can be seen in Table 4-1 that Wells ER-EC-5, ER-EC-2A, and ER-EC-8 contain groundwater from screened intervals that were not likely remediated during development and testing of those wells. As a result, it is difficult to determine if these composite samples are really a composite of all the completion intervals that produced water, or a sample of just the formation with the highest hydraulic head. However, it was pointed out earlier in this section that all three completion intervals for Well ER-EC-5 were completed within the same lithologic unit. The composite groundwater characterization sample for Well ER-EC-7, on the other hand, represents both completion intervals. It can be seen in the table that both intervals were developed and that crossflow in the lower completion interval was removed during development and testing. As a result, the composite sample for this well is representative of both completion intervals.

4.3 Sampling Issues

In general, two types of groundwater characterization samples were taken for each investigation well. The composite groundwater characterization sample should represent the proportional contributions from water producing sections of the well. The discrete bailer characterization samples should be representative of the composite groundwater chemistry of the producing sections of the well below the discrete location. For the most part, the discrete bailer and composite groundwater characterization samples were sampling groundwater originating from the same lithologic units. This explains why the analytical results showed very few differences in the groundwater chemistry between the two types of samples. One potential discrepancy, however, between the two sampling methodologies was seen in the oxidation-reduction sensitive parameters. The analytical reports showed that there were minor, but distinct differences in the concentrations of oxidation-reduction sensitive parameters between the discrete bailer and the composite groundwater characterization samples. Consequently, it will be necessary to reevaluate the methodology used to obtain representative groundwater samples for the oxidation-reduction sensitive parameters.

The discrete bailer provides the ability to obtain groundwater samples potentially more representative of discrete intervals in the well. A composite sample mixes groundwater from different completion intervals, which has the potential to mask the presence of a given analyte that is specific to a low-producing interval. The only way to obtain a completely representative sample of a discrete interval would be to isolate the intervals from each other and take interval-specific discrete samples. Alternatively, a succession of samples below and above the different intervals can be taken, and changes in chemistry evaluated with respect to the proportional production of the intervals. Data from composite groundwater characterization samples are less than ideal for evaluating groundwater flow paths and travel times in three dimensions.

4.4 Groundwater Chemistry Characterization

The analytical results from the groundwater characterization samples for each well were examined in previous reports. Those reports examined the groundwater chemistry of the wells and compared the chemistry of each well to that of nearby wells or springs. This discussion compares the major ion and stable isotope data for all of the investigation wells to each other.

In order to compare the groundwater chemistry data from the investigation wells, a trilinear diagram was constructed. The groundwater chemistry data from the composite groundwater characterization samples were used to construct the trilinear diagram shown in Figure 4-1. The composite groundwater characterization samples were used to construct the trilinear diagram because for the most part both types of groundwater characterization samples were composed of groundwater from the same lithologic units. In addition, for most of the wells, only one screened interval was providing the majority of the groundwater flow, and discrete bailer samples were not collected for every well. Trilinear diagrams contain three different plots of major-ion chemistry and are used to show the relative concentrations of the major ions in a groundwater sample. The triangular plots in Figure 4-1 show the relative concentrations of the major cations and anions. The diamond-shaped plot in the center of the figure combines the information from the adjacent cation and anion triangles. The concentrations of the ions in all three plots are expressed in milliequivalents per liter, and are used to illustrate various groundwater chemistry types, or hydrochemical facies, and the relationships that may exist between the types.

Examination of Figure 4-1 reveals several interesting observations. For example, it can be seen in the cation triangle that the relative concentrations of the major cations fall within the sodium (plus potassium) groundwater type. This can be ascertained from the figure because the relative concentrations of the major cations plot in the lower right corner of the cation triangle. It can also be seen from the cation triangle that all of the wells have relatively low concentrations of magnesium compared to the other two cations. It can be seen from the figure, however, that as the calcium concentrations increase the magnesium concentrations also appear to increase incrementally. Specifically, it can be seen from the figure that these groundwaters range anywhere from 50 to 100 percent sodium, 0 to 40 percent calcium, and 0 to 10 percent magnesium. It is also interesting to note that the relative concentrations of the major cations appear to plot along a straight line with Well ER-18-2 at one end and Well ER-EC-7 at the other end.

Further inspection of Figure 4-1 and the anion triangle in particular, reveals that half of the investigation wells can be classified as having bicarbonate-type groundwater. This can be seen in the figure for those wells whose relative anion concentrations plot in the lower left side of the anion triangle. It can also be seen from the figure, however, that four of the investigation wells tend to have anion concentrations that plot within the center of the anion triangle. These wells (i.e., ER-EC-1, ER-EC-4, ER-EC-2A, and ER-EC-6) have no dominant anion type. Specifically, it can be seen from the anion triangle that the groundwaters vary from approximately 30 to 90 percent bicarbonate (plus carbonate), 5 to 35 percent sulfate, and 5 to 35 percent chloride. It is interesting to note that the characterization samples from the wells that have no dominant anion groundwater type are composed of groundwater from lithologic units composed of primarily of rhyolitic lava or trachyte. The composite groundwater characterization samples for the other four wells were composed of groundwater from lithologic units composed of volcanic tuff. The differences in the major ion concentrations may be due to differences in the flow path/hydrogeology and how that affects alteration products and fracture minerals rather than compositional differences. It can also be seen from Figure 4-1 that the relative concentrations of the anions for each well tend to plot along a straight line with Well ER-18-2 at one end and Well ER-EC-1 at the other end. This trend indicates that sulfate to chloride ratios remain relatively constant regardless of the bicarbonate concentration.

In general, the groundwater chemistry data reveal that, for the most part, the groundwater from these wells can be classified as sodium-bicarbonate type water. This water type is typically found in volcanic terrain and alluvium derived from volcanic material (DOE/NV, 1999). The wells that have no dominant anion type are somewhat atypical, but it was pointed out that sulfate and chloride comprise a greater portion of the total anions in groundwater from wells and springs in Oasis Valley (DOE/NV, 1999). It was postulated that higher concentrations of sulfate and chloride may be related to evapotranspiration of water from springs and shallow groundwater in Oasis Valley combined with precipitation of carbonate minerals (DOE/NV, 1999). However, application of these ideas to the sample results is not clear because of the great depth of the wells. Presumably the source are for groundwater sampled from these wells is not local. It was also pointed out that unusually high total dissolved solids and/or disproportionate concentrations of calcium, magnesium, sulfate, and chloride observed at some locations on Pahute Mesa may be related to hydrothermal alteration or mineralization along the groundwater flow path.

The groundwater chemistry data from the composite groundwater characterization samples were also used to construct Figure 4-2. The figure shows the stable oxygen and hydrogen isotope compositions for each of the investigation wells. Also plotted on Figure 4-2 are the weighted averages of precipitation for various sites on Buckboard Mesa, Pahute Mesa, Rainier Mesa, and Yucca Mountain based on data from Ingraham et al. (1990) and Milne et al. (1987). As can be seen from the figure, the precipitation data, as expected, lie along the local and global meteoric water lines of Ingraham et al. (1990) and Craig (1961), respectively. It can be seen from the figure that the stable isotope compositions of the investigation wells are similar except for Well ER-EC-7. All of the other investigation wells tend to have stable isotope compositions that plot isotopically lighter than the precipitation data. This suggests that these wells have little to no influence of modern atmospheric recharge. One possible explanation for the isotopically lighter groundwater of these wells is that the recharge areas for the groundwater at those sites are located north of Pahute Mesa. Rose et al. (1998) report that the oxygen and hydrogen isotope composition of Pahute Mesa groundwater is similar to the composition of groundwater and alpine spring water in central Nevada. An alternate explanation for the lighter isotopic signature of most of the wells is that the groundwater was recharged during cooler climatic conditions. The stable isotopic composition of Well ER-EC-7, on the other hand, shows influence of modern atmospheric recharge. It plots relatively near the weighted precipitation averages. It is also interesting to note that the wells plot below the global and local meteoric water lines. In general, data that fall below the meteoric water lines indicate that some form of secondary fractionation has occurred. The isotopic shift in the groundwater data for areas near Pahute Mesa has been ascribed to fractionation during evaporation of rainfall, sublimation of snowpack, or fractionation during infiltration (White and Chuma, 1987). Because the recent precipitation data plot along the meteoric water lines, it appears that fractionation during precipitation can be ruled out as causing the isotopic shift observed in most of the groundwater data. This tends to suggest that the isotopic shift in the investigation wells can be attributed to sublimation of snowpack or fractionation during infiltration.

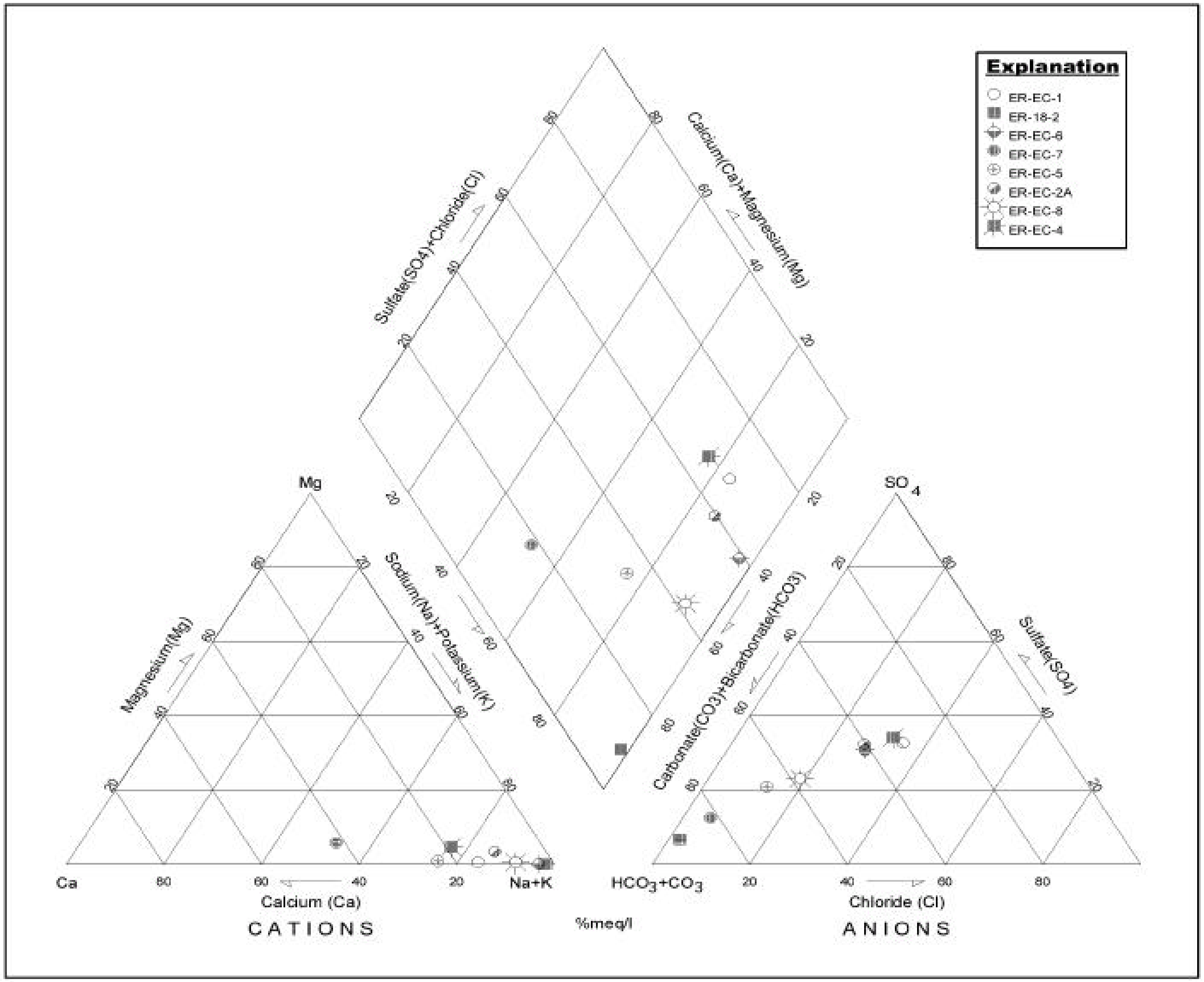

Figure 4-1
Piper Diagram Showing Relative Major Ion Percentages

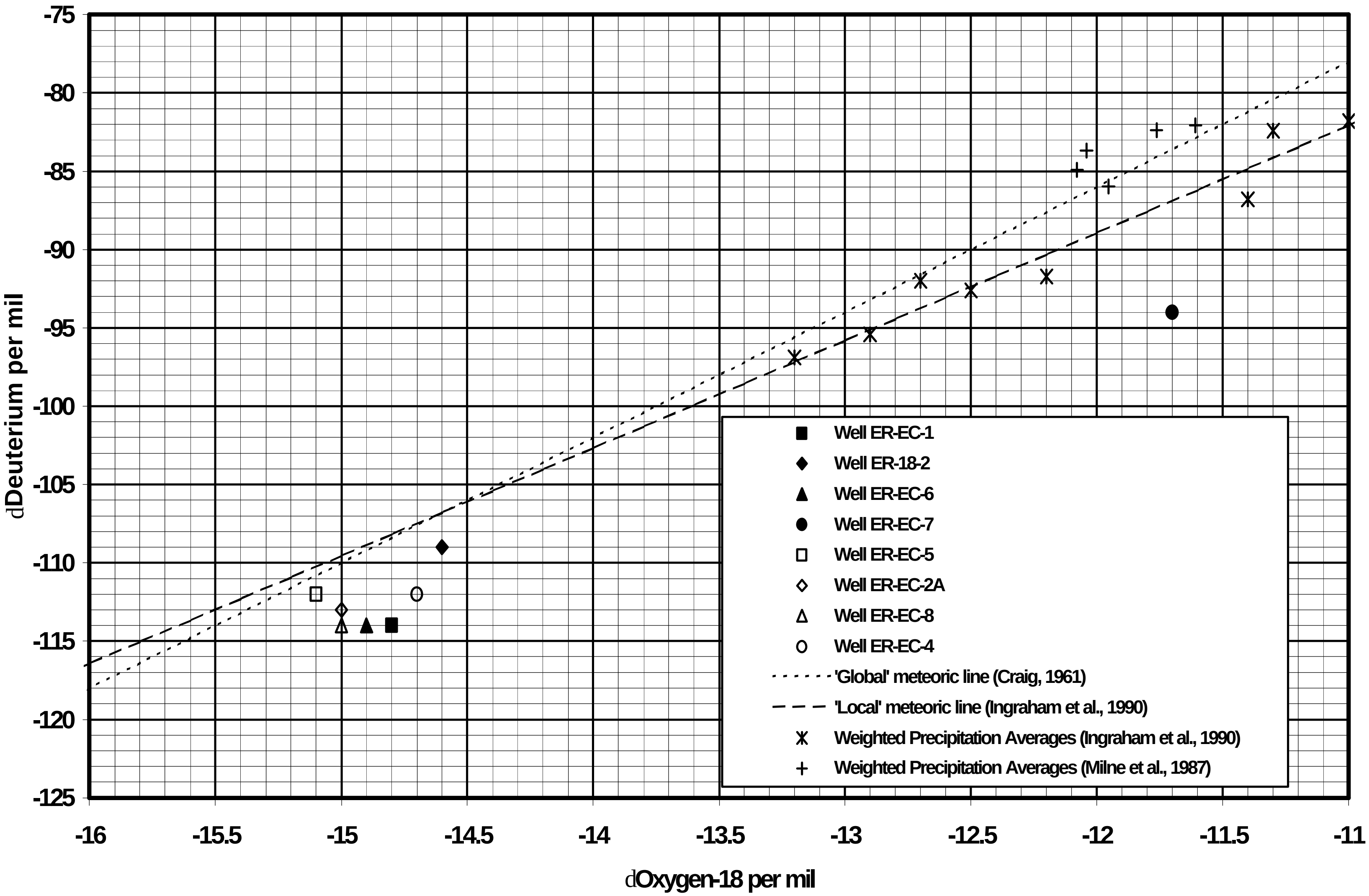

Figure 4-2
Stable Isotope Composition of Groundwater for the ER-EC Wells

5.0 Observations on Well Hydrology, Well Design, and Testing Methodology

This section presents general observations on well hydrology, well design, and testing methodology based on the results of the analysis of the WPM-OV well development and testing program. Recommendations are offered for changes in the testing methodology to improve data quality. Detailed information on each well was documented in individual reports, and the results have been summarized in the previous sections.

5.1 Observations on Well Hydrology and the Testing Methodology

During the course of the WPM-OV testing program, a wide range of hydrologic conditions and hydraulic situations were encountered. The results of the analyses presented in previous sections lead to a variety of observations about the hydrology in the area of the wells and the interaction of the wells with the hydrologic system. The use of wells of this multiple-completion design to provide access to the formations for measurements, testing, sampling, and monitoring is also discussed in this section.

5.1.1 Nonpumping Well Hydraulics

The bridge plug head measurements produced results indicating predominantly downward vertical gradients with the exception of Well ER-EC-2a, which apparently has an upward gradient, at least seasonally. The head differences between completion intervals ranged from not measurable to 10+ ft. The head responses of the completion intervals to isolation by the bridge plugs proved to be complicated in interpretation due to a variety of factors. The individual completion intervals each have their own head trends, which were poorly defined in the short monitoring periods. The intervals also adjust to isolation at different rates depending upon such things as the interval transmissivity, the prior rate of flow to/from the interval, and temperature changes that were induced by that flow. In one case, Well ER-EC-2a, the well was still recovering from drawdown induced by water production during drilling when the bridge plug head measurements were made. Consequently, there is no one head difference between completion intervals for each well, but an approximate value was determined qualified by the shortness of the monitoring periods.

Crossflow between completion intervals was observed in most of the wells, but was poorly determined. Moreover, the rate of crossflow was not well predicted from the vertical gradients that were determined, with the highest rates occurring in wells where the gradient was low. This is to be expected from the range of hydraulic conductivities that were determined for the different wells. The long-term crossflow resulted in a variety of changes to the hydrology around each well from the natural state that introduced uncertainty in many of the subjects that were examined. These include the vertical gradient, the temperature profile, and water quality of the completion intervals. These impacts precluded acquiring good information in a variety of cases.

5.1.2 Pumping Well Hydraulics

The pumping of these wells produced a wide range of results. Well ER-18-2 was pumped at a low rate, about 10 gpm, with drawdown of close to 200 ft after 8 days, and still drawing down rapidly. Well ER-EC-4 was pumped at about 181 gpm and appeared to stabilize at a drawdown of a little over 4 ft in the first few minutes. Drawdown increased slightly during the period from 1 to 5 days, at which time the test was terminated. Well ER-EC-1 was pumped at about 126 gpm and drawdown was only about 4 ft after 6 days, and the rate of head decline was steady throughout that period. Well ER-EC-2a was also pumped at about 121 gpm, and drawdown was over 270 ft at the end of 10 days of pumping. The behavior of the other wells varied between these extremes. Both the low and high ends of the pumping range and the drawdown range were less than optimal for a variety of reasons having to do with equipment capability and associated measurement problems.

The observed production distributions were based on the flow logging and covered a wide range. In several wells all of the production originated from the upper completion interval, in some cases from only the top of the upper interval. Either the lower intervals were not stressed or they were so much less transmissive that they produced no measurable flow; both cases were observed. Consequently, little information on their hydraulic parameters was gained. Other wells produced predominantly from lower completion intervals. Well ER-EC-4 produced totally from the upper completion interval, and downward flow from the lower part of the upper interval to the lower intervals was observed even during pumping at the maximum rate.

Analysis of the hydraulics of water production indicates that downward vertical gradients and flow losses in the casing can have a significant impact on production from lower completion intervals where the upper interval is very productive. The vertical gradient was a major factor in the very restricted production in Wells ER-EC-1 and ER-EC-4, and flow losses added to the inability to stress the lower intervals in these wells.

The analyses of the constant-rate tests all appeared to be best modeled with a dual-porosity solution. However, the duration of the tests generally were not long enough to define the latter part of the dual porosity behavior, at which time drawdown begins to increase again after an intermediate-time quasi-stabilization. However, the duration would have to increase substantially to define the later-time behavior well due to the log-time rate of response. For several of the wells, the duration of the tests were inadequate or barely adequate to observe dual-porosity behavior. This applies to the two wells (i.e., ER-EC-2a and ER-18-2) which had very large drawdowns. The wells with small drawdowns exhibited the dual-porosity behavior much earlier in time. Presumably, this is related to the degree of fracturing in the formation since the matrix hydraulic conductivity from the constant-rate test analysis was very similar to that of comparable lithology in wells that had much less drawdown and showed the dual-porosity behavior earlier. This points to the need to characterize the nature/degree of fracturing as a primary guide to the areal distribution of hydraulic conductivity within a formation.

Ranges of hydraulic conductivities were calculated for producing screened intervals using the flow rates derived from the flow logs. Calculations of ranges rather than single values of hydraulic conductivity were made to account for all major sources of uncertainties. The uncertainty of the interval hydraulic conductivity values varies, depending on the well and the greater uncertainty is associated with the small hydraulic conductivity intervals. Uncertainty in the interval hydraulic conductivity values is primarily due to uncertainty in the calculation method and uncertainty in parameters. The calculation method uncertainty could not be fully tested because the two methods used are based on the Cooper-Jacob equation. Uncertainties could result from violations of the assumptions underlying the Cooper-Jacob equation, especially the horizontal flow assumption. The main sources of parameter uncertainty are the contributing interval thickness and the drawdown during the time the flow logging data were collected. The contributing interval thickness produced a maximum uncertainty in interval hydraulic conductivity that was a factor of 3 or less, except in one case which was a factor of 17. Drawdown uncertainty produced a maximum uncertainty in interval hydraulic conductivity that is about a factor of 2. The maximum uncertainty in the K was a factor of 55, but was generally less than 27.

5.2 Observations on Water Quality Characterization

With regard to groundwater quality characterization, the results were also very mixed. The completion intervals that were characterized are limited, first of all, to those that produced water during pumping, and then to the proportional extent that they were represented in the composite discharge. Some completion intervals that were poorly represented in the composite samples were partially characterized with discrete samples. However, it was often found that even the lower completion intervals that produced water had probably not been purged of crossflow that had occurred during the period between well completion and testing. Consequently, the discrete samples most closely reflect the water quality of the upper interval rather than the lower interval(s). This complication makes it difficult to come to many conclusions about differences in water quality between completion intervals.

The discrete samples may have another application in finding occurrences of localized low concentrations of contaminants. Due to the distribution of production, the composite characterization sample often represents a large dilution ratio for the water produced from the lower completions. This pattern of compositing makes inferences about the water quality in the intervals with low proportional representation in the composite sample dubious. This would be particularly true of parameters that are present at trace levels such as contaminants.

Crossflow in these multiple completion wells appears to be a problem. In the majority of cases characterized, the pumping did not remove as much water from the lower intervals as had entered the interval from crossflow. This is a simplistic criteria since various factors affect the restoration of natural water quality, and this criteria does not guarantee restoration of representative samples. Consequently, there are a variety of uncertainties about the representativeness of the subsequent samples from intervals receiving crossflow. This situation generally restricts the usefulness of these wells for monitoring to the upper completion interval, especially in view of the much lower production rate of the sampling pumps.

5.3 Observations on Use of This Type of Multiple Completion Well Design

The hydrology of each well was different, and the responses of the wells to testing was often very different. The strictly standardized approach was not optimal, and some flexibility in adapting testing program parameters would substantially improve the testing data and allow better analysis. To drive such adaptation, real-time preliminary analysis of the data would be required to guide and justify the adjustments. This would have the added benefit of providing improved knowledge of testing methodologies and applications to the immediate future of the characterization program. Most of the improvements are a function of additional time for various parts of the testing program: longer monitoring periods for the bridge plug head measurements, more extensive ambient thermal flow logging, and longer pumping periods for the constant-rate tests. There were many opportunities that would have yielded hydraulic parameters for intervals that were not otherwise characterized because of the well hydraulics, but data was lacking. These opportunities only require improvements in the ambient flow logging and bridge plug head measurements.

5.3.1 Well Design

The WPM-OV wells were all constructed with similar specifications, primarily differing in overall depth, the number of completion intervals, and the configuration of the screens within the completion intervals. The completion intervals extend over substantial vertical distances and often access different HSUs and/or lithologies. In general, the well design supported all aspects of the testing program but did not provide results for many of the completion intervals. The main limitation of this design with respect to testing was the inability to sufficiently stress many of the individual completion intervals and produce substantial amounts of water from them. The testing did not yield hydraulic parameters or water quality samples for those intervals which did not produce sufficient amounts of water. This problem could be overcome using packers to isolate pumping to individual intervals and collect data specific to each interval, eliminating the problem of interacting hydraulics. The other aspect of the well design that resulted in analysis difficulties in many instances resulted from the discontinuous installation of screens in many completion intervals. This design feature introduced considerable uncertainty in the interpretation of the flow logging in many cases, especially when the percentage of the completion interval that was screened was low.

5.3.2 Specification of Completion Intervals

The specification of completion intervals after drilling and logging is based on a variety of objectives for characterization and evaluation of the available data collected to date. One of the main criteria is generally to place completion intervals into formation with high hydraulic conductivity. The data available to identify such formation (drilling characteristics, lithologic identification, geologic interpretation, geophysical logs, water production during drilling) does not directly measure hydraulic conductivity, but may give indications of conditions associated with high hydraulic conductivity. The general ability to identify formation with high hydraulic conductivity at the time of completion appears to be fair. This conclusion is based on the observation that many of the completion intervals produced water if the hydraulics were conducive. However, there is no way to evaluate whether other locations in the borehole with high hydraulic conductivity were not identified. The direct approach would be to install a pump, and flow log the open borehole during pumping to identify the most productive intervals. The results would probably have to be interpreted considering flow losses to yield an accurate picture of the relative productivity of different intervals. The problem of hole stability during such work is recognized, and probably preclude this approach in many instances.

The production rate of water during drilling is often viewed as an indication of hydraulic conductivity of the formation. It appears that this data has to be interpreted with care. The production rates during drilling are probably highly influenced by the hydraulics of such production. The production rate of water during drilling does not appear to necessarily relate in direct proportion to the general productivity of the formation or to the relative productivity of the formation being drilled. An example of this is Well ER-EC-2a, which produced copiously during drilling, but the completion intervals were found to have relatively low hydraulic conductivity.

5.4 Recommendations

These analyses provide the basis for a variety of recommendations concerning various aspects of the testing, sampling, and analysis efforts.

5.4.1 Testing Program

The standardized testing program was conducted for each well with minor variations to accommodate the differences between wells, primarily relating to the number of completion intervals and the productivity of the well. The testing program included:

1. Discrete pressure measurements for each completion interval
2. Well development with step-drawdown tests
3. Flow logging at three pumping rates
4. Collection of discrete groundwater sample(s) with a downhole sampler

5. Constant-rate pumping test and recovery monitoring

6. Collection of composite groundwater characterization samples

7. Flow measurements and water quality parameter logging under natural gradient flow

Bridge Plug Measurements

The bridge plug head measurements worked fairly well, but some issues related to methodology and length of monitoring could be improved. Running a temperature log and a thermal flowmeter survey just prior to the bridge plug measurements is recommended. The temperature log will be used to in determining a density profile, and the flow measurements can be used with the head change data for calculating interval transmissivities. Bridge plugs equipped with PXDs/dataloggers to measure both below and above the bridge plug would greatly improve the data quality for the upper interval. Finally, a more structured and documented procedure for installing the bridge plugs is required, allowing time for temperature equilibration at each measurement station, adding additional measurement stations for calibration purposes, and keeping a detailed time log of the installation process.

Temperature/Pressure Logging

Temperature logs at various times in the testing process have been mentioned repeatedly as data that would improve the quality of analysis and, in some cases, are almost indispensable. These logs would be used to evaluate changes in the temperature regime, and would serve as a basis to correct downhole data for changes in the density profile. A further improvement would be to run a pressure log which would provide direct data on the change in density. Since a pressure log can be run in combination with the temperature log there would be no additional cost except for the equipment. Appropriate PXDs for such logging may also provide the temperature data with the pressure data.

Well Development

Well development appeared to be effective for the completion intervals that were productive, as observed by the reduction in drawdown at the various pumping rates during development. However, the flow logging revealed many cases in which lower intervals were not producing, and the flow loss analysis indicated that, in many of those cases, the interval was not being stressed. There is no obvious easy approach to overcoming this limitation; the choices appear to be larger capacity pumps or pumping isolated to individual completion intervals.

Well/Flow Losses

The analysis showed that well/flow losses were significant, accounting for up to 2/3 of the measured drawdown. In lieu of an observation well, the well/flow loss analysis approach provides the correction for these losses. Better data, as well as a more sophisticated approach to determining these losses, would improve the correction. In support of this analysis the final step-drawdown test at the end of development should be conducted with stricter protocol (starting from an equilibrium condition and equal step lengths) and include additional steps (4 or 5 pumping rates).

Flow Logging

The flow logging program generally provided good data, but several weaknesses in the data collection program were found during the analysis. This primarily relates to the representativeness of well conditions during flow logging. Based on the records from development and the constant-rate test, most of the well condition can be predicted with sufficient records. The flow logging should not start until the well has achieved a relatively stable rate of drawdown so that the rate is not changing significantly during the period of one log. Good records of the start and end times for the individual flow logs should be kept. Also, any improvement in the flow logging method that would reduce the noise would be valuable. Simultaneous pressure logging would greatly improve the accuracy of the interpretation by providing information for flow and well loss analyses.

Constant-Rate Test

The constant-rate test data was generally very good. There were instances of noisy PXD data that provided problems for analysis. The reason for this noise was not positively identified but appeared to be caused by the pump. The large drawdowns that were produced in several of the wells also caused data collection problems that resulted in offsets in the data which had to be corrected in processing. The ability to change pumps for one with a more appropriate range would eliminate this problem. An effect was observed in the recovery records that is attributed to shifts in the downhole temperature regime during the course of pumping. This effect could be corrected using temperature profiles, and temperature logs should be run prior to the start of the test and just before pumping is terminated to support this correction.

Groundwater Sampling

The analytical results from the groundwater characterization samples provided good geochemical data. These data can be used to investigate groundwater flow paths, groundwater ages, and geochemical types. There are a few observations, however, that can be made to further enhance the effectiveness of future geochemical sampling of these wells. For example, for most of the wells, both the discrete bailer and the wellhead composite characterization samples were sampling groundwater from the same screened interval. This data was somewhat redundant. In order to really compare the geochemistry of different lithologic units, the different screened intervals need to be completely isolated from each other and sampled. Otherwise, there does not appear to be any reason to sample lower completion intervals that do not produce much groundwater during pumping. Those completion intervals are generally impacted from crossflow, and it would take a significant amount of pumping to completely remove the groundwater from the upper completion intervals. The hydrogeology and geochemistry of individual completion intervals should be characterized by discrete sampling to maximize the value and use of multiple-completion wells. In addition, the collection of composite groundwater characterization samples increases the risk of diluting any contamination that enters a well, unless the contamination is already dispersed vertically. Finally, further analysis/evaluation is necessary to develop a sampling process to obtain representative oxidation-reduction data, should those data be needed.

5.4.2 Analyses

The testing program was designed to provide information about local hydrologic conditions and HSU hydraulic parameters for use in the CAU-scale flow and transport model. The objective of the data analysis was to derive the maximum information about the hydrology from the data. Specific goals for the individual well analyses were to determine the discrete head for each completion interval and the resultant vertical gradients between completion intervals, representative hydraulic parameter(s) for the formation(s) in each completion interval, and representative groundwater quality for the formation(s) in each completion interval. With regard to the well design, goals included determination of the well hydraulics of the multiple completion interval design under both natural gradient and pumping conditions, and the best application of development and testing methodologies to this design. In general, these objectives and goals were met, although the results were not always optimal. Recommendations for improvements in data collection have been offered that could improve the results substantially. Recommendations for improvements in the analysis methodology or for additional analysis have also been offered in the various report sections. The improvements suggested for the data collection and for the analyses are interdependent. The information about the formations accessed by multiple completion wells can be both improved in quality and maximized with the further development in the testing and analysis methods suggested. The primary problem in the analyses that yet needs to be addressed conceptually is the scaling of the characterization of formations so that the results can be applied to the modeling with minimum uncertainty.

6.0 Conclusions

This section presents summary conclusions about the FY 2000 WPM-OV wells testing program and results. Detailed information for the individual wells is documented in individual well reports, and the comparative results for all of the wells have been presented and discussed in previous sections of this report.

6.1 Testing Program and Analysis

The WPM-OV testing program included a comprehensive, standardized suite of measurements and tests that were conducted at each of the wells, with adjustments for specific conditions at each well. The elements of the program are listed in detail in Section 1.2 and specifics for each well are discussed in the individual well reports. The WPM-OV wells are multipurpose wells designed to determine the geology to great depths and to access formation(s) with multiple completion intervals, which may be used for measurements, testing, and sampling. These wells presented a greater opportunity for collecting comprehensive hydrologic data than previous wells installed by the UGTA program but required a more complicated testing scenario. The results include information on vertical gradients, hydraulic conductivities specific to the different formations/lithologies in each well, and characterization of water quality specific to individual completion intervals.

New testing methods were introduced in the WPM-OV testing program. These included the use of instrumented bridge plugs to isolate individual completion intervals and determine heads, flow logging during pumping to define production distribution, and discrete bailer sampling during pumping to characterize intervals separately. Data collection during the constant-rate test was also improved. During the course of the testing program, a wide range of hydrologic conditions and hydraulic situations were encountered in the different wells, which were generally accommodated by the testing methodology and available equipment. In some cases, measurements were made near the limits of the capability of the equipment, resulting in less precision for those measurements. However, even in those situations, approximate or bounding values for parameters could usually be determined. Recommendations for improvements to the program were offered in Section 5.3.

The testing program was generally successful in collecting data to support analyses to determine head differences, hydraulic parameters, and water quality for individual completion intervals in each well. Limitations of the data resulting from the methodologies and the hydrologies of the wells are discussed in subsequent sections. The hydraulics of water production for each well were analyzed for use in evaluating the performance of the multiple completion well design. The testing and analysis for these wells provides more comprehensive information on the hydrology of these wells than is available for almost any other well in the CAU. Several factors (i.e., vertical gradient and associated flow, well losses, and production distribution) that have not been accounted for in previous testing were shown to make substantial differences in the derived parameter values. The clear conclusion from these analyses is that completion interval head measurements, flow logging, and hydraulic analysis were definitely required to accurately analyze and properly qualify the testing and sampling results. Without this information, parameter values derived from the testing and conclusions about the sampling results would have been in substantial error.

6.2 Vertical Gradients and Resultant Flow

Data on the relative heads of the different intervals and natural-gradient driven flow in the well were obtained in a wide range of circumstance in these wells. Table 6-1 lists the greatest head difference between completion intervals measured in each well, and the greatest measured natural-gradient flow rate in the well. Vertical head differences ranged from nil to 10+ ft, and the associated flows commonly exceeded the thermal flow logging tool's upper limit of 2.2 fpm (2.2 gpm). There was not a strong correlation between the gradients and the flow rates, indicating a wide range for hydraulic conductivity for the formations in the individual completion intervals.

Table 6-1
Vertical Head Differences and Resultant Flows

Well Name	Vertical Head Difference (ft)	Maximum Flow Downhole (gpm)
ER-EC-1	-1.46	-2.2+
ER-EC-6	-5.57	-0.6
ER-18-2	NA	NA
ER-EC-5	-0.11	-2.2+
ER-EC-7	-0.96	-2.2+
ER-EC-8	-1.02	-0.8
ER-EC-2a	+10?	NA
ER-EC-4	-8.17	-2.2+

Pressure equilibration curves captured following setting of the bridge plugs for a number of the completion intervals in combination with the flow measurements were used to calculate transmissivity values for completion intervals. An average hydraulic conductivity value can then be derived for the formation. This methodology can provide parameter values for intervals that did not produce water during the pumping tests. For cases where transmissivities could be calculated both from this information and from pumping test results, the resulting values mostly agreed with the pumping test results within a factor of four or less. This is reasonable agreement considering the measurement uncertainties in both the pressure equilibration measurements and the flow measurements. Both of these measurements can be readily improved.

6.3 Hydraulic Conductivity

Table 6-2 summarizes the results of the hydraulic conductivity analyses by both stratigraphic unit (see Table 1-2 for key to abbreviations) and lithologic type. In several cases the smallest-scale analysis included multiple stratigraphic units, and several of the stratigraphic units contain multiple lithologic types. The summary by lithologic type shows fairly clear distinctions at both the lower and upper ends of the range.

Table 6-2
Hydraulic Conductivity Results

Stratigraphic Unit	Lithologic Types	Minimum Hydraulic Conductivity (ft/d)	Maximum Hydraulic Conductivity (ft/d)
Tpb	Lava, Flow Breccia	0.25	194.79
Tmar	Welded Tuff	4.01	318.00
Tmap	Welded Tuff	0.10	111.78
Tfbw	Lava, Flow Breccia	2.67	14.17
Tfbr,Tfb	Lava	31.89	63.23
Tfbw,Tfb	Non-Welded Tuff	0.03	62.72
Tf,Tmaw	Non-Welded Tuff	0.02	0.21
Ttc	Lava	55.78	2,225.84
Lithologic Type	**Stratigraphic Units**	**Minimum Hydraulic Conductivity (ft/d)**	**Maximum Hydraulic Conductivity (ft/d)**
Lavas, Flow Breccias	Tpb, Tfbw, Tfbr, Tfb, Ttc	0.25	2,225.84
Welded Tuffs	Tmar, Tmap	0.10	318.00
Non-Welded Tuffs	Tfb, Tfbw, Tf, Tmaw	0.02	62.72

The analysis of the various pumping tests found that a dual porosity solution produced the best fit to the data for all of the tests. This, in conjunction with drilling and geophysical data, indicates that the primary hydraulic conductivity in these wells was in the fracturing of the formations. The hydraulic conductivity of fractured formations is distributed as a function of the fracturing related to the density of fracturing and the individual character of the fractures. The flow logging showed that the distribution of production in the completion zones was unevenly distributed, often varying greatly across different segments of the completion intervals, and exhibiting stepwise increases in some cases. This is interpreted as reflecting the variation in the fracturing.

The hydraulic conductivities determined by the analyses are based on an arbitrary scale of screen length, and show large variations within a completion interval. This scale was convenient both for averaging out small-scale noise and for looking at general differences within the completion intervals. The values are highly scale dependent; the range of the values that may be determined for a formation increases as the scale decreases. There is no established basis for quantifying or specifying the scale dependence of the analysis, nor is there any basis for determining how representative the parameter values are for the stratigraphic or lithologic units in general. The tested intervals of formations generally include only a small percentage of the total formation, and were selected specifically for apparent productivity. They are not necessarily representative of the rest of the formation. Methodology for dealing with scale dependence and representativeness needs to be developed to guide appropriate scaling of testing and analysis.

The differences in parameter values reported from the different analyses reflect both differences in the data used for each analysis, the methods of analysis, and particularly differences in the scales of the analyses. The various values could probably be compared by rolling the more detailed analyses values up to the largest common scale. Comparison of the values of hydraulic conductivity from these analyses with values from other sources is even more uncertain since the scale dependence for those analyses are generally not known.

6.4 Water Quality Characterization

The groundwater quality characterization effort produced mixed results. The completion intervals that were characterized by the groundwater characterization samples are limited, first of all, to those that produced water during pumping, and then to the proportional extent that they were represented in the composite discharge. As mentioned in Section 6.3, the vertical gradients resulted in vertical flow which flooded the lower head completion intervals with water from the highest head completion interval. The highest head completion interval was the upper interval in all cases except perhaps Well ER-EC-2a, for which the situation is not well defined. The interaction of the middle completion intervals in this "crossflow" was poorly characterized. Table 6-3 provides basic information about the production from completion intervals in these wells and about the completion intervals that were represented in the samples.

Table 6-3
Completion Intervals Represented in Testing/Sampling

Well Name	Number of Completion Intervals	Intervals With Quantifiable Production	Intervals Represented in Composite Samples
ER-EC-1	3	1	1
ER-EC-6	4	1	1,2?
ER-18-2	1	1	1
ER-EC-5	3	1,2,3	1,2
ER-EC-7	2	1,2	1,2
ER-EC-8	3	1,3	1
ER-EC-2a	3	1,2	1?,2
ER-EC-4	3	1	1

Some completion intervals that were poorly represented in the composite samples (low percentage of the production) were partially characterized with discrete samples. However, in about half the cases where lower completion intervals produced water, it was found that the total amount of the production from lower completion intervals at the time of sampling was not as great as the amount of crossflow that had previously entered the interval. While this is not a direct measure of the remediation of such intervals, it is a relative measure of the amount of purging that occurred before sampling. Consequently, the discrete samples taken above those intervals most closely reflect the water quality of the upper interval rather than the lower interval(s). This situation makes it difficult to determine differences in water quality between completion intervals. Some method to stop crossflow during periods between sampling is probably required to ensure that representative samples of the lower head formations can be obtained. Purging even at high-rate pumping could take more time than is usually allowed, and will not even effect many of the lower completion intervals. A method to pump from the lower intervals individually is required to acquire good quality samples.

Many of the wells have very long completion intervals, and the compositing of water across all of the producing portion of the completion intervals in a well provides an average groundwater composition. The distribution of production in many cases is dominated by the upper part of the uppermost completion interval. This situation results in substantial dilution of contributions from lower in the well. Discrete samples taken during pumping may have further application in identifying differences in water quality, especially where completion intervals include different formations. This would be particularly true for parameters present at trace levels such as contaminants. More complete sets of discrete samples may be warranted, with locations selected based on criteria for significant changes in the source formation and guided by the results of flow logging.

However, the ability to sample natural formation water will still be limited to that portion of the well that produces water. The proportion of each well that will produce water will be even more limited at the lower pumping rate of the permanent sampling pumps. The purging of crossflow and remediation of the lower intervals will also be even more problematic at the lower pumping rates. As they are now configured, these wells can generally only provide representative samples from the upper completion intervals, and typically only the upper part of that interval.

6.5 Effectiveness of the Well Design for Testing and Sampling

The use of this design of multiple-completion well to provide access to formations for measurements, testing, sampling, and monitoring was only partially successful. The effectiveness of the multiple completion interval well design for stress testing multiple completion intervals was highly variable, dependent upon the specific hydrologic conditions for each well. Three factors control the distribution of production during pumping: (1) the transmissivities of the different completion intervals, (2) the well losses and flow losses for flow from each completion interval, and (3) the vertical gradient. The production from each interval is a function of the interval transmissivity and the applied drawdown, which is determined by the second and third factors. In many cases, enough drawdown could not be imposed on lower completion intervals to substantially exceed the flow losses and vertical gradient. Higher pumping rates would only have driven up flow losses, maintaining a similar situation.

Table 6-3 summarizes the results with respect to completion intervals that produced water and provided data for hydraulic conductivity analysis (Table 4-1 contains more detailed information). Typically, production was dominated by the uppermost completion interval with substantially less production from the second completion interval. In only one case was there production from a third (lower) interval. This table shows that the pumping tests often did not produce data for quantifying hydraulic parameters for the lower intervals.

Also indicated in Table 6-3 are those completion intervals that contributed probable representative water to samples that were collected. The ability to purge and sample the different completion intervals in each well is directly affected by the production from each interval. In most cases, water production was dominated by the uppermost completion interval. The upper interval was usually the source interval for crossflow to other intervals. In several cases, the amount of water estimated to have been removed from lower, producing intervals at the end of the constant-rate test was less than the estimated amount of crossflow that had entered the interval. In those cases where the amount removed did exceed the amount that entered, there was no way to determine if the receiving interval had been purged to the point where it was producing natural water quality. In general, sampling these wells only provided information for the uppermost completion interval.

6.6 Completion Design to Support Testing and Sampling

The ability to test and sample each completion in the multiple completion design using the simple methods that were tried in the WPM-OV program is mostly dependent on the happenstance of hydrologic conditions. Information to determine if hydrologic conditions are such as to yield production from multiple completion intervals under projected testing is generally not readily available at the time of completion. Some criteria for well design based on proposed testing could be developed to help guide completion decisions, although such criteria could not necessarily ensure the success of future testing. Testing before completion would be required to ascertain conditions accurately enough to make predictions about the hydraulics of pumping. A more comprehensive program of natural-gradient flow measurements combined with a pressure log might provide a basis for an initial quantitative analysis of the hydrology that could be used to estimate relationships for various scenarios. Open-hole pumping with flow/pressure logging could provide more complete data.

The parameter of the well design that could most readily be altered at the time of completion to adjust the responses of multiple completion intervals is the lengths of the intervals. Specifying lengths to control transmissivities of the individual intervals could provide a means for balancing the responses of the different intervals. However, for productive formation, this could mean relatively short intervals. Very short completion intervals would probably compromise other objectives, requiring narrower targets than available information may support. The WPM-OV well completions are exceedingly long and the possible production rates based on the sizes of the casing and the pumps that can be installed are relatively low for the extent of the completion intervals. In two cases, the productivity of the formation restricted production to only a portion of the one of the completion intervals. Larger diameter wells and larger capacity pumps may be required to provide the capability to stress lower completion intervals with extensive completions.

Other approaches would be a well design that provides for accessing the completion intervals individually, or a testing methodology that can access the individual intervals. Clusters of wells with single completion intervals could provide a simple solution to the problem. Equipment to isolate individual completion intervals in a multiple completion well is readily available. The completion intervals in the WPM-OV well could be accessed individually for data collection and sampling using packers and bridge plugs to isolate pumping. This approach would require a lot of manipulation of downhole equipment during the course of a testing program. Well designs that have built-in equipment for isolating individual intervals have been previously investigated by the UGTA program. The shortcomings of this equipment for the type of testing that was done in the WPM-OV wells results from the very limited access to the formation that equipment provides. Large intervals are accessed by short ports, which precludes determining production distribution and results in significant limitations in the pumping stress that can be applied.

A general problem with the WPM-OV well design for the discrete analyses was the discontinuous installation of screens (alternating screen and blank casing) in many completion intervals. This introduced considerable uncertainty in the interpretation of the flow logging, especially when the percentage of the completion interval that was screened was low. It is recommended that the completion intervals have continuous slotted casing.

7.0 References

Cassiani, G., and Z.J. Kabala. 1998. "Hydraulics of a partially penetrating well: solution to a mixed-type boundary value problem via dual integral equations." In *Journal of Hydrology*, Vol. 211:100-111. New York, NY: Elsevier Science.

Cooper, H.H., Jr., and C.E. Jacob. 1946. "A generalized graphical method for evaluating formation constants and summarizing well-field history." In *Transaction American Geophysical Union*, Vol. 27:526-534. Washington, DC.

Craig, H. 1961. "Isotopic Variations in Meteoric Waters." In *Science*, 26 May, Vol. 133, p.1702-1703. Washington, DC: American Association for the Advancement of Science.

DOE/NV, see U.S. Department of Energy, Nevada Operations Office.

Driscoll, F.G. 1986. *Groundwater and Wells*. St. Paul, MN: Johnson Filtration Systems.

Earlougher, R.C., Jr. 1977. *Advances in Well Test Analysis*. Dallas, TX: Society of Petroleum Engineers of AIME.

Hayter, A.J. 1996. *Probability and Statistics for Engineers and Scientists*. Boston, MA: PWS Publishing Company.

HydroSOLVE, Inc. 1996-2000. *AQTESOLV for Windows, User's Guide*. Reston, VA.

Ingraham, N.L., R.L. Jacobson, J.W. Hess, and B.F. Lyles. 1990. *Stable Isotopic Study of Precipitation and Spring Discharge on the Nevada Test Site*, DOE/NV/10845-03, Publication No. 45078. Las Vegas, NV: Desert Research Institute.

Milne, W.K., L.V. Benson, and P.W. McKinley. 1987. *Isotope Content and Temperature of Precipitation in Southern Nevada, August 1983 - August 1986*, USGS OFR 87-463. Denver, CO: U.S. Geological Survey.

Molz, F.J., R.H. Morin, A.E. Hess, J.G. Melville, and O. Guven. 1989. "The impeller meter for measuring aquifer permeability variations: evaluation and comparison with other tests." In *Water Resources Research*, Vol. 25(7):1677-1683. Washington, DC: American Geophysical Union.

Molz, F.J., and S.C. Young. 1993. "Development and application of borehole flowmeters for environmental assessment." In *The Log Analyst*, Jan-Feb, p. 13-23. Houston, TX: Society of Professional Well Log Analysts.

Rehfeldt, K.R., P. Hufschmeid, L.W. Gelhar, and M.E. Schaefer. 1989. *Measuring Hydraulic Conductivity with the Borehole Flowmeter*, Report No. EN6511, Research Project 2485-5. Palo Alto, CA: Electric Power Research Institute.

Rose, T.P., M.L. Davisson, D.K. Smith, and J.M. Kenneally. 1998. "Isotope Hydrology Investigation of Regional Groundwater Flow in Central Nevada." In *Smith, D.K., A.B. Kersting, T.P. Rose, J.M. Kenneally, G.B. Hudson, G.F. Eaton, and M.L. Davisson. 1998. Hydrologic Resources Management Program and Underground Test Area Operable Unit FY 1997 Progress Report*, UCRL-ID-130792. Livermore, CA: Lawrence Livermore National Laboratory.

Ruud, N.C., and Z.J. Kabala. 1997a. "Numerical evaluation of the flowmeter test in a layered aquifer with a skin zone." In *Journal of Hydrology*, Vol. 203:101-108. New York, NY: Elsevier, BV.

Ruud, N.C, and Z.J. Kabala. 1997b. "Response of a partially penetrating well in a heterogeneous aquifer: integrated well-face flux vs. uniform well-face flux boundary conditions." In *Journal of Hydrology*, Vol. 194(1-4):76-94. New York, NY: Elsevier, BV.

Ruud, N.C, Z.J. Kabala, and F.J. Molz. 1999. "Evaluation of flowmeter-head loss effects in the flowmeter test." In *Journal of Hydrology*, Vol. 224:55-63. New York, NY: Elsevier, BV.

U.S. Department of Energy, Nevada Operations Office. 1997. *Regional Groundwater Flow and Tritium Transport Modeling and Risk Assessment of Underground Test Area, Nevada Test Site, Nevada*, DOE/NV-477. Las Vegas, NV: Environmental Restoration Division.

U.S. Department of Energy, Nevada Operations Office. 1999. *Corrective Action Investigation Plan for Corrective Action Units 101 and 102: Central and Western Pahute Mesa, Nevada Test Site, Nevada,* Revision No. 1, DOE/NV--516. Las Vegas, NV.

White, A.F., and N.J. Chuma. 1987. "Carbon and Isotopic Mass Balance Models of Oasis Valley-Fortymile Canyon Groundwater Basin, Southern Nevada." In *Water Resources Research*, Vol. 23, (4):571-582. Washington, DC: American Geophysical Union.

Part II

Borehole Testing and Characterization of Western Pahute Mesa - Oasis Valley ER-EC Wells

(Prepared by Desert Research Institute)

(64 Pages)

DOE/NV/13609-23

SUMMARY REPORT

Borehole Testing and Characterization of Western Pahute Mesa – Oasis Valley ER-EC Wells

prepared by

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submitted to

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ABSTRACT

Hydraulic conductivity with depth is calculated based on measurements of borehole flow during pumping at wells ER-EC-1, ER-EC-2a, ER-EC-4, ER-EC-5, ER-EC-6, ER-EC-7 and ER-EC-8 at the Nellis Air Force Range in Nye County, Nevada. Groundwater inflow to the well is calculated over 61-cm intervals from the upper screened section to the maximum accessible depth of the well. The interpretative methodology is based on the hydraulic conductivity over an interval being a function of an interval's contribution to the well discharge and the pressure change caused by pumping (Rehfeldt *et al.* (1989). Static fluid pressure in the formation is estimated based on the height of the fluid column and the influence of temperature and pressure on fluid density. The estimation of fluid pressure during pumping includes the density effects of temperature changes in the water-producing zones. The effects of friction between the moving fluid and the casing wall, well screen, and filter pack are also considered.

The major water-producing zones and high values of hydraulic conductivity can be located in the upper, middle, or lower screened sections. Wells can have major producing zones in one, two or three of the screened sections. Therefore, no simple relationship can be attributed to permeability with depth. Locations where the change in groundwater inflow is abrupt indicate flow in fractures. Other locations have a nearly uniform groundwater inflow over tens of meters, which suggests a highly fractured media. Hydraulic conductivities in tuff were calculated for a combined vertical interval of 97 m (318 ft) and range from 66 to 0.2 m/d (217 to 5.4 ft/d). Hydraulic conductivities in lava were calculated for a combined vertical interval of 38 m (124 ft) and have a maximum value of 183 to 0.7 m/d (600 to 2.2 ft/d). There were only three hydraulic conductivity values that can be assigned to a breccia lithology and these averaged 22 m/d (70 ft/d).

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1.0 INTRODUCTION TO BOREHOLE FLOW LOGGING

1.1 Background

The U.S. Department of Energy, National Nuclear Security Administration Nevada Operations Office (NNSA/NV) constructed a series of deep characterization and monitoring wells as part of the Underground Test Area (UGTA) project in southern Nevada. Figure 1 illustrates the location of the ER-EC wells west of the Nevada Test Site on the Nellis Air Force Range near Beatty, Nevada. Stratigraphy of western Pahute Mesa consists of several thousand feet of Tertiary extrusive volcanics containing alternating layers of ash-fall tuff, welded tuff, and rhylolite. The region is fractured and faulted, which provides much of the aquifer transmissivity. The wells evaluated are screened exclusively in the volcanic units at depth beneath the alluvial materials. Hydraulic testing was performed according to the guidelines presented by IT (1999).

The Desert Research Institute (DRI) characterized the downhole water quality and borehole flow rates as a part of the characterization program. The water quality parameters of temperature, pH, and electrical conductance (EC) were continuously measured with depth in the open boring before casing was installed and in the completed well. The borehole flow rates at depth were measured in the completed well under ambient and pumping conditions. The rate of groundwater inflow to the well is used to calculate the hydraulic conductivity at depth. Borehole temperature and flow rate measurements are made at 6.1-centimeters (cm) (0.2-feet (ft)) spacing and averaged over 61-cm (2-ft) intervals to ensure that small-scale hydrologic features are characterized.

1.2 Data Collection Purposes

Interpretation of the borehole flow and temperature data collected during pumping provides a more explicit description of water-production zones within the formation than can be obtained from traditional aquifer testing conducted solely at land surface. The borehole flow logging is specifically seeking to identify small spatial features such as fractures that contribute discrete flow to the well. Identifying these small features will aid in understanding the groundwater flow and geochemical characteristics of the various hydrostratigraphic units.

Borehole flow logging is ideally conducted under ambient and pumping conditions. Calculation of hydraulic conductivity at depth requires geophysical logging while the well is being pumped. The flowmeter is trolled up and down the borehole while making flow and temperature measurements every 6.1 cm (0.2 ft). The changes in the vertical flow rate are attributed to horizontal groundwater flow into the well.

These data can be evaluated with this methodology to:

- identify the location of groundwater inflow and outflow zones,
- differentiate between discrete fractures of high capacity and intervals that have numerous fractures that function similar to porous media,
- identify the amount of groundwater contributed from each screened interval,
- evaluate the mixing of groundwater from various locations for interpretation of water chemistry samples collected at depth,
- calculate the aquifer hydraulic conductivity for discrete vertical intervals, and
- determine the statistical frequency of hydraulic conductivity for various lithologies.

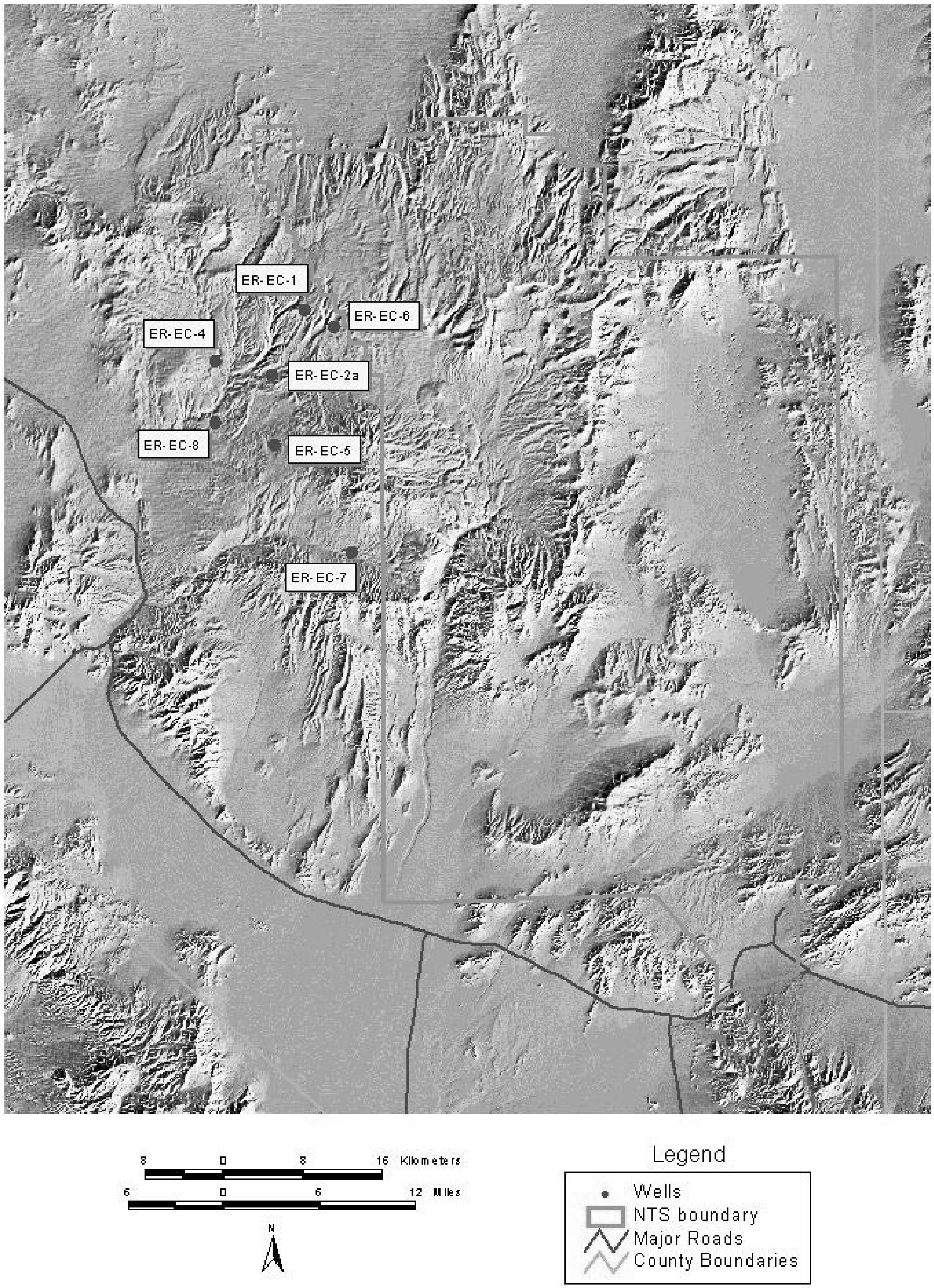

Figure 1. Location of ER-EC wells.

Specifically, the stated hydraulic testing objectives of the UGTA testing program include establishing the hydraulic parameters for each screened interval and determining the relative contribution of flow of the screened intervals.

1.3 Scope

The scope of this work is to evaluate the temperature and flow logging data collected at depth and provide a summary description of conditions at depth. This includes describing the borehole flow under ambient and pumping conditions and interpreting the distribution of hydraulic conductivity at depth. Ancillary information necessary for this scope includes the well construction from “as-built” records, well screen slot specifications, development pumping rates and water levels, aquifer test results, static water levels, and pressure measurements in hydraulically isolated screened sections. This information was provided in IT (2000a-g). Where direct measurements of parameters are not available, estimations are made that include the effects of fluid mechanical processes.

1.4 Interpretive Methodology

Hydraulic conductivity with depth is calculated based on measurement of borehole flow rate with depth while the well is being steadily pumped. The borehole flowmeter data are interpreted using the methodology developed by Rehfeldt *et al.* (1989), which is based on the hydraulic conductivity of an interval being a function of the interval’s contribution to the well discharge and the pressure change caused by pumping. Well screen and filter pack are accounted for in the hydraulic conductivity analysis and do not mask hydraulic features at a vertical interpretative scale of 61 cm (2 vertical ft).

In deep boreholes, the pressure change at depth during pumping is not simply the water level drawdown extrapolated to depth. The pressure change caused by pumping can actually be greater at depth than at the top of the water column when cooler (and more dense) fluids in the upper portions of the well are replaced by inflowing groundwater that is warmer (and less dense). This consideration is most important in determining hydraulic conductivity when the drawdown during pumping is less than 3 m. A fluid temperature log is collected under ambient and pumping conditions to calculate the change in fluid density with depth.

1.5 Borehole Flowmeter Logging

The borehole flow logging at the ER-EC wells started when the water level drawdown in the well was believed to reach a pseudo-steady state. Borehole flow logs were typically made at three pumping rates representing the maximum, minimum, and intermediate pump capacity. Logging was conducted while the geophysical tools were moved continuously upward or downward. The flowmeter impeller can stall (insufficient flow velocity to cause rotation) when the relative flow rate between the moving fluid column and the moving geophysical tool is less than about 152 cm per minute (cm/min) (5 ft per minute (ft/min)). The stall speed limitation was addressed by trolling the flowmeter at up to three different speeds. This logging approach produced up to nine individual flow logs from the top of the upper screened section to the maximum accessible depth. These data were evaluated in composite to ensure that potential sources of mechanical bias were minimized. Stationary flowmeter logs were also used to ensure the calibration of the surface and borehole flowmeters.

A second type of flowmeter was also used to evaluate ambient flow conditions and can measure flow rates as low as 3.0 cm/min (0.1 ft/min). This flowmeter measures the response time of a thermal pulse and is used only at stationary positions. The thermal-pulse flowmeter is used to supplement the information collected continuously with the impeller flowmeter.

The wells are screened at selected locations where drilling and geophysical information suggested permeable zones. Slotted casing joints 9.14 or 12.19 m (30 or 40 ft) in length are placed adjacently or separated by a single joint of blank casing. A series of slotted casing joints is collectively referenced as a screened section. The screened sections are typically separated by about 200 m of blank casing and are designated as the upper, middle and lower screened sections. Screen joints are numbered herein as 1 at the top of the upper screened section and continue progressively downward with the largest number designation at the bottom of the lower screened section.

1.6 Flow Logging Equipment

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 flowmeter has a collapsible impeller that opens inside casing diameters greater than 12 cm (4.75 inches).

The collapsible feature provides two advantages in flow logging:

1. The tool can enter access tubing as small as 3.8 cm (1.5 inches) in diameter to pass beneath the pump and motor assemblies, and
2. The impeller sizes can be selected to maximize impeller coverage of the well diameter for more accurate measurements.

The tool string has a maximum collapsed diameter of 2.7 cm (1.06 inch). The temperature tool is rated for maximum conditions 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 is fully centered in the casing. The temperature tool provides measurement of temperature as well as differential temperature to supplement the flow rate information. The thermal flowmeter can be adjusted to a minimum of 3.8 cm (1.5 inch) diameter, which is used in well casing as small as 5 cm (2.0 inches) in diameter.

The Computalog® Flexstak borehole flowmeter records the impeller revolution rate and temperature with depth. These readings are processed with other information to calculate the borehole flow rate at the various locations in the well. Specifically, the effects of well diameter, vertical travel speed of the logging tool, vertical direction of the logging tool, impeller response to changing fluid density, and instrument efficiency are considered in calculating the borehole flow rate. The measurement devices are subject to mechanical variations, flow turbulence, and response time delay that cause the data sets to have various degrees of uncorrelated noise.

The borehole flowmeter is recalibrated for each logging run by comparing downhole flow rate above the well screen to the well-site flowmeter used to control discharge rate. The well-site flowmeter installation has an appropriate length of straight pipe upgradient and downgradient of the flowmeter, which limits flow turbulence and promotes accuracy. For example, the well-site flowmeter at ER-EC-2a exhibited very steady readings with standard deviations ranging between 0.00182 to 0.00053 m^3/min (0.49 to 0.14 gpm) when pumping at 0.27 to 0.65 m^3/min (71 to 171gpm). The geophysical logging computer is linked via a communications cable to the well-site flowmeter and simultaneously records readings by both the well-site flowmeter and the borehole flowmeter. When the borehole flowmeter is positioned above the uppermost well screen, the two meters should provide similar results. However, the borehole flowmeter is also affected by foreign material adhering to the impeller and by grit entering the bearings. By starting or stopping each logging run above the uppermost well screen, the calibration of the borehole flowmeter can be evaluated for each logging run. Additional logs are collected while pumping with the borehole flowmeter stationary in the well. This information provides a means to recalibrate the borehole flowmeter for each logging run.

2.0 ANALYSIS METHODOLOGY

2.1 Hydraulic Conductivity Determined from Borehole Flow Rates and Pressures

The borehole flowmeter data were interpreted using the methodology developed by Rehfeldt *et al*. (1989). The vertical distribution of hydraulic conductivity can be calculated from borehole flow measurements under three sets of conditions: 1) ambient flow in the well is insignificant and borehole flowmeter logging is conducted during pumping, 2) flow in the well is logged under ambient and pumping conditions, and 3) pumping rates and durations are prescribed according to a specific ratio that eliminates the need for ambient flow logging. The interpretation of ER-EC wells is according to the second condition of measured ambient borehole flow. The equation (Rehfeldt *et al*., 1989) for hydraulic conductivity for an interval when ambient flow is significant is:

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

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

The information necessary for ambient and pumping conditions is the flow through the screen over an interval, the pressure at a point, the radius of the filter pack, and the apparent radius of influence (radius of the cone of depression). Flow through the well screen and the radius of the filter pack are measured directly through flow logging in the completed well and geophysical logging in the open bore. All inflow to the well is assumed to be in the horizontal direction. In some instances, vertical flow in the filter pack (such as the tops and bottoms of screen joints) is possible and would violate the assumed horizontal flow condition. The other necessary parameters are calculated based on supporting data and reasonable estimates.

The apparent radius of influence is calculated by (Rehfeldt *et al*., 1989):

$$1.5\sqrt{\frac{Kbt}{Sc}} \qquad (2)$$

where K is the depth-averaged hydraulic conductivity (LT^{-1}),
b is the saturated thickness contributing to transmissivity (L)

t is the pumping time (T), and
Sc is the storage coefficient (dimensionless).

Storativity is estimated at 0.001 (dimensionless). An apparent radius of influence is calculated for each pumping rate. Because the well was not allowed to fully recover between the change in pumping rates, the effective time of pumping is used to calculate the apparent radius of influence in a manner similar to interpreting a step drawdown test based on the Cooper-Jacob Step Pumping Method (Kruseman and de Ridder, 1970).

Pressure with depth is determined indirectly based on measured temperature, the height of the fluid column, and the well-known temperature dependence of fluid properties. Fluid density as a function of chemical constituents and entrained/dissolved gases was not considered. The accuracy of the pressure predictions under static conditions were generally within 6895 Pascals (1 psi) of the observed value and believed sufficient without additional considerations. 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. The methodology for these processes is described in a later section.

2.2 Calculated Fluid Pressure within the Well Casing for Ambient Conditions

Fluid pressure with depth 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.

Calculation of pressure at depth is complicated by three major factors: 1) variable density fluid is present under ambient and pumping conditions, 2) water production during pumping exchanges fluid of one density and viscosity with fluid of a different density and viscosity, and 3) the fluid column is up to 1,280 m (4,226 ft) long, so fluid compressibility and friction loss with the casing are important considerations in calculating fluid pressure.

The ambient and pumping fluid pressures are estimated based on a series of calculations that incorporate:

- gravitational acceleration at the measurement point,
- height of the fluid column above the measurement point for ambient and pumping conditions,
- temperature-dependent fluid density, fluid compressibility, and fluid viscosity,
- friction within the well casing based on the vertical flow velocity and laminar and turbulent flow conditions,
- friction within the well screen based on horizontal flow velocity, viscosity, slot geometry, and estimated percent of the slot clogged with particulates, and
- friction within the filter pack based on measured filter pack hydraulic conductivity, borehole diameter, casing diameter, and horizontal fluid velocity.

The effects of minor processes are included in the pressure calculation to ensure as much accuracy as possible is achieved, and because the fluid column is long, minor processes can be important over long distances.

Fluid pressure is calculated at the bottom of averaging intervals in a two-step process. First, the pressure exerted by an averaging interval is calculated based on the properties within the interval. Fluid density is initially estimated based on the temperature-dependent density and the fluid compressibility caused by the weight of the overlying intervals. Second, the pressure contribution from the averaging interval is added to the pressure of the overlying intervals to provide a provisional pressure estimate at a point. Then the fluid compressibility contribution to fluid density is updated based on the provisional pressure and a final, more accurate, pressure is calculated for the point. In this manner, the pressure at depth is progressively calculated downward by summing the results of each overlying averaging interval. This technique effectively integrates the effects of variable temperature and its effect on fluid density and fluid compressibility. The fluid pressure at the water table is taken as zero.

Also, in a variable density environment, a single scalar cannot represent the three-dimensional fluid potential, and the simplifications necessary to consider a pressure as a potentiometric head do not exist (Hubbert, 1956). Therefore, all calculations are performed as pressures and converted to an equivalent hydraulic head of water at the nominal discharge temperature. These values are appropriate for calculations involving lateral pressure changes, such as the pressure change at a point caused by pumping. However, these equivalent hydraulic heads can only be used when comparing values at a constant elevation, and cannot strictly be used to estimate vertical flow or vertical hydraulic gradients.

Fluid pressure is defined by the Bernoulli equation (Vennard and Street, 1975) as the sum of the hydraulic head pressure, velocity pressure, and external pressure. These components are represented as:

$$P_t = (g * \rho * h) + (\tfrac{1}{2}\, \rho_p * V^2) + P_e \qquad (3)$$

where P_t is the total pressure at the measurement point ($ML^{-1}T^{-2}$),
g is gravitational acceleration at the measurement point (LT^{-2}),
ρ is the effective fluid density above the measurement point (ML^{-3}),
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 and only the hydraulic head pressure and the velocity pressure are considered further. The ambient fluid pressure for non-pumped conditions where the fluid is essentially static in the borehole is calculated by:

$$P = (g * \rho * h) \qquad (4)$$

where P is the fluid pressure at the measurement point ($ML^{-1}T^{-2}$),
g is gravitational acceleration at the measurement point (LT^{-2}),
ρ is the effective fluid density above the measurement point (ML^{-3}), and
h is the height of the fluid column above the measurement point (L).

As described above, the pressure calculation is made for each averaging interval and summed to estimate pressure at depth. The details of each component of Equation (4) are described below.

Gravitational acceleration is estimated using the standard gravity formula altered slightly to account for the mass above the measurement point (Oberlander, 1989). In surface-based hydrology, gravity is usually taken as a constant. However, in long boreholes, gravitational acceleration changes vary slightly down the length of the well. Including the effect of gravity variation with depth can raise the estimated pressure head by about 10 cm (3.9 inches) in a 1,200-m (3,937-ft) water column. This is a minor effect and is within the reported precision of the transducer-based pressure measurements reported for the ER-EC wells. Including this minor effect may be much more important when comparing pressures at an elevation among different wells than when comparing pumping and ambient pressure changes within a single well.

Gravity at a point is based on the elevation of the measurement point, elevation of land surface, latitude, and average rock density. The standard formula is altered slightly to include the effects of rock mass above the measurement point as:

$$gz = g_0 - (Fa * Elv) + ((Bg * Elv) - (Bg * Depth)) \quad (5)$$

where gz is the gravitational acceleration at a point (LT^{-2}),
g_0 is the gravity at sea level corrected for latitude (LT^{-2}),
Fa is the free air correction (T^{-2}),
Elv is the elevation of the measurement point (L),
Bg is the Bouguer Correction (T^{-2}), and
Depth is the distance between the measurement point and land surface (L).

Fluid density decreases as fluid temperature increases in a well-known relationship (CRC, 1987). Linear interpolation is used to estimate fluid density for observed fluid temperatures located between the published values of temperature (at 1°C increments) and fluid density. This addresses only the effect of temperature on fluid density. Fluid density also increases with pressure (Freeze and Cherry, 1979) by the equation:

$$\rho_p = \rho * (e^{\beta * P}) \quad (6)$$

where ρ_p is the compressed fluid density (ML^{-3}),
ρ is the fluid density at standard pressure (ML^{-3}),
is the temperature-dependent compressibility coefficient ($M^{-1}L^{3}$), and
P is the pressure at the measurement point ($ML^{-1}T^{-2}$).

Equation (6) is iteratively solved for fluid density because the compressed fluid density changes the pressure estimate very slightly in Equation (4). Fluid compressibility is a function of temperature and initially decreases with increasing temperature. At about 50°C, compressibility begins to increase as temperature increases in a well-known relationship (CRC, 1987). An exponential interpolation is used to estimate fluid density for observed fluid temperatures located between the published values of temperature (at 1°C increments) and compressibility. The height of the fluid column is calculated based on the composite water level and the elevation at the measurement point.

2.3 Calculated Fluid Pressure within the Formation for Pumping Conditions

Calculation of pressure at depth during pumping includes all of the considerations described above in Equation (4) and adds the effects of water-level drawdown, friction loss between the fluid and casing, and the vertical velocity head component of the Bernoulli equation. 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 effect is the replacement of fluids of different density during pumping. When the replaced fluid has lesser density (i.e., warmer fluid), the fluid has less mass per unit volume than the more dense fluid initially in the well. Therefore, there is a corresponding decrease in fluid pressure at depth. This effect functions in concert with the water-level drawdown. In a thermally controlled, variable density environment, fluid replacement during pumping can have a significant influence on pressure at depth.

Calculating the pressure during pumping conditions includes the considerations for ambient conditions and adds the physical processes caused by water flow in the casing as well as through the well screen and filter pack. Each of these processes is described below.

2.3.1 Friction Loss within the Casing

Water flowing in the well experiences friction loss with the side of the casing. The friction loss with the casing is considered for two types of conditions, laminar flow and turbulent flow. The friction loss (Vennard and Street, 1975) is defined by:

$$CF_L = \frac{(f * L * V^2)}{\frac{d}{2g}} \quad (7)$$

where CF_L is the casing friction loss (L),
f is the friction factor as defined below,
L is the interval length (L),
d is the casing inside diameter (L),
V is the vertical fluid velocity (LT^{-1}), and
g is the gravitational acceleration (LT^{-2}).

The friction factor (f) is adjusted for conditions of laminar and turbulent flow. When the Reynolds number is greater than 2,500 (dimensionless), the flow is assumed to be turbulent. The Reynolds number (Vennard and Street, 1975) is defined as:

$$R = \frac{V * d * \rho}{\mu} \quad (8)$$

where R is the Reynolds number,
V is the vertical fluid velocity (LT^{-1}),
d is the casing inside diameter (L),
ρ is the temperature- and pressure-dependent fluid density (ML^{-3}), and
is the temperature-dependent dynamic fluid viscosity ($ML^{-1}T^{-1}$).

Fluid viscosity decreases as fluid temperature increases in a well-known relationship (CRC, 1987). Linear interpolation is used to estimate fluid density for observed fluid temperatures located between the published values of temperature (at $1^{o}C$ increments) and fluid viscosity. The friction factor for smooth casing (Vennard and Street, 1975) is defined for turbulent conditions (R > 2,500) as:

$$f = \frac{0.316}{R^{0.25}} \quad (9)$$

and for laminar conditions (R < 2,500) as:

$$f = \frac{64 * \mu}{V * d * \rho} \quad (10)$$

where all notations are as in above equations.

2.3.2 Fluid Velocity Pressure

The flow of water affects the pressure as defined (Vennard and Street, 1975) by the velocity component of the Bernoulli equation in:

$$Pv = ½ \rho * V^2 \quad (11)$$

where Pv is the velocity component of the Bernoulli equation ($ML^{-1}T^{-2}$).
ρ is the fluid density (ML^{-3}), and
V is the vertical fluid velocity (LT^{-1}).

2.3.3 Pressure Loss in the Filter Pack

The energy loss through the filter pack is defined by the Thiem (Driscoll, 1986) equation for confined porous media as:

$$FP_L = \frac{2.73 * Q * \log \left| \frac{r_1}{r_2} \right|}{K * L} \quad (12)$$

where FP_L is the filter pack friction loss (L),
Q is the horizontal flow rate (L^3T^{-1}),
r_1 is the radius of the outside of the well casing (L),
r_2 is the radius of the filter pack (L),
K is the hydraulic conductivity of the filter pack (LT^{-1}), and
L is the length of the vertical averaging interval (L).

2.3.4 Pressure Loss in the Well Screen

Samples of well screen and filter pack were obtained for direct measurement of head loss. The sample screen was 14-cm (5.5-inch) outside-diameter stainless steel casing about 1.5 m (5 ft) in length. Vertical slots had been milled into the casing that were 5 cm (2 inches) long on the casing inside diameter and the nominal slot opening width was 0.203 cm (0.08 inch). There were 18 slots per casing circumference. A set of slots is centered every 15 cm (6 inches) and they are rotated 20 degrees every other set. Screen slots begin about 70 cm (2.3 ft) from the end of the casing. Five sets of slots were exposed for testing. The filter pack consisted of 0.95 cm (3/8 inch) by 0.635 cm (1/4 inch) gravel obtained from the materials storage yard at the Nevada Test Site.

A flow tank experiment was conducted at DRI’s Boulder City testing facility. The screen sample was placed vertically in a testing tank and surrounded by a representative thickness of filter pack. The filter pact was held in place by a cylinder of thin wire mesh (i.e., hardware cloth) with a 0.64 cm (0.25 inch) square opening. There was free water outside of the filter pack. Water was pumped from within the well screen and recirculated to outside the filter pack. Pressure transducers and a datalogger were used to record pressures within the well casing, directly outside the well casing within the filter pack, and in the water tank. The pumping rates were measured with an inline flowmeter and recorded by the datalogger. Pumping rates were adjusted between 0.02 cubic m per minute (m^3/min) (5.5 gpm) to 0.13 m^3/min (35.5 gpm). These flow rates produced horizontal flow velocities of 2.26 to 14.8 m/min (7.4 to 48.5 ft/min) through the slot openings. These velocities are representative of screen slot flow velocities in the ER-EC wells. Pressure loss through the well screen was generally linear with the slot Reynolds number and this relationship was used to estimate head loss for both the 5-cm and 7.6-cm (2- to 3-inch) slot lengths used to construct the ER-EC wells.

Previous reports of hydraulic conductivity at depth for the ER-EC wells used a theoretical pressure loss equation from Rehfeldt *et al.* (1989). The measured pressure loss through the well casing is less than the previous estimate. The hydraulic conductivity values presented herein are based on the observed relationship between slot Reynolds number and screen pressure loss.

2.3.5 Summary of Fluid Pressure Calculations

The equations presented above require measuring or calculating a few essential parameters:

- well discharge rate and water-level drawdown during pumping,
- composite aquifer transmissivity and storativity,
- lateral flow contribution with depth in the borehole, and
- change in formation pressure with depth caused by pumping.

Not all of these values were measured directly during flow logging and some values are estimated from related information. Consideration of many processes is included in these estimates to extract as much information as possible from the borehole flow logging. Consideration is also given to minor contributors in the process descriptions of pressure in the borehole.

2.4 Abstraction of Logging Information

Calculation of hydraulic conductivity with depth relies on accurate measurement of the borehole flow during pumping. Therefore, it is important to remove as much as possible small-scale variations in the measurements caused by instrument noise, flow turbulence, or irregular alignment of the borehole flowmeter in the well so that flow rate variations are not attributed to hydraulic conductivity. To reduce the effects of small variations over short distances, the flow measurements are spatially averaged at 61-cm (2-ft) vertical intervals in the screened sections. This is believed adequate to average out some of the minor fluctuations in the flowmeter readings while still preserving the characterization of small discrete hydrologic features.

In the cased sections of the well, flow measurements are averaged over a nominal interval of 6.1 m (20 ft). A longer distance was selected because there is no advantage to averaging over short intervals when the flow rate within each cased section is spatially and temporally constant. The averaging distance in cased sections is based on the precision needed to estimate the variable fluid density for the calculation of pressure at depth. The averaging process abstracts the important information and reduces the set of many thousands of measurement points to a more manageable set of a few hundred points representing average properties over discrete intervals. Temperature data are averaged over the same intervals and frequency as the borehole flow data. These intervals are referred to herein as calculation intervals.

The individual logs are then grouped by pumping rate, as illustrated in Figure 2, and the properties for each calculation interval are averaged. This step combines the information collected at various logging speeds into a single representation of flow in the well for each pumping rate and smoothes potential measurement bias related to the logging speed. For example, when logging in the same direction as the water flow, the impeller may stall when the logging speed and the water flow speed are similar. Under those conditions, moderate changes in flow rate are not recognized until the logging speed and the water flow speeds are substantially different. By logging at various speeds, information is gained at one logging speed that is not recognized at another speed. By compositing the individual logs, this information is available for analysis.

3.0 AMBIENT FLOW AND WATER QUALITY INDICATORS

Chemistry and thermal flowmeter (TFM) logs were collected from each well before installing casing, and after well completion and aquifer testing. The open borehole logging was performed immediately after the wells were drilled, with the intention of using the chemistry and TFM logging results to help identify inflow/outflow zones in the well bore. In most cases, these logging results were instrumental in placement of screened and blank-cased sections. The chemistry well log is a continuous profile of the temperature, electrical conductance and pH of the water column. Measurements are digitized every two seconds, or approximately every 0.5 m, (20 inches) based on an average logging rate of 15 m/min (50 ft/min). These data are plotted and analyzed to determine the areas of the borehole that may indicate vertical flow, and the point of inflow/outflow.

The TFM is a station measurement tool. A caliper log is used to identify sections of the borehole that are within the diameter range of the TFM flow diverter. Washout zones greater than about 10 percent of the gauge section of borehole cannot be measured; therefore, great care must be taken to identify stations (depth zones) where reasonable diverter seats can be made. These zones are compared to the chemistry logging results to identify the most suitable depth intervals, or stations. Vertical flow in the borehole is diverted through the centralized TFM by means of a rubber-peddled flow diverter. A heat pulse is delivered to the packet of water in the TFM flow-through cell, and the pulse response time is measured by a thermistor above and below the heat grid (for more details of the TFM theory, see Lyles, 1994). Repeated pulse response time measurements are made at each depth and statistics are calculated.

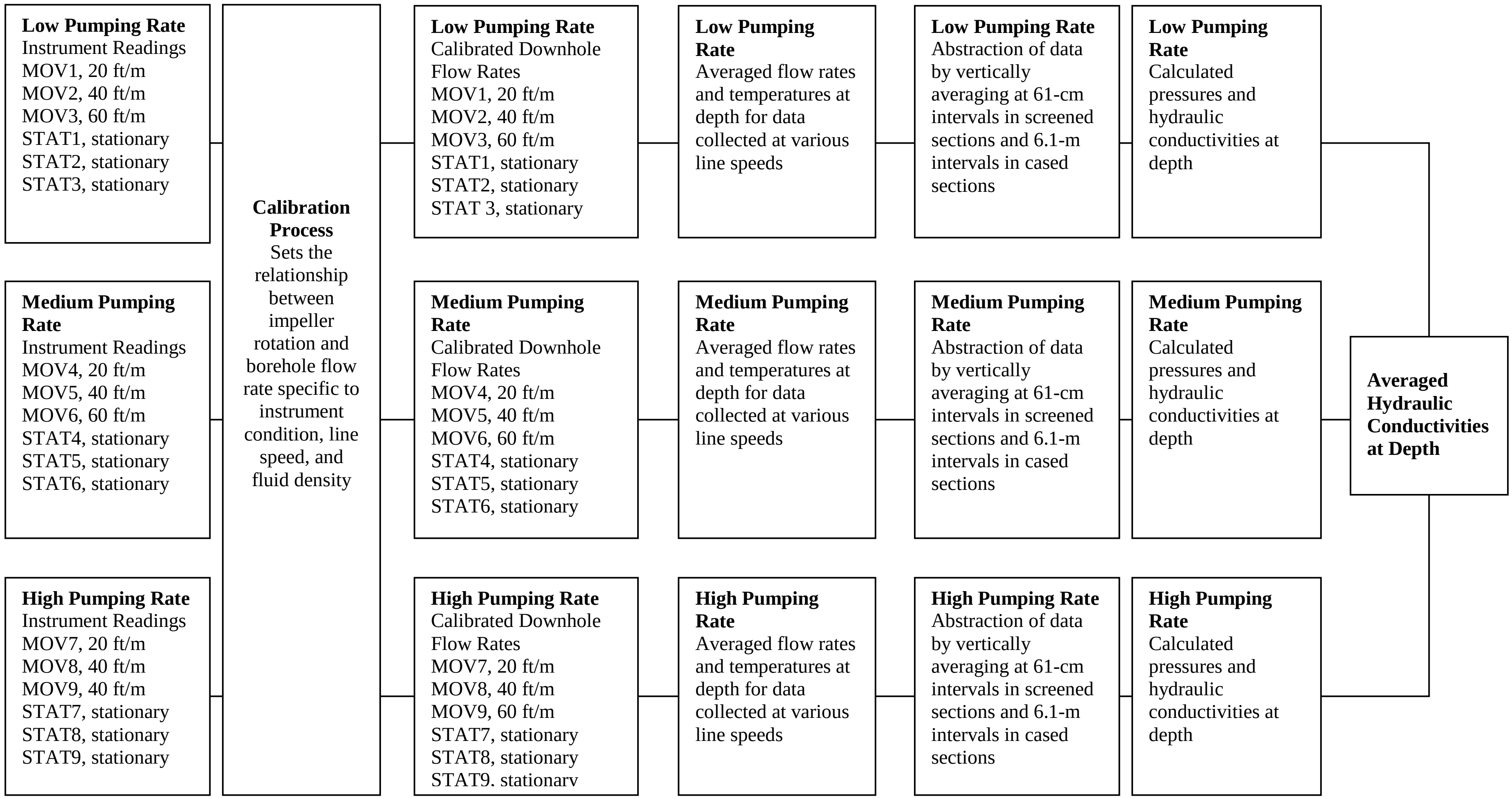

Figure 2. Information processing of flow logs to calculate hydraulic conductivity.

Results from the measurements made in the uncased boreholes are shown in Figures 3a through 9a. Measurements performed in the freshly drilled wells are in most cases still show the impacts of the drilling activity. Therefore, the quantity of vertical flow, the change in temperature gradient, or the relative change in pH or EC may vary from pre-completion to post-completion logs. All wells showed dominantly downward vertical flow, with the exception of ER-EC-5, which showed upward vertical flow. A summary of the TFM logging results is shown in Table 1.

After the wells were constructed, developed, stress-flow tested, and aquifer tested, the chemistry and TFM logs were repeated to measure the water quality and to quantify the volume of water flow between screened intervals. Results from the pre-construction and post-construction well logs were relatively similar, and in most cases were performed approximately one year apart. Most notably, temperature trends observed just after the well drilling was completed were still obvious one year later. Flow within the completed wells was less than the values measured in uncased boreholes, possibly due to the added resistance of the gravel and well screen, with the exception of well ER-EC-1 and ER-EC-7. The reason for these increases is unknown, but may be a result of increased permeability flow during well development. The well logging results are listed in Figures 3b through 9b.

4.0 WATER-PRODUCING ZONES

This section presents flow rate logging results. The borehole flowmeter was recalibrated for each logging run by comparing the impeller revolutions per second to the surface flowmeter reading as described above in Section 1.6. This allows instrument factors that change over time and affect the flowmeter calibration to be considered. The factors believed responsible for changes in calibration are based on observations of grease adhering to the impeller as well as grit entering the flowmeter bearing assembly. Bearing seals are minimal to reduce friction and allow the impeller to rotate under low-flow conditions. It is only after the logging run is completed that a comparison between the borehole flowmeter and the surface flowmeter can be performed and incorporated into a "fine tuning" the calculated borehole flow rate. The additional processing of the flow logging data provides more accurate measurements of borehole flow than the field interpretation, which uses more general instrument constants calculated before logging.

4.1 ER-EC-1

The flow rate within the well was observed at pumping rates of 0.48, 0.39, and 0.24 m^3/min (127, 104, and 64 gpm). Flow rates in the well at 0.48 m^3/min are presented in Figure 10. The entire suite of over 12,000 flow measurements is presented on the figure to illustrate the range and variation of readings before vertical averaging in the abstraction process.

The rectangular bars on the left of the figure indicate the location of well screen slots. Much of the groundwater entering the well comes in through the first, second, and third joints of well screen in the upper screened section. The middle and lower screened sections provide essentially no water to the well when pumped at 0.48 m^3/min. Below the upper screened section, the flowmeter data indicate a downward flow to the bottom of the well. This downward flow is not confirmed with the thermal flowmeter, which is more accurate at low flow rates.

The major observations are:

- nearly all of the groundwater inflow occurs in screen joints 1 through 4 of the upper screened section and
- the middle and lower screened sections are not contributing significantly to well discharge.

4.2 ER-EC-2a

The borehole flow rate was observed at 0.27, 0.46, and 0.65 m^3/min (71, 121, and 171 gpm). The full suite of 17,500 flow measurements is used to illustrate borehole flow at 0.65 m^3/min in Figure 11. The flow regime is very similar to that during pumping at 0.27 and 0.46 m^3/min. The water production is greatest in the middle screened section with about one third of the water coming from the upper screened section and two thirds from the middle screened section. The borehole flow rates change over intervals as small as a meter within the slotted screen sections. These flow rate changes occur despite the dampening effect of the filter pack.

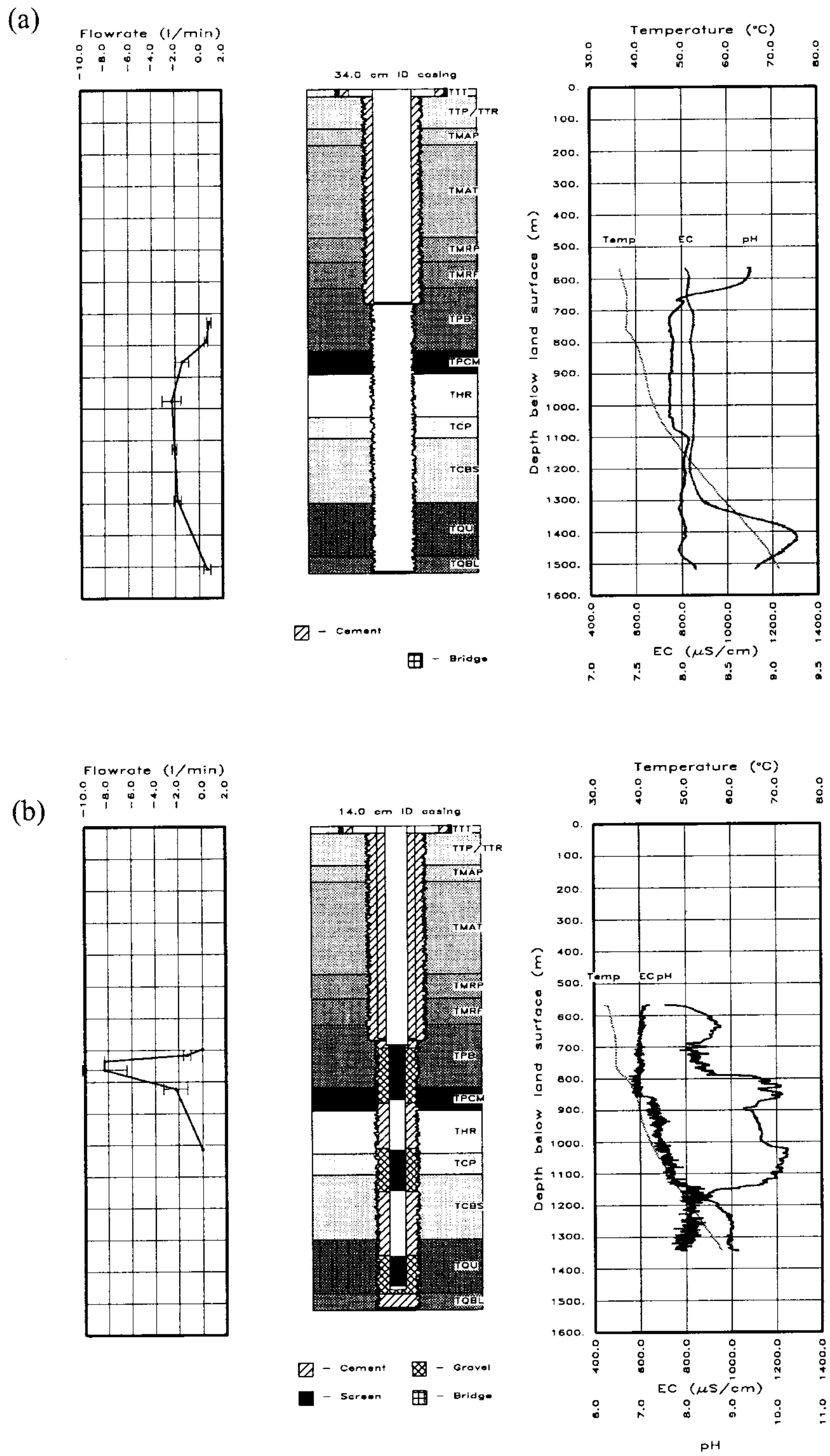

Figure 3. ER-EC-1 chemistry and TFM well-logging results: a) open borehole and b) cased well.

(a)

(b)

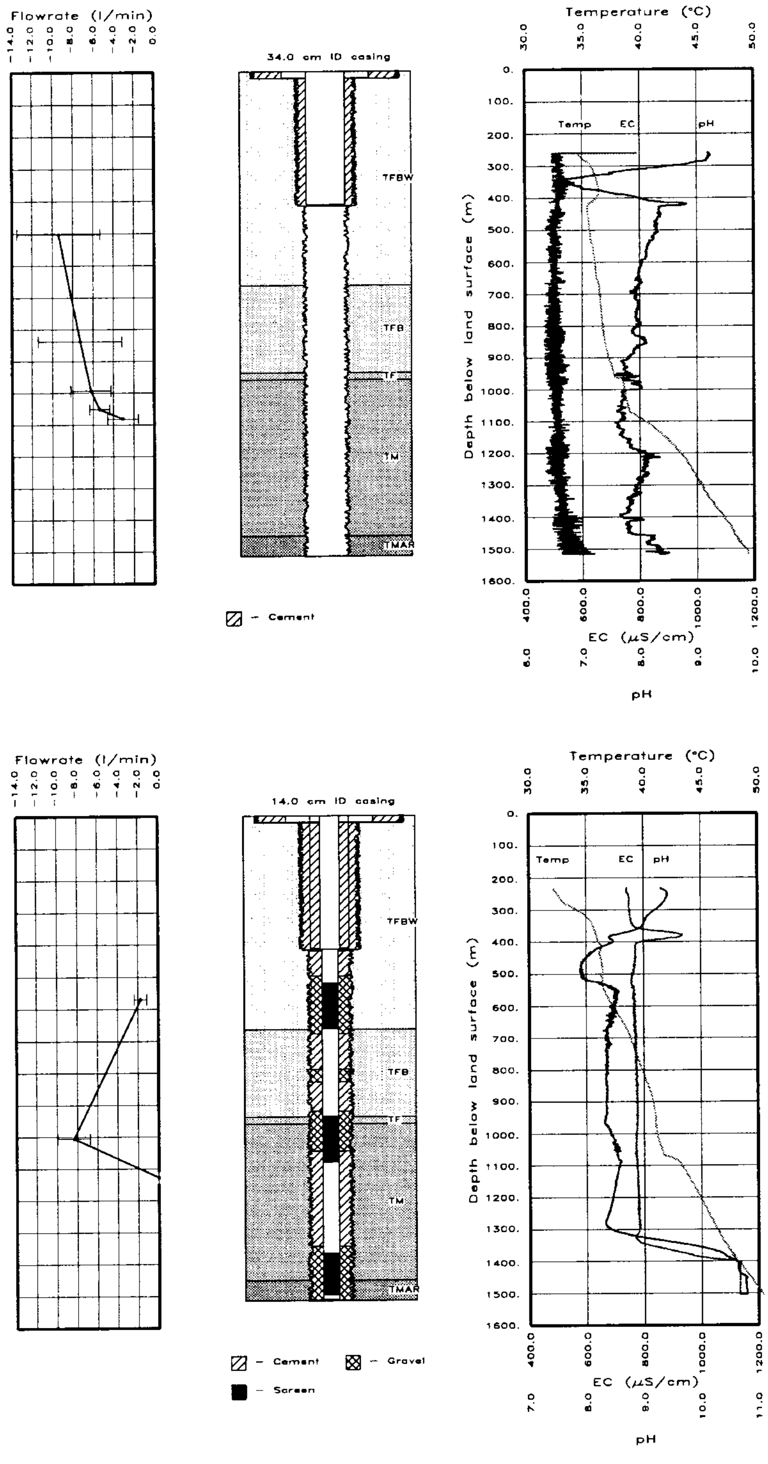

Figure 4. ER-EC-2a chemistry and TFM well-logging results: a) open borehole and b) cased well.

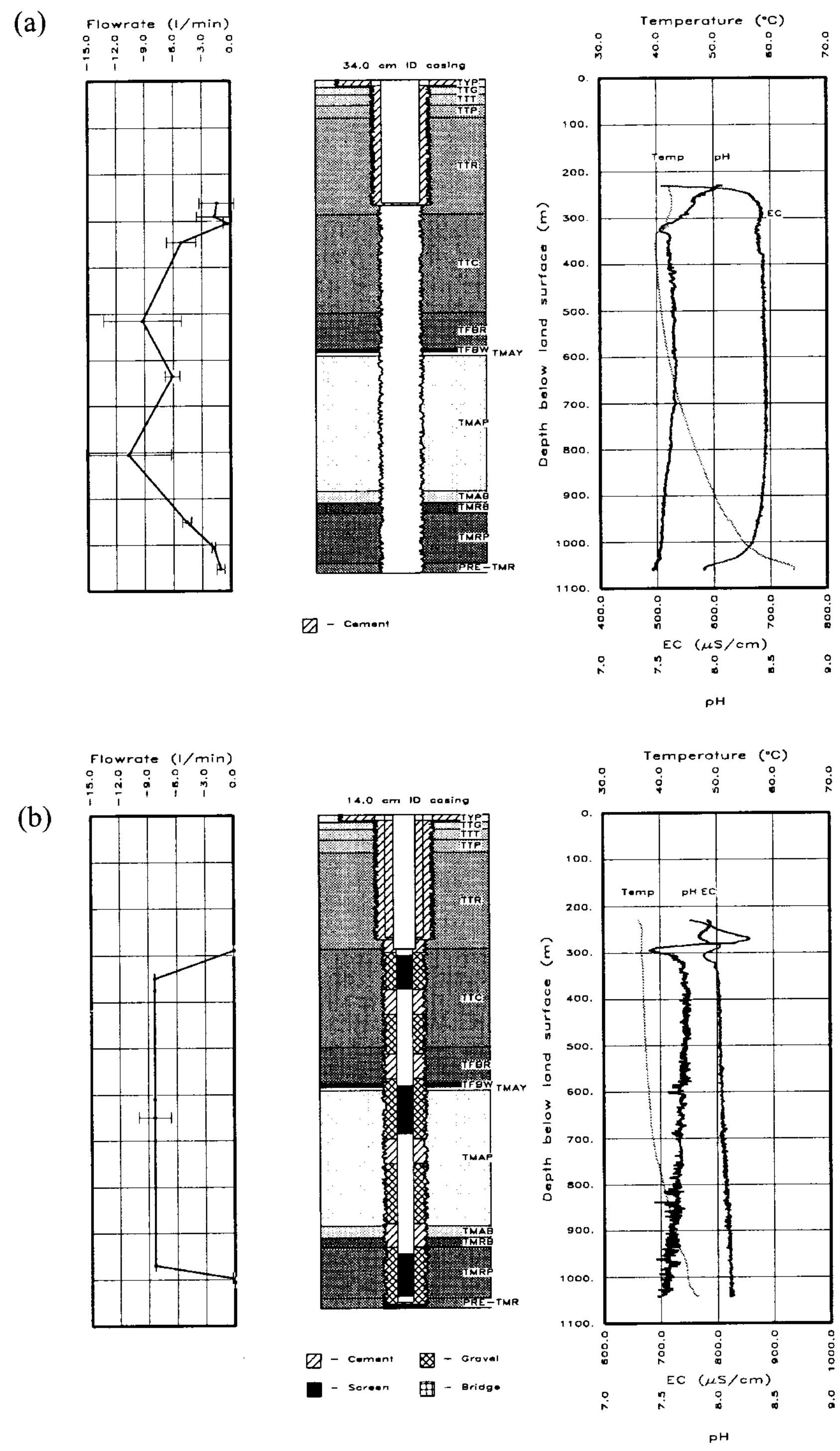

Figure 5. ER-EC-4 chemistry and TFM well-logging results: a) open borehole and b) cased well.

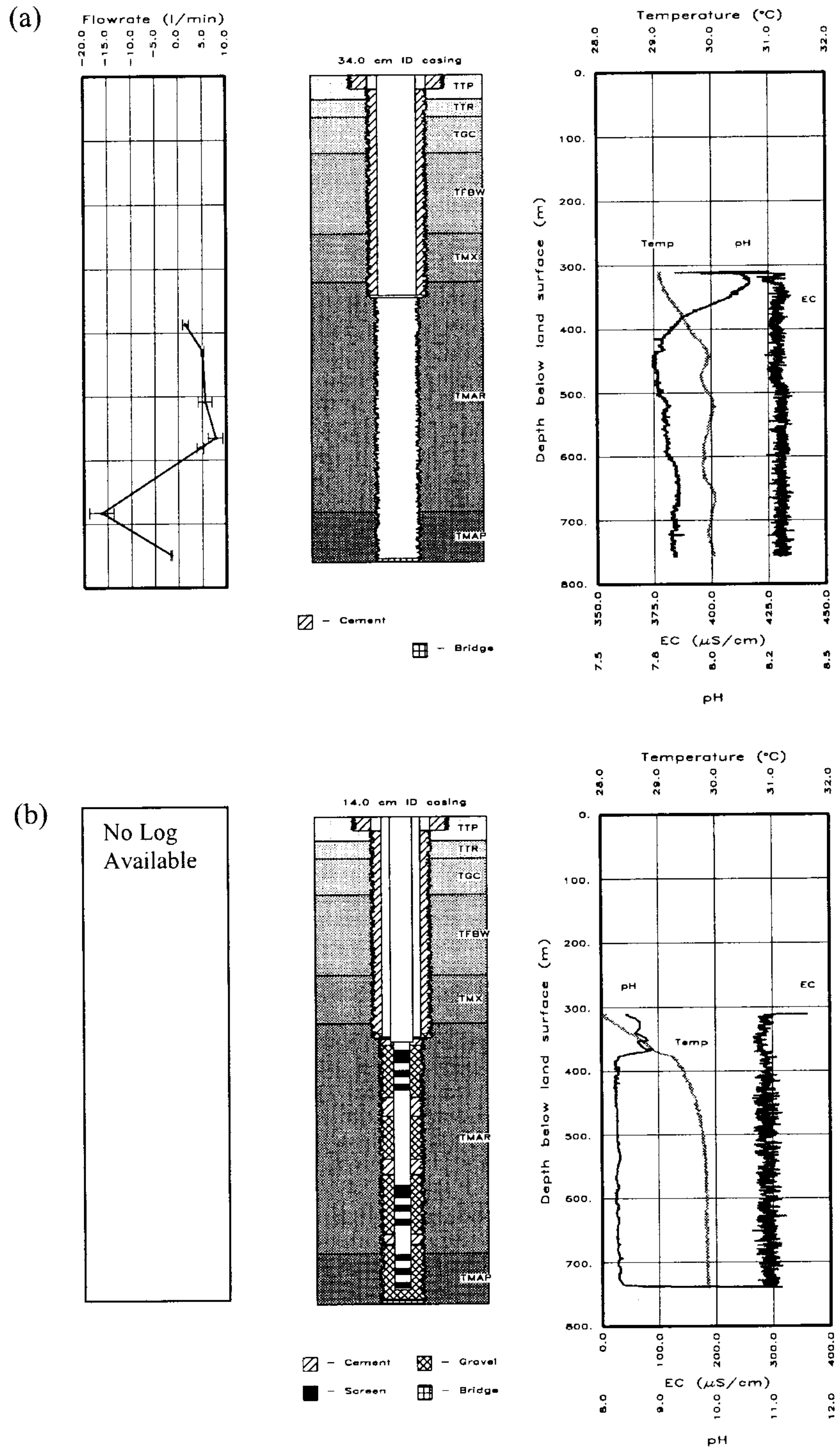

Figure 6. ER-EC-5 chemistry and TFM well-logging results: a) open borehole and b) cased well.

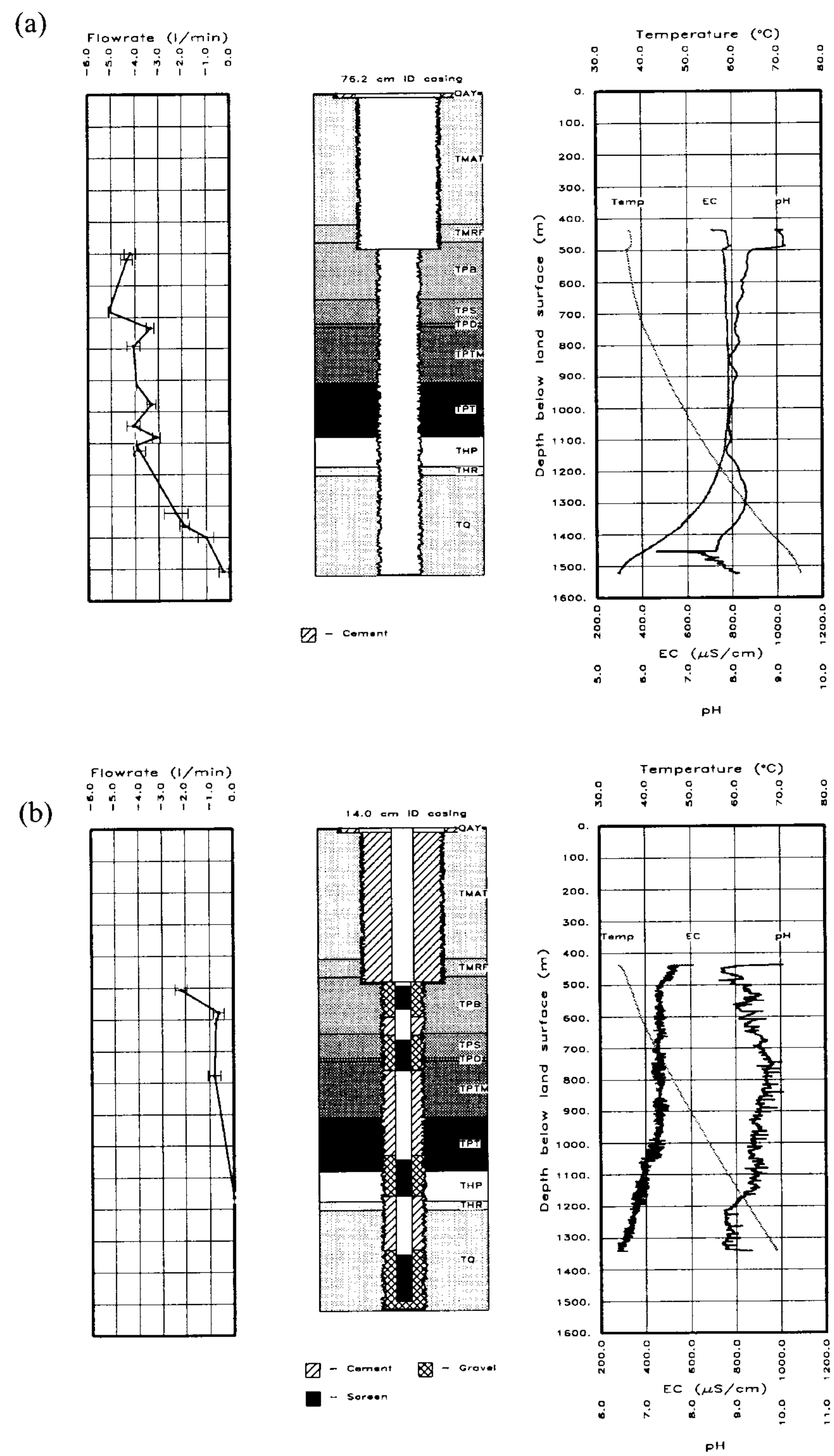

Figure 7. ER-EC-6 chemistry and TFM well-logging results: a) open borehole and b) cased well.

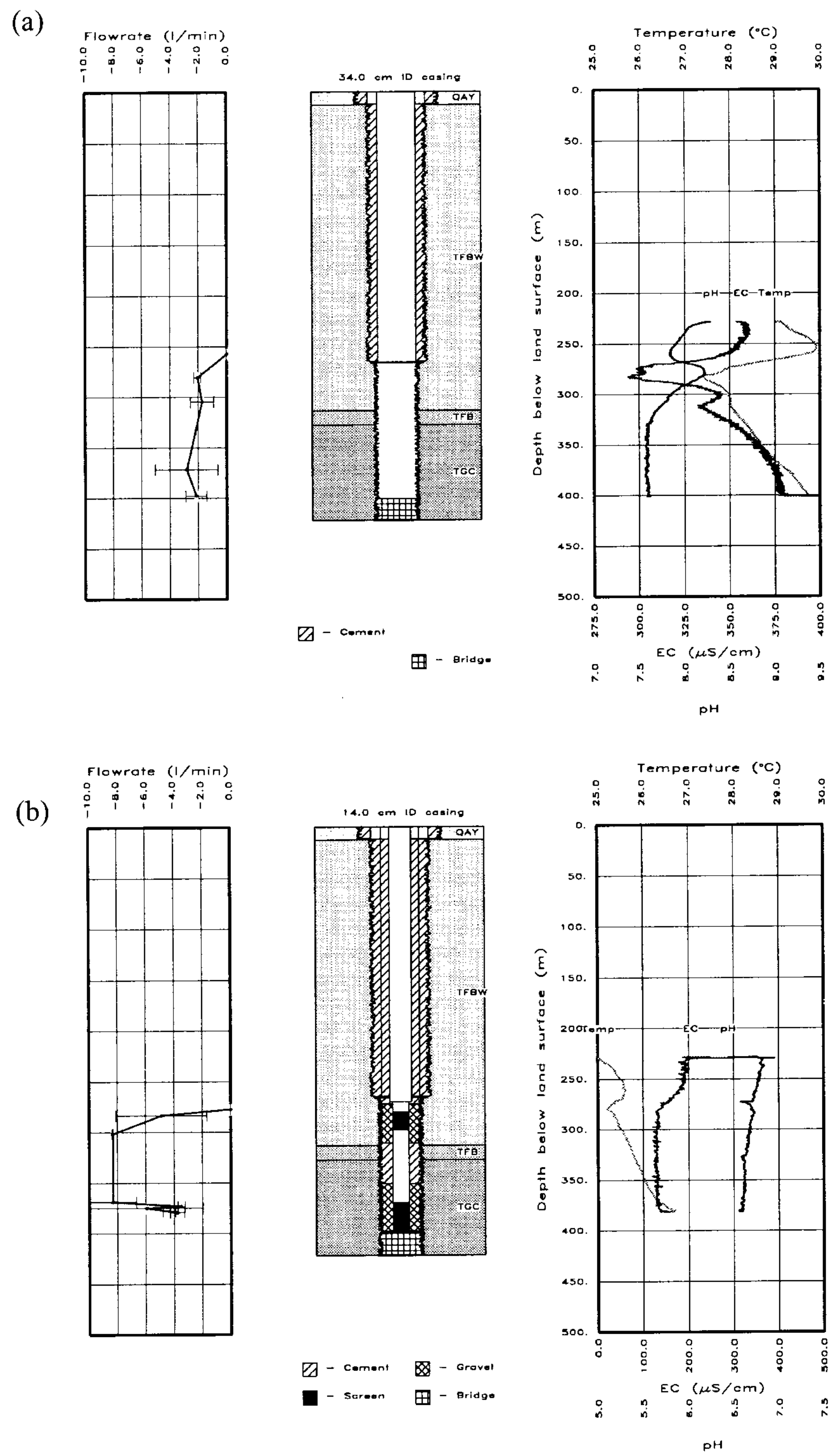

Figure 8. ER-EC-7 chemistry and TFM well-logging results: a) open borehole and b) cased well.

(a)

(b)

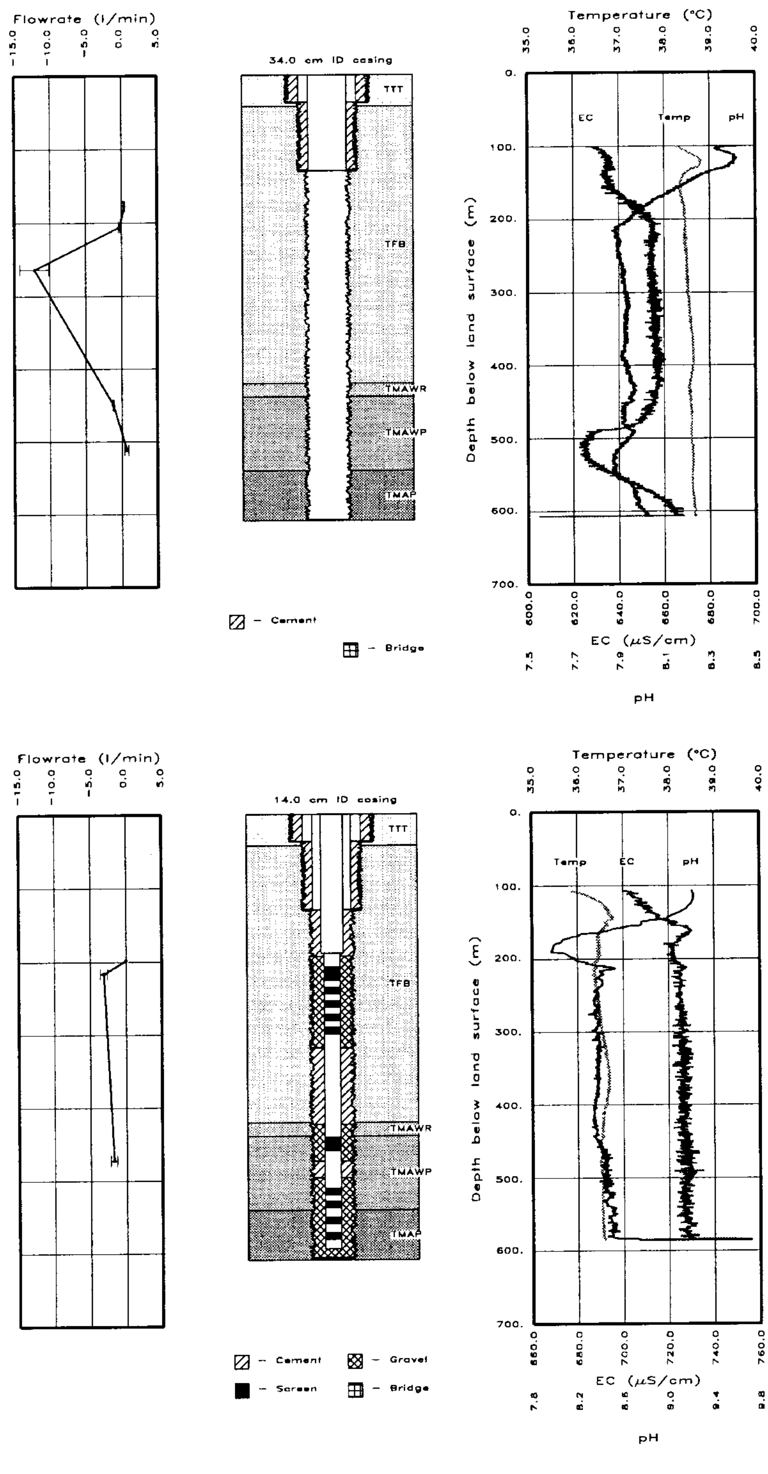

Figure 9. ER-EC-8 chemistry and TFM well-logging results: a) open borehole and b) cased well.

Table 1. Thermal flowmeter well logging results from wells ER-EC-1, 2a, 4, 5, 6, 7, and 8.

Depth (m)	Diameter (cm)	Open hole flow rate (lpm)	Completed well flow rate (lpm)
ER-EC-1			
698.0	12.70		0.000 ± 0.000
716.2	12.70		-1.299 ± 0.310
729.0	33.02	0.873 ± 0.170	
734.5	12.70		-8.329 ± 0.003
762.0	12.70		-8.329 ± 11.909
789.4	33.65	0.636 ± 0.158	
822.9	12.70		-2.266 ± 1.020
853.4	33.65	-1.388 ± 0.558	
976.8	32.38	-2.286 ± 0.785	
1,014.9	12.70		0.000 ± 0.000
1,128.3	32.38	-2.045 ± 0.201	
1,292.3	31.75	-1.815 ± 0.336	
1,508.7	33.65	0.669 ± 0.307	
ER-EC-2a			
502.9	31.75	-9.390 ± 4.066	
569.9	12.70		-1.735 ± 0.623
838.2	31.75	-7.272 ± 4.111	
993.6	31.75	-6.222 ± 1.995	
1,005.8	12.70		-8.329 ± 1.606
1,051.5	31.75	-5.362 ± 0.978	
1,082.0	31.75	-3.073 ± 1.503	
1,127.7	12.70		0.000 ± 0.000
ER-EC-4			
261.8	33.97	-1.441 ± 1.849	
289.5	12.70		0.000 ± 0.000
290.8	33.02	-1.679 ± 1.870	
304.8	32.00	-0.316 ± 0.411	
345.9	33.27	-5.155 ± 1.518	
349.9	12.70		-8.329 ± 0.033
375.8	12.70		-8.329 ± 0.033
515.1	33.02	-9.230 ± 4.102	
609.6	12.70		-8.329 ± 0.033
635.5	33.53	-6.084 ± 0.754	
649.8	12.70		-8.329 ± 1.666
699.5	12.70		-8.329 ± 0.033
805.2	31.24	-10.697 ± 4.457	
950.9	34.29	-4.611 ± 0.458	
969.2	12.70		-8.329 ± 0.033
996.6	12.70		-0.245 ± 0.007
1,005.8	12.70		0.000 ± 0.000
1,005.8	34.29	-1.815 ± 0.183	
1,053.0	31.11	-1.076 ± 0.415	
ER-EC-5			
387.1	33.78	1.445 ± 0.640	No results are available
428.5	33.02	5.002 ± 0.342	No results are available
509.0	33.27	5.600 ± 1.406	No results are available
565.7	34.92	7.765 ± 1.565	No results are available
580.9	33.02	4.582 ± 0.705	No results are available
682.7	33.65	-16.232 ±2.517	No results are available
749.2	33.02	-1.615 ± 0.134	No results are available
ER-EC-6			
499.8	33.53	-4.198 ± 0.243	
506.2	12.70		-2.197 ± 0.255

Table 1. Thermal flowmeter well logging results from wells ER-EC-1, 2a, 4, 5, 6, 7, and 8 (continued).

Depth (m)	Diameter (cm)	Open hole flow rate (lpm)	Completed well flow rate (lpm)
579.1	12.70		-0.614 ± 0.232
612.9	12.70		-0.747 ± 0.003
682.7	32.51	-5.105 ± 0.024	
735.4	33.02	-3.350 ± 0.162	
777.5	12.70		-0.801 ± 0.268
792.4	32.77	-4.063 ± 0.281	
914.4	33.53	-3.937 ± 0.005	
977.1	32.77	-3.305 ± 0.194	
1,045.4	31.24	-4.063 ± 0.281	
1,082.0	34.29	-3.093 ± 0.172	
1,106.4	31.75	-3.937 ± 0.005	
1,124.7	32.51	-3.817 ± 0.251	
1,164.3	12.70		0.000 ± 0.000
1,322.8	32.77	-2.274 ± 0.508	
1,362.4	33.78	-1.919 ± 0.204	
1,399.0	33.53	-1.019 ± 0.324	
1,508.7	32.51	-0.278 ± 0.201	
ER-EC-7			
257.5	33.02	0.000 ± 0.000	
277.4	12.06		0.000 ± 0.000
280.7	33.02	-2.045 ± 0.239	
283.5	12.06		-4.884 ± 3.221
301.7	12.06		-8.329 ± 0.033
304.8	34.29	-1.727 ± 0.803	
368.8	12.06		-8.329 ± 1.666
371.8	33.02	-2.817 ± 2.207	
373.4	12.06		-3.475 ± 0.242
374.9	12.06		-5.937 ± 3.991
377.9	12.06		-4.331 ± 0.436
379.5	12.06		-3.763 ± 0.500
397.7	31.75	-2.144 ± 0.748	
ER-EC-8			
176.8	37.47	0.399 ±0.118	
198.1	12.70		0.000 ±0.000
205.7	34.92	-0.289 ± 0.109	
216.4	12.70		-3.102 ± 0.507
263.6	35.18	-12.158 ± 12.008	
449.6	32.77	-1.188 ± 0.093	
472.4	12.70		-1.766 ± 0.463
512.0	35.56	0.690 ± 0.286	

The major observations are:

- nearly all of the groundwater inflow is in the upper and middle screened sections,
- the upper screened section behaves as highly fractured media,
- the middle screened section behaves as having a few high-capacity fractures, and
- the lower screened section is not contributing a significant amount of water to the well discharge.

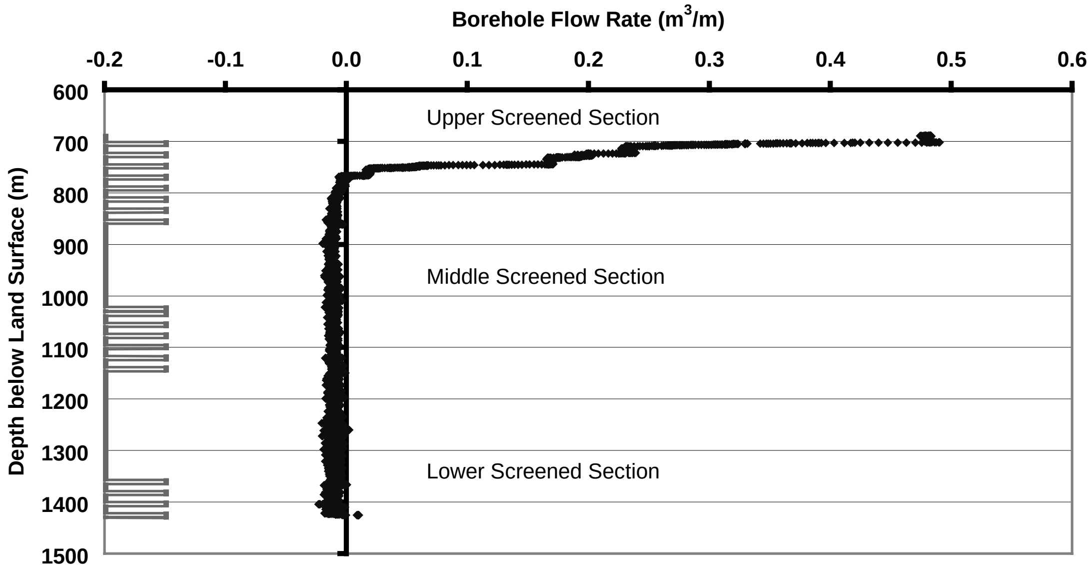

Figure 10. Borehole flow rates while pumping ER-EC-1 at 0.48 m^3/min.

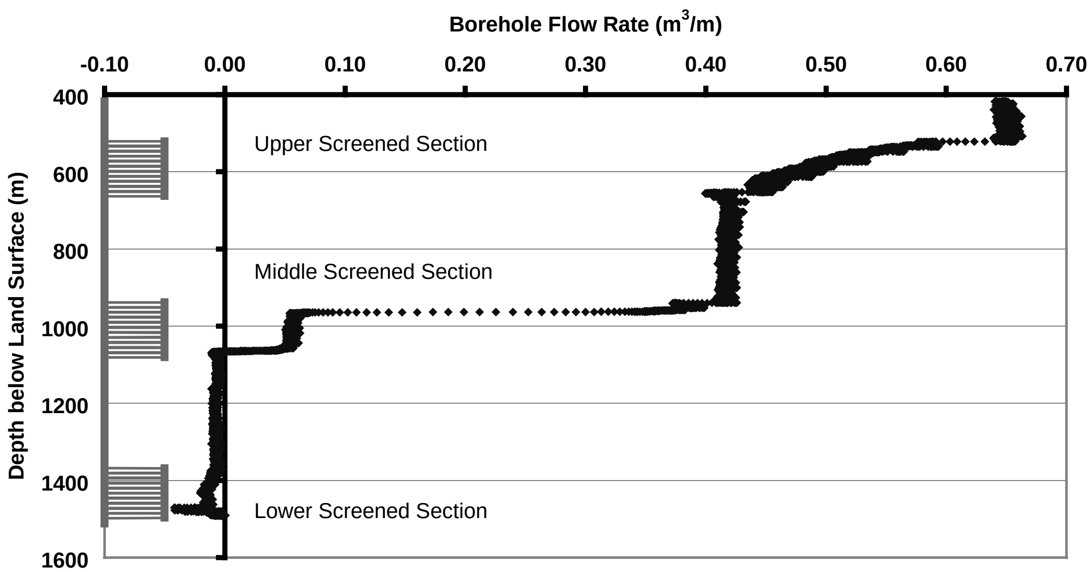

Figure 11. Borehole flow rates while pumping ER-EC-2a at 0.65 m^3/min.

4.3 ER-EC-4

The well was pumped at 0.23, 0.47 and 0.70 m^3/min (61, 123, and 183 gpm). The full suite of 12,250 borehole measurements is used to illustrate flow at 0.70 m^3/min in Figure 12 so that the full range and variation in flow measurements can be observed. The flow regime is very similar to that during pumping at 0.23 and 0.47 m^3/min. The water production is entirely from the upper three screen joints of the upper screened section. Downward flow below screen joint 3 was observed at all three pumping rates. The rate of downward flow is less at the higher pumping rates but downward flow still occurs to the lowest screen joint in the well.

The major observations are:

- flow is from the upper screened section to lower screened section during pumping,
- most of the groundwater inflow is in the upper three screen joints of the upper screened section, and
- the middle and lower screened sections are not contributing to well discharge.

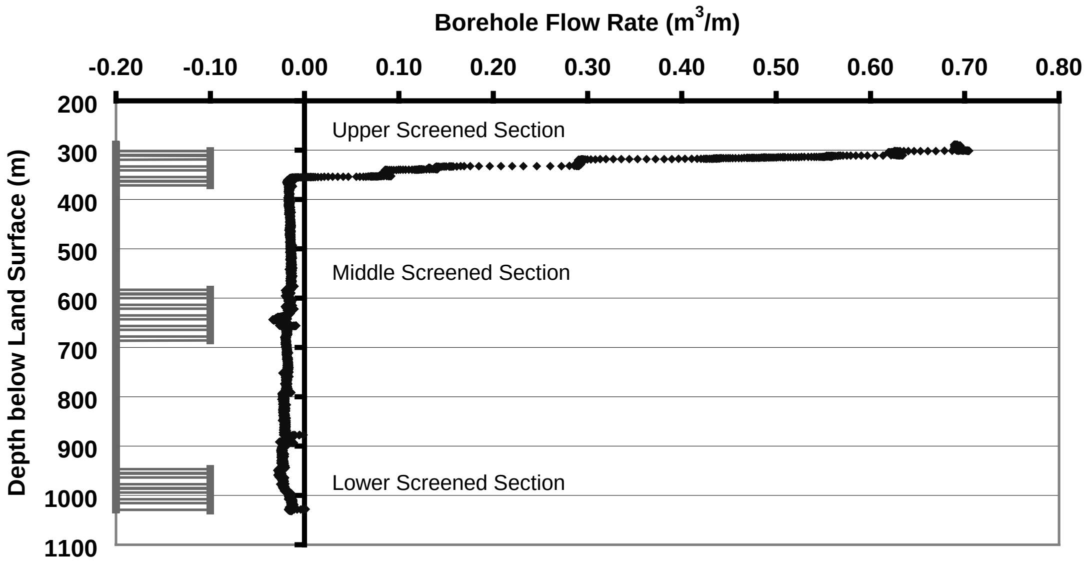

Figure 12. Borehole flow rates while pumping ER-EC-4 at 0.70 m^3/min.

4.4 ER-EC-5

The flow within the well was observed at pumping rates of 0.23, 0.42. 0.61 m^3/min (61, 111, and 162 gpm). The full suite of 6,300 measurements is used to illustrate borehole flow at 0.61 m^3/min in Figure 13. The flow regime at 0.61 m^3/min is very similar to that when pumping at 0.23 and 0.42 m^3/min. The water production is moderate from the upper and lower screened sections and greatest in the middle screened section.

The major observations are:

- the upper and middle screened sections are contributing nearly all of the water to the well,
- the middle screened section behaves as having a few high-capacity fractures, and
- the lower screened section contributes some water during pumping and is located a relatively short vertical distance from the middle and upper screened sections.

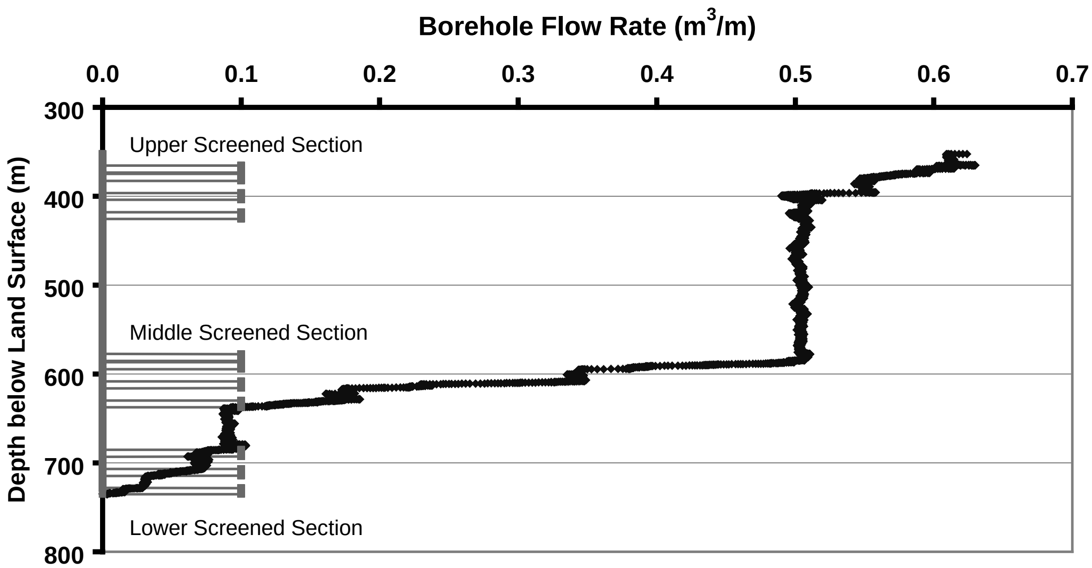

Figure 13. Borehole flow rates while pumping ER-EC-5 at 0.61 m^3/min.

4.5 ER-EC-6

The well was pumped at the rates of 0.24 and 0.26 m^3/min (63 and 69 gpm). The flow regimes are similar when pumping at 0.24 and 0.26 m^3/min. Much of the flow entering the well when pumped at 0.26 m^3/min comes in the first through fourth screen joints in the upper screened section as illustrated in Figure 14. The figure is based on the full suite of over 11,000 flow measurements to illustrate the range and variation in borehole flow. The upper middle and lower middle screened sections are seen to provide very little water to the well. Below the upper part of the upper screened section, the figure suggests that there is minimal flow during pumping.

The major observations are:

- nearly all of the groundwater inflow occurs in the first three screen joints of the upper screened section,
- the upper screen joint behaves as having a few high-capacity fractures, and
- the middle and lower screened sections contribute almost no water to well discharge.

4.6 ER-EC-7

The well was pumped at 0.25, 0.46, and 0.67 m^3/min (66, 122, and 177 gpm). The borehole flow at 0.67 m^3/min is presented in Figure 15. The full suite of over 1,900 flow measurements is used in the figure to illustrate the full range and variation in borehole flow rates. The bottom of the well was obstructed and the lowest screen joint was not accessible for logging. Most of the flow enters the well in the lower screened section. Additional water enters at the first screen joint in the upper screened section. However, the flow log indicates an unusual condition within the well. At the second screen joint water flowing upward in the well bore exits the well and preferentially flows upward in the filter pack rather than the open well bore. This exiting flow then re-enters the well bore in screen joint 1. The water flow path suggests that: 1) there is a flow diversion (possibly the borehole flowmeter) in the well that forced water moving upward out of the well bore into the filter pack, and then back into the well bore and/or 2) there is a formation washout outside of the casing filled with filter pack producing a very high permeability at that location.

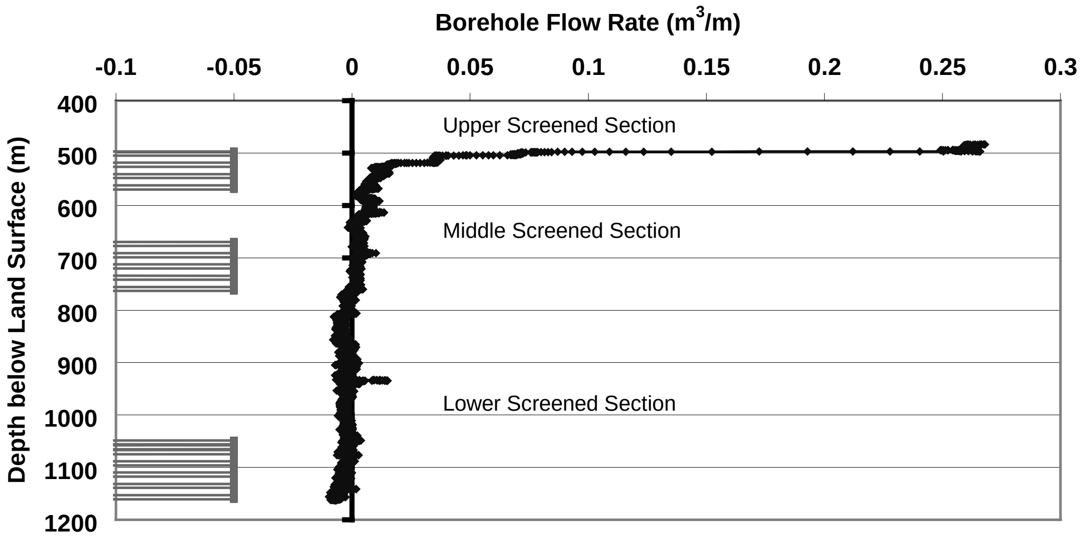

Figure 14. Borehole flow rates while pumping ER-EC-6 at 0.26 m^3/min.

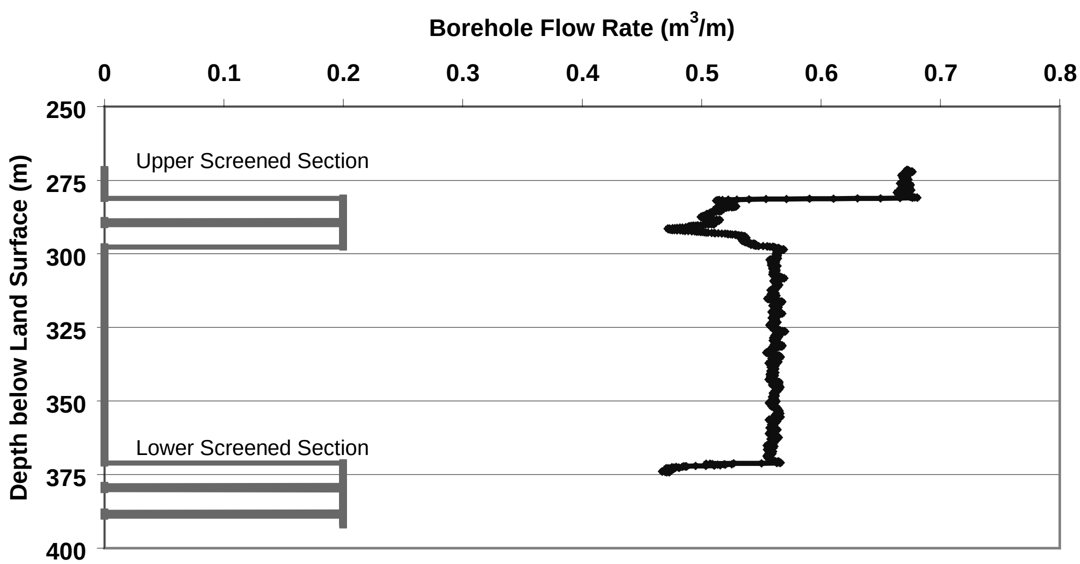

Figure 15. Borehole flow rates while pumping ER-EC-7 at 0.67 m^3/min.

The cause of the flow diversion in the upper screened section is unknown. Possible causes for the flow diversion include:

- partial obstruction of the well bore by the geophysical tools in the 12-cm (4.75-inch) inside-diameter fiberglass well casing (instead of the typical 14-cm (5.0-inch) casing inside diameter) and the additional size limitation of the interior couplings; and
- the filter pack having a very high transmissivity because of formation washouts, which are indicated on geophysical logs.

This aspect of well logging occurred at each of the three pumping rates and complicated hydraulic interpretation. If the geophysical tools restrict the flow, then the flow rate within the well bore is neither at steady state nor strictly a function of well diameter and pumping rate. Interpretation of hydraulic conductivity with depth is continued with the understanding that only coarse features of the aquifer can be estimated and that there is a greater level of uncertainty in the interpretation of ER-EC-7 hydraulics compared to the other ER-EC wells. Interpretations are limited to average values for the upper and lower screened sections.

The major observations are:

- the narrow diameter of this well is believed to be a contributing factor to irregular flow rate measurements and the probable flow diversion through the filter pack, and
- most of the water enters the well in the lower screened section.

4.7 ER-EC-8

The well was pumped at 0.25, 0.48, and 0.67 m^3/min (66, 127, and 177 gpm). The full suite of 6,400 measurements is used to illustrate borehole flow at 0.67 m^3/min in Figure 16. The flow regime is very similar at all pumping rates. The water production is greatest in screen joint 1 through 3 in the upper screened section. Minor groundwater inflow occurs in the middle and lower screened sections.

The major observations are:

- nearly all of the groundwater inflow occurs in screen joints 1 through 3 in the upper screened section, and
- the middle and lower screened sections contribute almost no water to the well.

4.8 Summary of Borehole Flow

The following generalizations can be made concerning water production from the wells tested:

- four of the seven wells (ER-EC-1, ER-EC-4, ER-EC-6, and ER-EC-8) had nearly all of the water production from the upper screened section,
- two of the seven wells (ER-EC-2a and ER-EC-7) had approximately half of the flow production from the upper screened section,
- only ER-EC-5 produced water from all three screened sections, and
- only ER-EC-7 produced most of the water from the lower screened section.

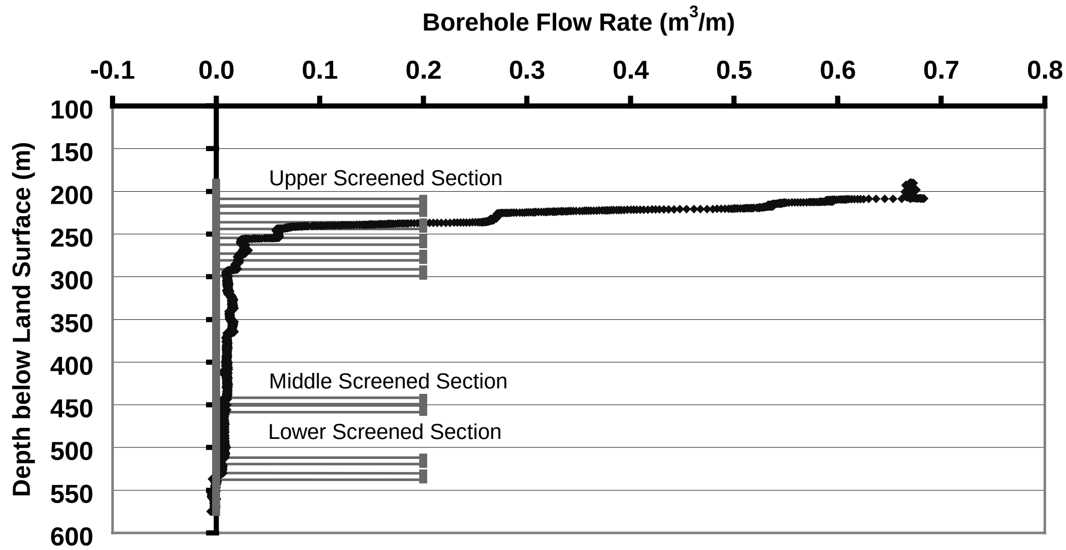

Figure 16. Borehole flow rates while pumping ER-EC-8 at 0.67 m^3/min.

5.0 TEMPERATURE DURING BOREHOLE PUMPING

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 interpretation assumes that the well was in thermal equilibrium 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 outside of the well casing. The temperature during pumping is used to calculate fluid density for fluid pressure estimates.

5.1 ER-EC-1

Fluid temperature while pumping was essentially the same at all three discharge rates. The fluid temperature while pumping at 0.48 m^3/min is presented in Figure 17. Temperature changes with depth in the upper screened section are abrupt and indicate the differing inflow rates and temperatures of the major contributing zones. The nearly constant temperature in the upper three screen joints indicates that these screen sections are in significant hydraulic communication. The numerous temperature inflection points in screen joints 4 through 8 also indicate inflow of groundwater. The nearly linear change in temperature with depth below the upper screened section is consistent with the borehole flow data that indicate minimal borehole flow below the upper screened section.

5.2 ER-EC-2a

Fluid temperature while pumping was essentially the same at all three discharge rates. The temperature in the borehole while pumping at 0.65 m^3/min is presented in Figure 18. The figure indicates sharp changes in fluid temperature at locations where significant quantities of water are entering the well. The upper screened section shows a progressive cooling of water moving up the well bore. This indicates contributions of cool water entering the well and is consistent with the borehole flow log. Screen joint 11 in the upper screened section appears to be contributing more water or cooler water than the screen joints above.

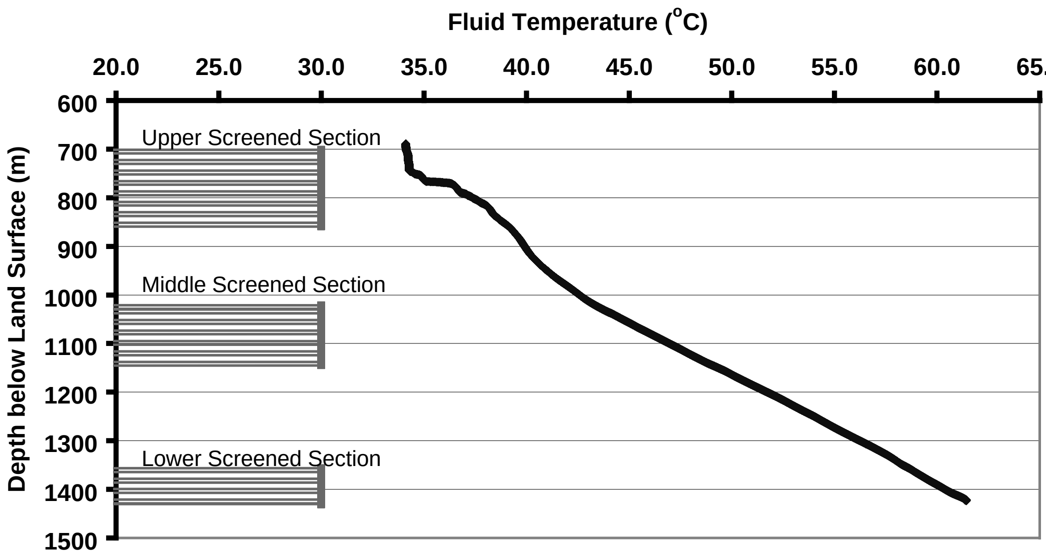

Figure 17. Fluid temperature while pumping ER-EC-1 at 0.48 m^3/min.

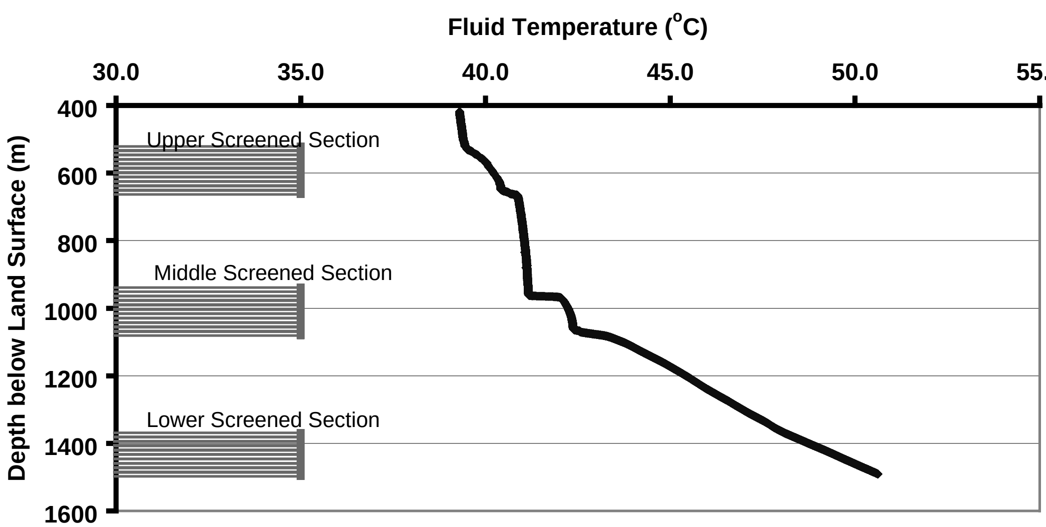

Figure 18. Fluid temperature while pumping ER-EC-2a at 0.65 m^3/min.

The fluid temperature is nearly constant between the middle of the middle screened section and the upper screened section. This is also consistent with the borehole flow data, indicating no significant flow contributions in the upper half of the middle screened section. The sharp change in fluid temperature in the lower portion of the middle screened section is the result of a strong inflow of groundwater from a highly productive zone. Below the middle screened section, the change in fluid temperature with depth is approximately linear, indicating that the only thermal influence is the geothermal gradient and minimal fluid movement during pumping.

5.3 ER-EC-4

Fluid temperature while pumping was essentially the same at all three discharge rates. The temperature of the borehole while pumping at 0.70 m^3/min is presented in Figure 19. The borehole flow log, Figure 12, shows that nearly all of the groundwater inflow is within the upper screened section. However, the temperature log shows no significant temperature changes associated with this groundwater inflow. The temperature log also shows reversals to the trend of increasing temperature with depth. These reversals are located in the middle and lower screened sections and are evident where the temperature becomes cooler for short intervals. There are no corresponding significant groundwater inflows at the locations evident on the borehole flow log.

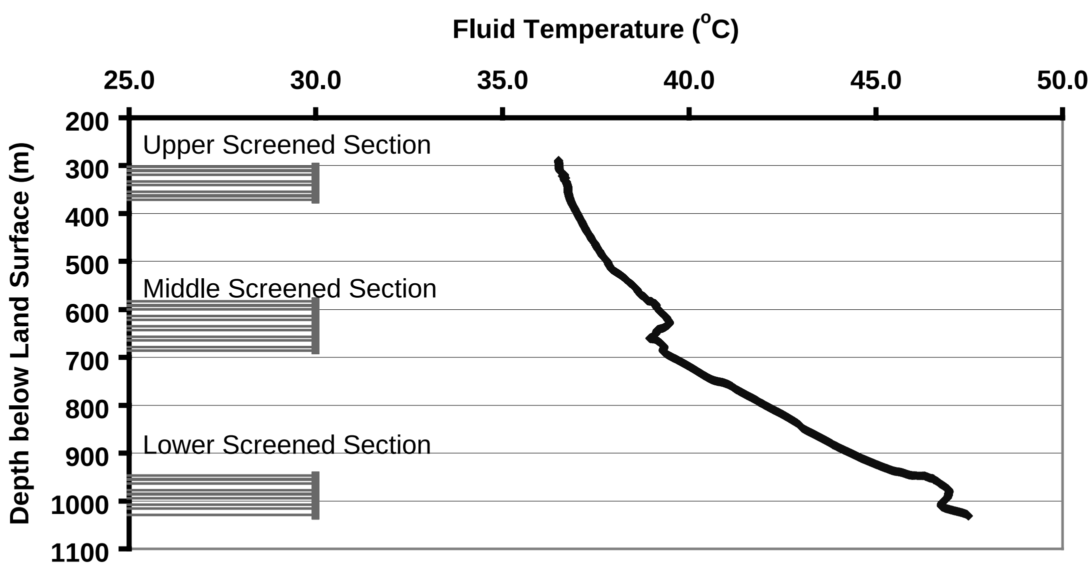

Figure 19. Fluid temperature while pumping ER-EC-4 at 0.70 m^3/min.

5.4 ER-EC-5

Fluid temperature while pumping was essentially the same at all three discharge rates. The fluid temperature while pumping at 0.61 m^3/min is used to represent borehole conditions in Figure 20. The fluid temperature with depth changes most abruptly in the upper three screen joints of the upper screened section. This well is unique among the ER-EC wells in that the fluid temperature is nearly constant with depth during pumping and exhibits less than 0.4°C of temperature change over a distance of 400 m. Other unusual features of this well are that fluid temperatures cooled during pumping and all three screened sections produced significant amounts of water during pumping. The similar temperature during pumping suggests that all three screened sections are intercepting the same source of water.

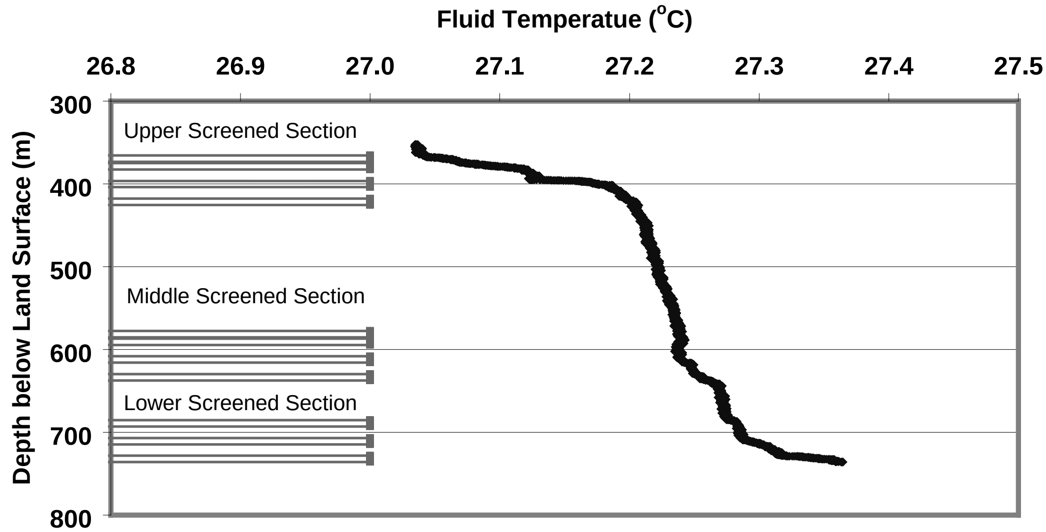

Figure 20. Fluid temperature while pumping ER-EC-5 at 0.61 m^3/min.

5.5 ER-EC-6

Fluid temperature in the well was essentially the same at both pumping rates. The temperature while pumping at 0.26 m^3/min is used to represent borehole conditions in Figure 21. The temperature log indicates a nearly linear temperature change with depth during pumping. There are small "steps" in the temperature profile in screen joints 1 through 3 in the upper screened section where cooler water is entering the well. This is also where almost all of the groundwater enters the well as previously discussed.

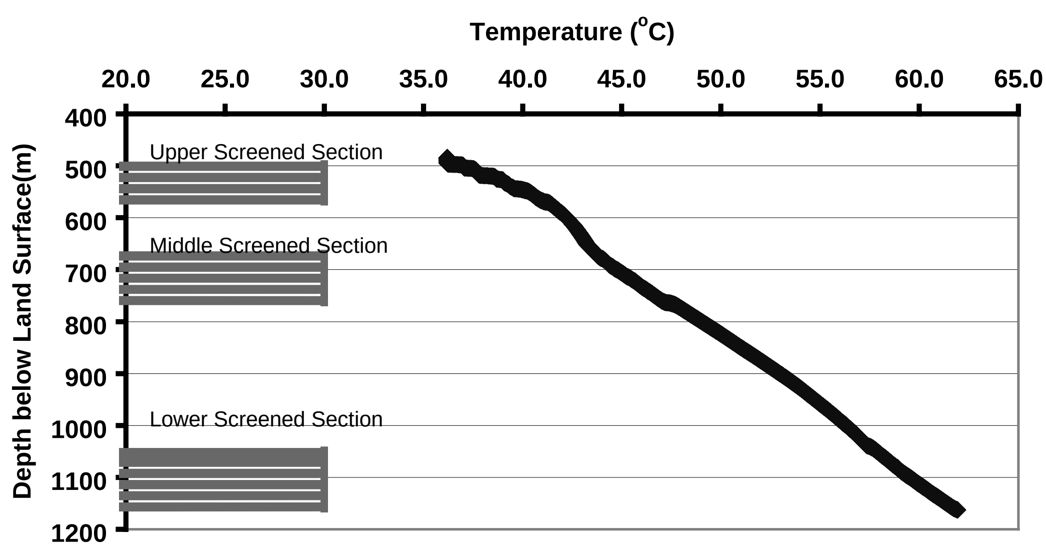

Figure 21. Fluid temperature while pumping ER-EC-6 at 0.26 m^3/min.

5.6 ER-EC-7

The temperature in the well was essentially the same at all three pumping rates. The temperature while pumping at 0.67 m^3/min is used as the representative case in Figure 22. The fluid temperature has a narrow range of only 0.8°C. The fluid temperature cools slightly in the upper screen section where water is entering the well at screen joint 1 and 2. The temperature in the lower screened section indicates that relatively warmer water is entering at screen joint 3. This information is consistent with the borehole flow log.

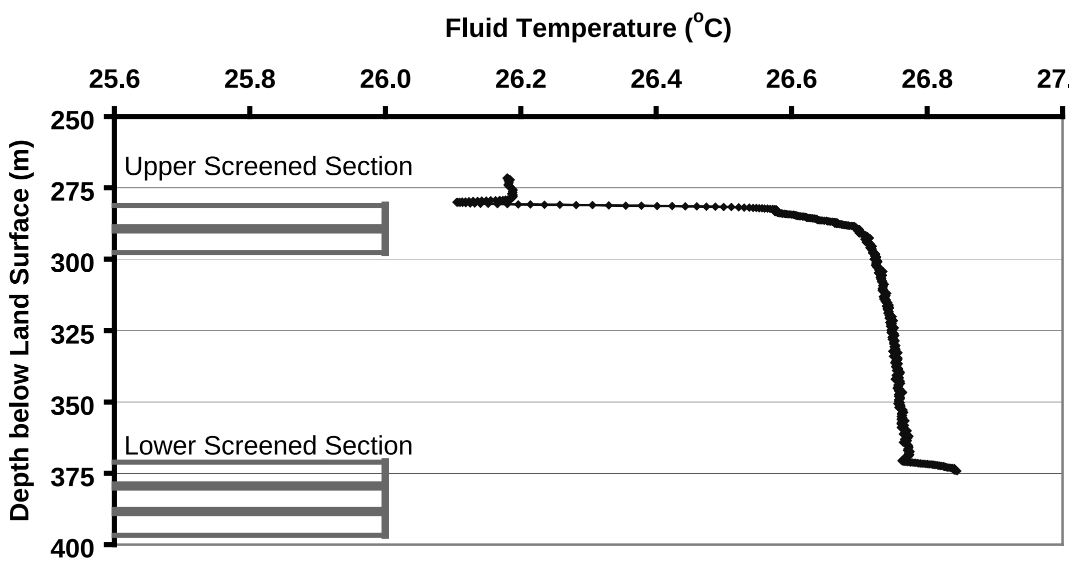

Figure 22. Fluid temperature while pumping ER-EC-7 at 0.67 m^3/min.

5.7 ER-EC-8

Fluid temperature while pumping was essentially the same at all three discharge rates. The fluid temperature in the borehole while pumping at 0.67 m^3/min is used in Figure 23 to represent pumping conditions. The temperature is very uniform, with less than 0.2°C change over a distance of 400 m. The warmest water is entering the well at screen joint 5 in the upper screened section and in screen joint 10 in the lower screened section.

Most groundwater inflow occurs in the upper screened section (screen joints 1 through 4) and is evidenced by the “steps” in the trend of temperature with depth. A relatively cooler zone is located at 400 m and indicates that water in the borehole at this location is affected by groundwater temperature outside the well casing. This result is consistent with the limited production of water from the middle and lower screened sections.

5.8 Summary of Borehole Temperature during Pumping

Fluid temperature in the borehole during pumping can provide supporting information for the interpretation of the borehole flow logs. Observations noted are:

- the temperature change with depth in wells ER-EC-1, ER-EC-2a, ER-EC-5, ER-EC-6, and ER-EC-7 corresponds to changes in the groundwater inflow rates;

- wells ER-EC-4 and ER-EC-8 have fluid temperatures with depth that are more complex in that they have intervals where temperature changes that do not correspond closely with groundwater inflow and where fluid temperature becomes warmer, then cooler then warmer; and
- wells ER-EC-5, ER-EC-7, and ER-EC-8 have temperature changes with depth of less than 1°C, whereas wells ER-EC-1, ER-EC-2a, ER-EC-4, and ER-EC-6 have temperature changes ranging from approximately 10 to 28 °C.

6.0 HYDRAULIC CONDUCTIVITY AT DEPTH

6.1 Minimum Quantification Limit

Variability among the calibrated borehole flowmeter values occurs because of turbulent flow past the flowmeter and changes in the alignment of the flowmeter within the well casing. The calibration for flow measurement is also dependent on the instantaneous correlation between the borehole flowmeter and the changes in logging line speed and the surface flowmeter readings. A lag in response time by the borehole flowmeter would add variability to the calculated borehole flow rates.

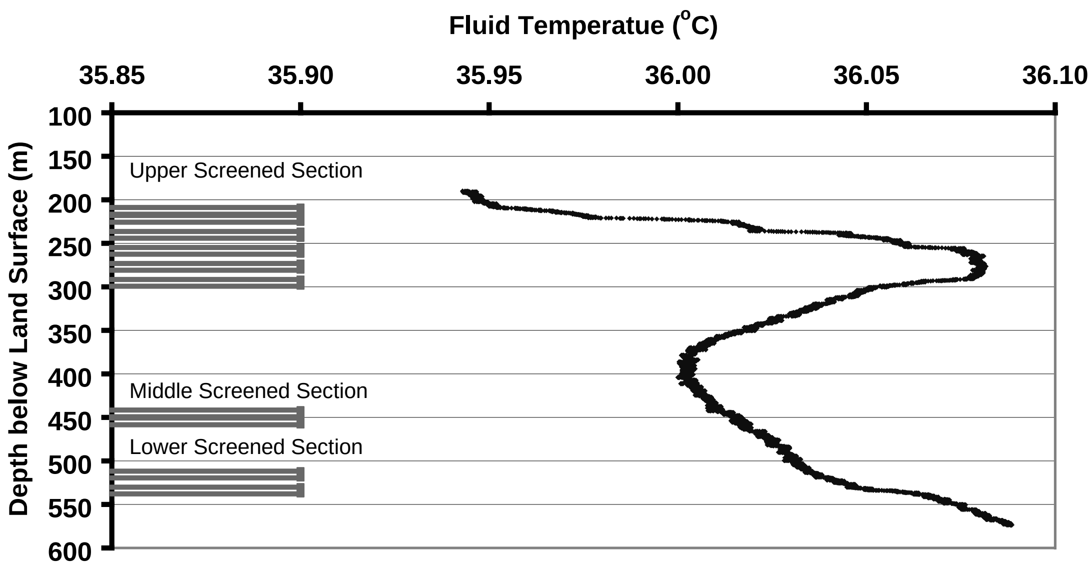

Figure 23. Fluid temperature while pumping ER-EC-8 at 0.67 m^3/min.

The amount of variability or “noise” in the flowmeter readings is also a function of the responsiveness of the flowmeter, which changes with time as the bearings wear, grit enters/exits the bearings, and foreign material such as oil and scale adhere to the impeller. The vertical flow velocity is essentially constant in sections of the well with blank casing, and the apparent borehole flow rate variations are indicative of measurement precision. For the purposes of this report, precision of the borehole flow rate measurements is defined as two standard deviations of the calibrated flow rates in sections of the well with blank casing. The minimum quantification limit is presented in the figures as one standard deviation greater than and one standard deviation less than the mean of zero.

The minimum quantifiable hydraulic conductivity is calculated with Equation (1). Hydraulic conductivity in Equation (1) is a function of pumping rate, storativity, well radius, and drawdown. Pumping rate and storativity are used to calculate the effective hydraulic radius, which is assumed constant during logging. The well radius (distance to formation) is also assumed constant. Drawdown, $h_o - h_n$, varies with depth. Setting the horizontal flux, $q_o - q_n$, equal to the standard deviation of the flow rate in cased sections permits calculation of the minimum quantifiable hydraulic conductivity. Values below this amount are indistinguishable from instrument noise.

Measurement precision is of interest because it has a direct relationship to the minimum quantifiable hydraulic conductivity that can be reliably interpreted from flow logging. The measurement precision of flow rates used to calculate hydraulic conductivities is estimated as flow rate variability measured in the blank casing overlying each screen joint. The length of the cased section used for this evaluation is equal to the length of the slotted portion of the screen joint located immediately below. Where the screen joints are adjacent and separated by only a few feet of blank casing, the measurement precision is defined as a function of the variability standard deviation of flow rate in the blank casing above and below each screened section. These values are applied as a linear trend with depth over the entire screened section.

For example, while pumping ER-EC-6 at 0.26 m^3/min (68 gpm) the standard deviation of borehole flow in the 9.1 m (30 ft) cased section above screen joint number 2 was 0.0012 m^3/min (0.315 gpm). The standard deviation was calculated over an interval ending 1.2 m (4 ft) above the screened section to avoid turbulent flow where groundwater was potentially entering the well. Applying the standard deviation as a change in flow rate in Equation (1) produced a calculated pseudo-hydraulic conductivity of 0.036 m/d (1.43 ft/d). The calculated hydraulic conductivity for the uppermost 0.61 m (2 ft) interval in screen joint number 2 was 1.9 m/day. Because the calculated value was above the minimum quantification limit, the value was included in the analysis. If the calculated hydraulic conductivity had been below 0.036 m/d (1.43 ft/d), the value would have been omitted from further analysis.

The calculated hydraulic conductivities for the 0.61 m (2 ft) calculation intervals are presented for each well in Tables 2 through 8. Only the values greater than the quantification limits are included. Depths are sequential downward, but have gaps where there is blank casing or where the hydraulic conductivity is too low to be quantified. Table 9 presents the average hydraulic conductivity for entire screen joints in the wells. As can be seen in Table 9, averaging over the entire screen lowers the composite hydraulic conductivity to below the screen detection limit in most cases. This illustrates that for most of the ER-EC wells, permeability is provided by discrete features generally smaller than an entire screen joint.

6.1.1 ER-EC-1

The average hydraulic conductivity considering all pumping rates in well ER-EC-1 is illustrated in Figure 24. The four uppermost screen joints of the upper screened section contain nearly all of the detected permeability. The vertical length of this permeable zone is about 70 m. The limited extent of the permeable zone causes only 27 of the 268 hydraulic conductivity calculation intervals to be above the minimum quantification limit of 11.2 to 24.8 m/d.

Table 2. Hydraulic conductivity values for well ER-EC-1.

Interval Top (m)	Interval Bottom (m)	Average Hydraulic Conductivity (m/d)*
701.7	702.3	77.7
702.3	702.9	161.1
702.9	703.5	88.0
703.5	704.1	68.4
704.1	704.8	61.4
704.8	705.4	41.0
706.0	706.6	27.3
706.6	707.2	43.2
707.2	707.8	43.6
707.8	708.4	30.3
708.4	709.0	33.3
723.2	723.8	53.7
723.8	724.4	61.6
724.4	725.1	27.6
744.7	745.4	60.2
745.4	746.0	86.7
746.0	746.6	108.6
746.6	747.2	52.2
747.2	747.8	15.5
749.6	750.2	19.7
750.8	751.5	32.5
751.5	752.1	28.8
766.8	767.4	30.2
767.4	768.0	16.6
788.8	789.4	13.4
1,404.4	1,405.0	20.1
1,421.5	1,422.1	23.5

*Values less than the quantification limit are omitted.

Table 3. Hydraulic conductivity values for well ER-EC-2a.

Interval Top (m)	Interval Bottom (m)	Average Hydraulic Conductivity (m/d)*
521.0	521.6	0.5
521.6	522.2	0.9
522.2	522.9	0.6
522.9	523.5	0.5
531.4	532.0	0.2
534.7	535.4	0.4
535.4	536.0	0.3
536.0	536.6	0.3
539.6	540.2	0.2
547.8	548.4	0.4
548.4	549.0	0.3
549.0	549.6	0.3
549.6	550.2	0.3
550.8	551.4	0.3
554.5	555.1	0.2
561.5	562.1	0.4
562.1	562.7	0.3

Table 3. Hydraulic conductivity values for well ER-EC-2a. (continued).

Interval Top (m)	Interval Bottom (m)	Average Hydraulic Conductivity (m/d)*
570.6	571.3	0.4
573.9	574.5	0.5
574.5	575.2	0.4
575.2	575.8	0.3
587.0	587.6	0.4
587.6	588.2	0.3
588.2	588.8	0.2
588.8	589.4	0.3
600.1	600.7	0.3
600.7	601.3	0.3
601.3	601.9	0.3
610.5	611.1	0.3
613.1	613.7	0.4
613.7	614.4	0.4
616.8	617.4	0.2
626.8	627.4	0.3
627.4	628.0	0.2
628.0	628.6	0.4
639.9	640.5	0.3
640.5	641.1	0.3
649.7	650.3	0.2
652.3	652.9	0.2
652.9	653.6	0.6
653.6	654.2	0.3
655.4	656.0	0.4
939.1	939.8	0.3
939.8	940.4	0.6
940.4	941.0	0.4
941.0	941.6	0.7
952.9	953.5	0.3
959.6	960.2	0.2
960.2	960.8	0.3
961.4	962.0	0.2
962.0	962.6	0.3
962.7	963.3	0.9
964.7	965.3	1.3
965.3	965.9	0.5
966.5	967.1	0.2
999.4	1,000.0	0.2
1,063.5	1,064.1	0.2
1,064.1	1,064.7	0.3
1,064.7	1,065.3	0.2
1,065.3	1,065.9	0.2
1,071.7	1,072.3	0.2
1,470.3	1,470.9	0.3
1,476.6	1,477.2	0.4
1,480.3	1,480.9	0.2
1,489.7	1,490.4	0.3

*Values less than the quantification limit are omitted.

Table 4. Hydraulic conductivity values for well ER-EC-4.

Interval Top (m)	Interval Bottom (m)	Average Hydraulic Conductivity (m/d)*
302.2	302.8	92.3
302.8	303.4	88.1
311.3	311.9	99.4
311.9	312.5	133.0
313.8	314.4	59.2
314.4	315.0	49.0
315.5	315.6	49.2
315.6	316.2	74.7
317.4	318.0	60.1
318.0	318.6	168.2
318.6	319.2	141.4
332.8	333.5	148.0
333.5	334.1	183.3
334.1	334.7	97.8
340.2	340.8	74.0
354.4	355.0	87.3
355.0	355.6	122.7
355.6	356.3	54.0
681.8	682.4	66.2

*Values less than the quantification limit are omitted.

Table 5. Hydraulic conductivity values for well ER-EC-5.

Interval Top (m)	Interval Bottom (m)	Average Hydraulic Conductivity (m/d)*
365.5	366.1	27.6
366.1	366.7	17.9
368.5	369.1	17.8
369.1	369.7	15.5
369.7	370.3	11.7
374.8	375.5	12.9
380.3	380.9	47.6
396.4	397.0	46.4
397.0	397.6	20.1
398.2	398.8	14.5
398.8	399.4	12.7
417.9	418.5	12.5
418.5	419.1	8.5
584.8	585.4	12.1
587.3	588.0	18.3
588.0	588.6	28.0
588.6	589.2	32.9
589.2	589.8	27.6
589.8	590.4	28.2
590.4	591.0	37.8
591.0	591.6	30.5
591.6	592.2	14.5
592.2	592.8	16.0

Table 5. Hydraulic conductivity values for well ER-EC-5 (continued).

Interval Top (m)	Interval Bottom (m)	Average Hydraulic Conductivity (m/d)*
593.4	594.1	21.6
594.0	594.6	24.7
608.3	608.9	35.6
608.9	609.5	27.0
609.5	610.1	31.6
610.1	610.7	37.9
610.7	611.3	45.0
611.3	611.9	28.4
611.9	612.5	11.4
613.7	614.4	10.3
614.4	615.0	20.3
615.0	615.6	27.8
615.5	616.1	48.3
629.8	630.4	14.5
630.4	631.0	15.4
631.0	631.6	10.1
632.2	632.8	12.4
632.8	633.4	15.4
633.4	634.0	9.1
634.7	635.3	11.6
635.3	635.9	9.0
636.5	637.1	17.0
637.0	637.6	26.1
685.3	685.9	18.5
685.9	686.5	15.9
692.4	693.1	13.3
714.0	714.6	11.4
728.9	729.5	13.8
732.6	733.2	23.4
734.4	735.0	31.0

*Values represent the upper and lower screened sections.

Table 6. Hydraulic conductivity values for well ER-EC-6.

Interval Top (m)	Interval Bottom (m)	Average Hydraulic Conductivity (m/d)*
497.1	497.7	15.3
497.7	498.3	15.4
498.3	498.9	1.8
503.8	504.4	0.8
504.3	504.9	3.3
518.6	519.3	1.8
519.3	519.9	1.5
568.9	569.5	0.7

*Values less than the quantification limit are omitted.

Table 7. Hydraulic conductivity values for well ER-EC-7.

Interval Top (m)	Interval Bottom (m)	Average Hydraulic Conductivity (m/d)*
281.1	297.7	2.8
371.7	396.8	14.8

*Values represent the upper screened section and the upper two screen joints of the lower screened section.

Table 8. Hydraulic conductivity values for well ER-EC-8.

Interval Top (m)	Interval Bottom (m)	Average Hydraulic Conductivity (m/d)*
208.7	209.3	28.0
209.3	209.9	26.9
209.9	210.6	12.1
210.6	211.2	10.6
211.8	212.4	6.1
212.4	213.0	10.2
213.0	213.6	17.0
213.6	214.2	16.6
219.7	220.3	9.8
220.3	220.9	18.1
220.9	221.5	34.3
221.5	222.1	36.2
222.1	222.7	21.2
222.7	223.4	17.6
223.4	224.0	17.6
224.0	224.6	11.3
224.6	225.2	14.9
225.2	225.8	11.8
236.3	236.9	14.0
236.9	237.5	22.8
237.5	238.1	24.5
238.1	238.7	20.3
238.7	239.3	14.8
239.3	239.9	17.1
239.9	240.5	18.9
240.5	241.2	15.6
241.2	241.8	9.2
241.8	242.4	7.5
243.6	244.2	4.6
254.6	255.2	7.3
255.2	255.8	10.8
255.8	256.5	12.3
256.5	257.1	6.9
274.3	274.9	2.8
291.3	291.9	6.4
291.9	292.5	6.4
512.9	513.5	5.7
517.8	518.4	6.0
532.4	533.0	5.2

*Values less than the quantification limit are omitted.

Table 9. Average hydraulic conductivity for individual screen joints.

Screen Joint (uppermost)	ER-EC-1 (m/d)	ER-EC-2a (m/d)	ER-EC-4 (m/d)	ER-EC-5 (m/d)	ER-EC-6 (m/d)	ER-EC-7 (m/d)	ER-EC-8 (m/d)
1	47.0	*	*	*	2.9	2.8	8.2
2	*	*	57.3	*	*	2.8	15.7
3	33.2	*	*	*	*	14.8	13
4	*	*	*	*	*	14.8	*
5	*	*	*	*	*		*
6	*	*	*	20.8	*		*
7	*	*	*	24.4	*		*
8	*	*	*	11.3	*		*
9	*	*	*	*	*		*
10	*	*	*	*	*		*
11	*	*	*	*	*		*
12	*	*	*		*		
13	*	*	*		*		
14	*	*	*		*		
15	*	*	*		*		
16	*	*	*		*		
17	*	*	*				
18	*	*					
19	*	*					
20		*					
21		*					
22		*					
23		*					
24		*					
25		*					
26		*					
27		*					
28		*					
29		*					
30		*					
31		*					
32		*					

*Value below the screen joint quantification limit

Note: these values are the average hydraulic conductivity over the entire screened interval and includes zeros for locations below the detection limit

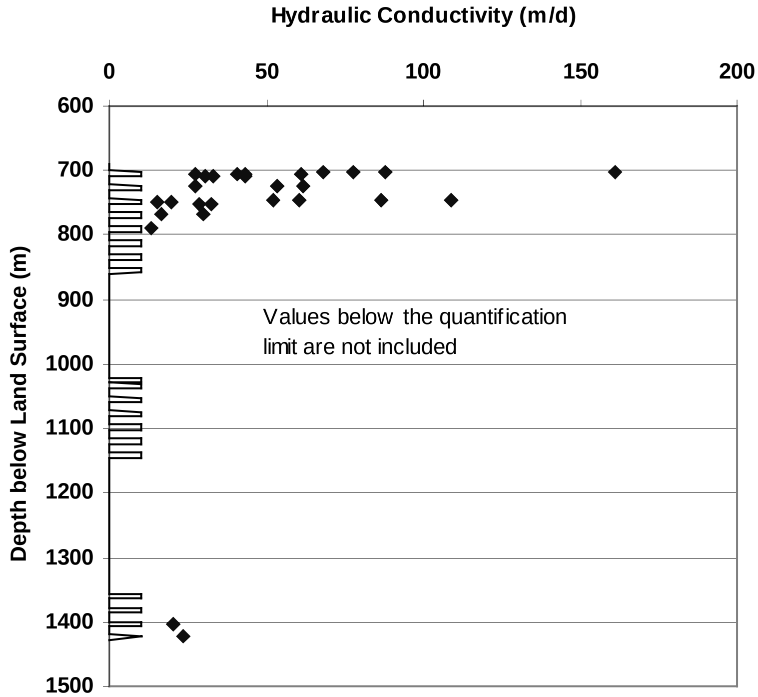

Figure 24. Hydraulic conductivity with depth at well ER-EC-1.

Calculated hydraulic conductivities have a maximum value of 183m/d. The maximum hydraulic conductivity is calculated from 0.6 to 1.2 m below the top of screen joint 1 in the upper screened section. This suggests that the flow is associated with a natural feature and is not flow moving down the overlying filter pack and entering the well at the top of the well screen. The lower portion of the upper screened section and the entirety of the middle and lower screened sections produced almost no water during pumping and have hydraulic conductivities below the quantification limit.

The statistical frequency of the average log hydraulic conductivities calculated for all pumping rates is presented in Figure 25. Low values of hydraulic conductivity have been removed from the analysis by the application of the minimum quantification limit.

6.1.2 ER-EC-2a

The average hydraulic conductivity considering all pumping rates in well ER-EC-2a is illustrated in Figure 26. The higher permeability values are located within the upper and middle screened sections. The lower screened section is contributing only slightly to the well discharge.

The upper screened section contains similar hydraulic conductivities varying only slightly between 0.2 and 0.6 m/d. Many of the calculated hydraulic conductivity values in the upper screened section are less than 0.2 m/d, and just below the minimum quantification limit. The quantification limits are approximate for this well because the screen joints are adjacent, which does not allow computation of the quantification limit above each screen joint. Therefore, the quantification limit is calculated only at the top and bottom of the screened section and applied as a linear function across the screened section.

The statistical frequency of the average log hydraulic conductivities calculated for all pumping rates is presented in Figure 27. Low values of hydraulic conductivity have been removed from the analysis by the application of the minimum quantification limit. The figure also represents only 66 of the 610 hydraulic conductivity calculation intervals to be above the minimum quantification limit of 0.18 to 0.04 m/d.

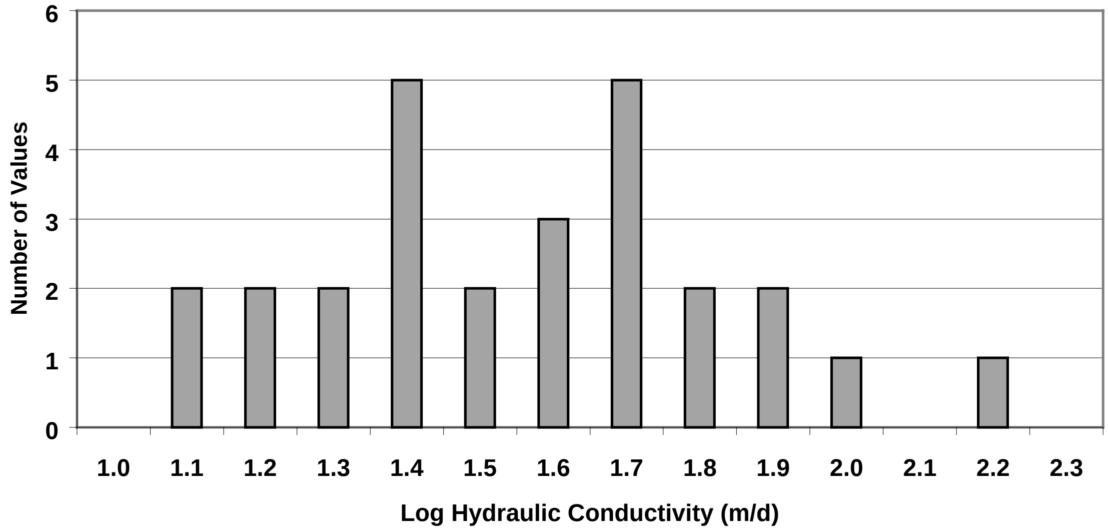

Figure 25. Histogram of ER-EC-1 log hydraulic conductivity.

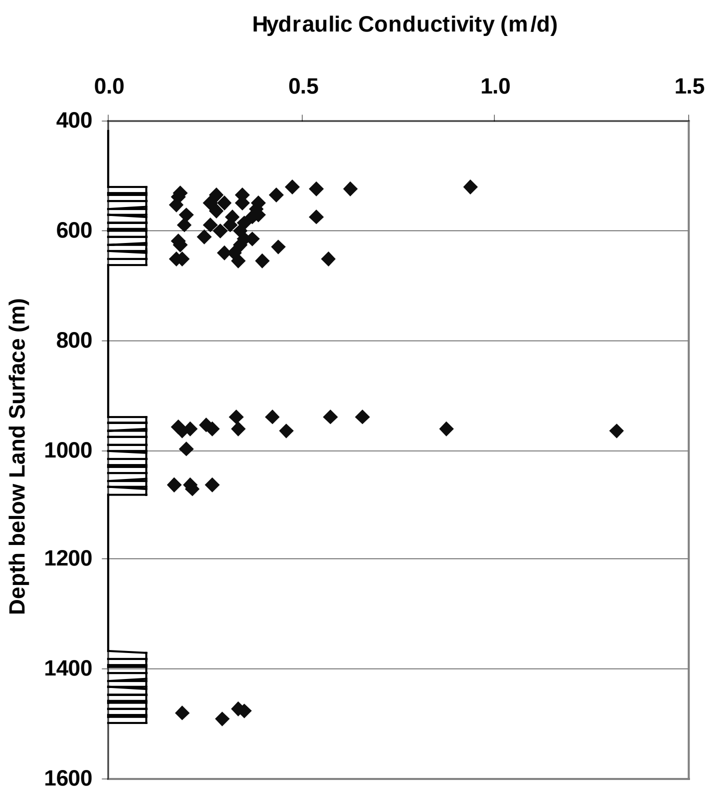

Figure 26. Hydraulic conductivity with depth at well ER-EC-2a.

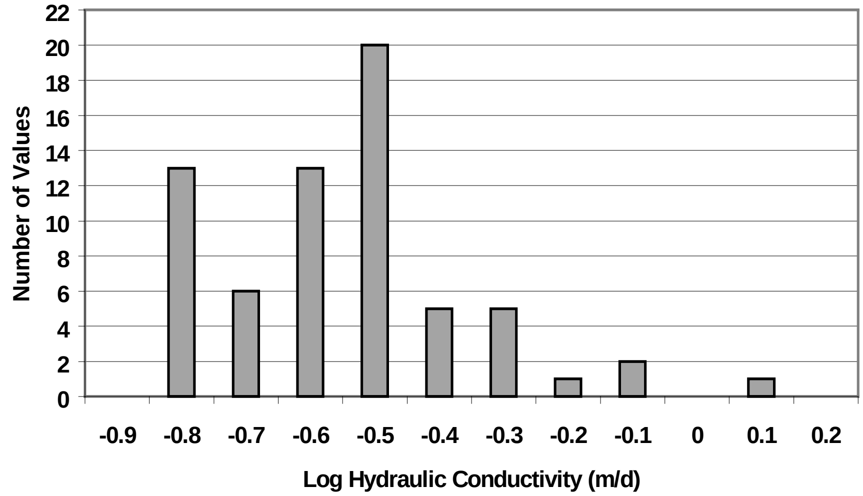

Figure 27. Histogram of ER-EC-2a log hydraulic conductivity.

6.1.3 ER-EC-4

The average hydraulic conductivity considering all pumping rates in well ER-EC-4 is illustrated in Figure 28. The upper screened section contains most of the detected permeability at well ER-EC-4. Calculated hydraulic conductivities in the upper screened section have a high value of 168.2 m/d.

The statistical frequency of the average log hydraulic conductivities calculated for all pumping rates is presented in Figure 29. Low values of hydraulic conductivity have been removed from the analysis by the application of the minimum quantification limit. The figure also represents only 19 of the 218 hydraulic conductivity calculation intervals to be above the minimum quantification limit of about 49 to 230 m/d.

6.1.4 ER-EC-5

The average hydraulic conductivity considering all pumping rates in well ER-EC-5 is illustrated in Figure 30. The middle screened section, having screen joints 5 through 8, contains most of the permeability. Calculated hydraulic conductivities in the middle screened section have a highest value of 48.3 m/d. The upper and lower screened sections have hydraulic conductivities above the quantification limit of about 20 m/d.

The statistical frequency of the average log hydraulic conductivities calculated for all pumping rates is presented in Figure 31. Low values of hydraulic conductivity have been removed from the analysis by the application of the minimum quantification limit. The figure also represents only 53 of the 148 hydraulic conductivity calculation intervals to be above the minimum quantification limit of about 8.0 to 13.0 m/d.

6.1.5 ER-EC-6

The average hydraulic conductivity considering all pumping rates in well ER-EC-6 is illustrated in Figure 32. The upper screened section, specifically screen joints 1 and 2, contains nearly all of the detected permeability. The maximum hydraulic conductivity in the upper screened section is 15.4 m/d. This value is calculated for the interval from 0.0 to 0.6 m below the top of screen joint 1. This may indicate that some of the groundwater inflow is accumulated from the filter-packed interval extending above the well screen.

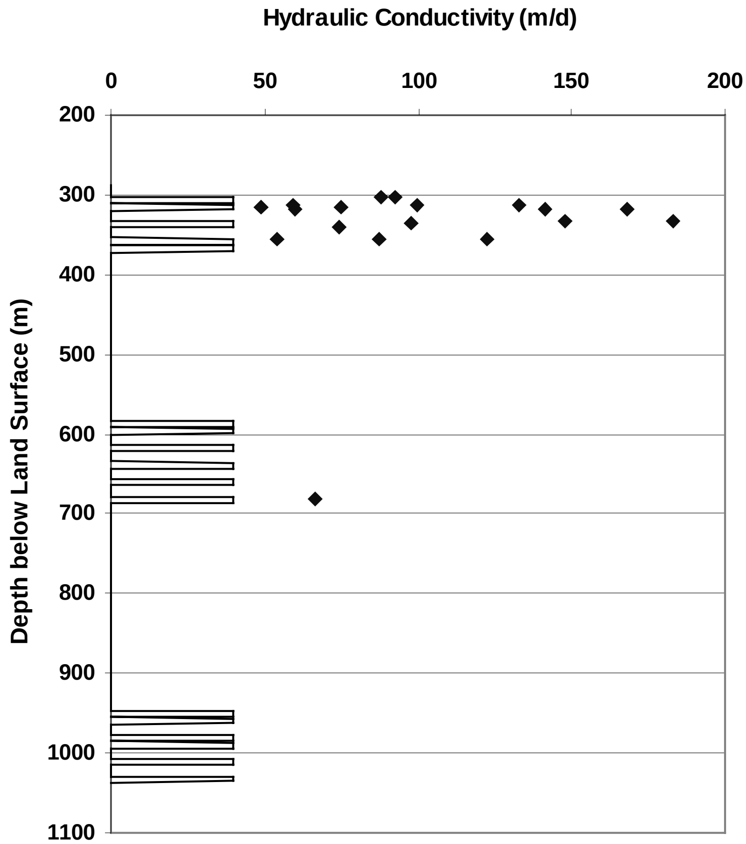

Figure 28. Hydraulic conductivity with depth in well ER-EC-4.

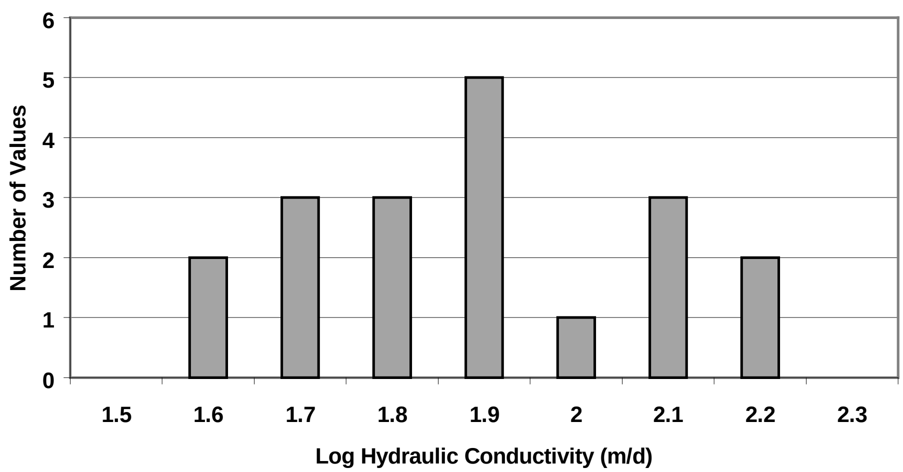

Figure 29. Histogram of ER-EC-4 log hydraulic conductivity.

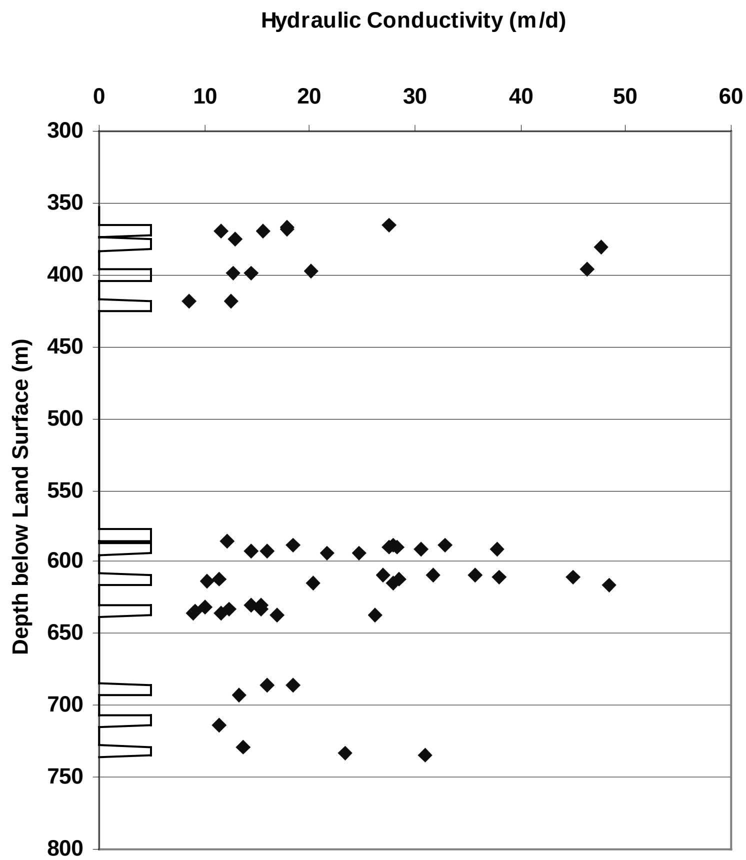

Figure 30. Hydraulic conductivity with depth in well ER-EC-5.

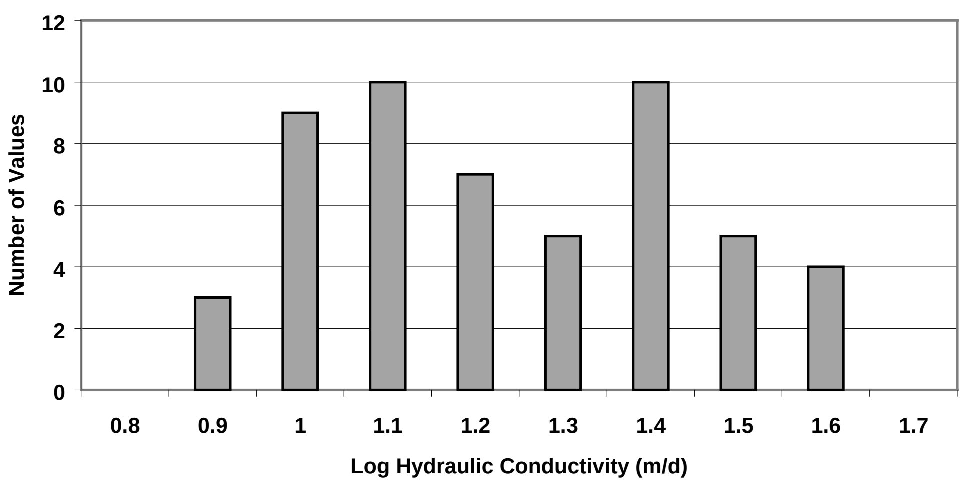

Figure 31. Histogram of ER-EC-5 log hydraulic conductivity.

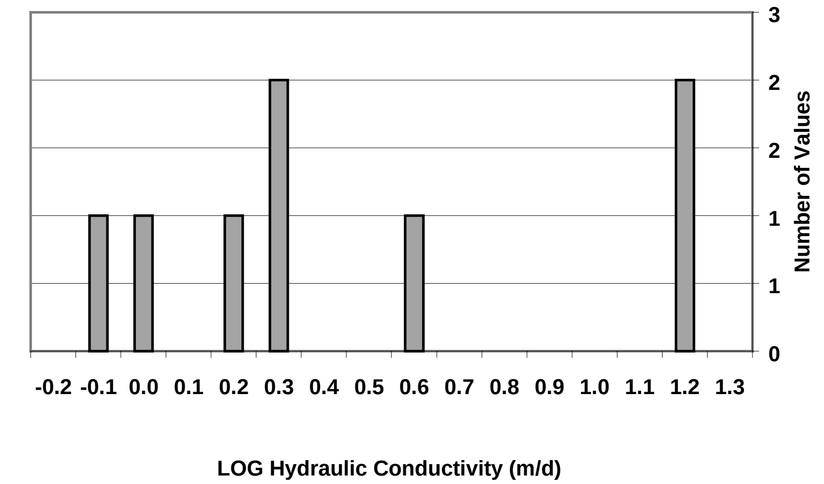

Figure 32. Hydraulic conductivity with depth in well ER-EC-6.

The lower portion of the upper screened section and the entirety of the upper middle and lower middle screened sections produced almost no water during pumping and have no hydraulic conductivities above the quantification limit of about 0.5 m/d.

The statistical frequency of the average log hydraulic conductivities calculated for all pumping rates is presented in Figure 33. Low values of hydraulic conductivity have been removed from the analysis by the application of the minimum quantification limit. The figure also represents only 8 of the 208 hydraulic conductivity calculation intervals to be above the minimum quantification limit of about 1.4 to 0.5 m/d.

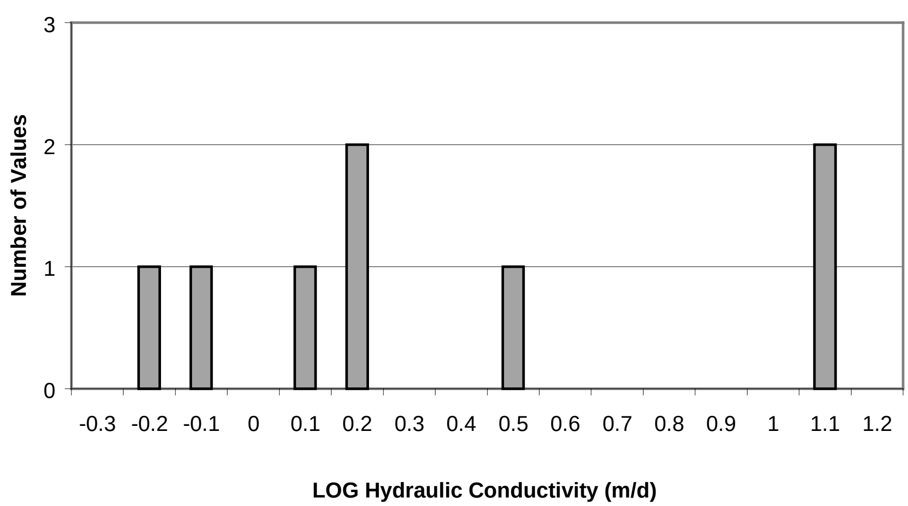

Figure 33. Histogram of ER-EC-6 log hydraulic conductivity.

6.1.6 ER-EC-7

The average hydraulic conductivity considering all pumping rates in well ER-EC-2a is illustrated in Figure 34. Because of the apparent flow diversion outside of the casing, the hydraulic conductivity is calculated only at the scale of the upper and lower screened sections using a simplified technique developed by Molz *et al*, (1989). The lowermost screen (screen joint

5) is omitted from the hydraulic conductivity calculation because it contains detritus and is not believed to be contributing water to the well. The percentage of flow from the upper and lower screened sections is uniform at all flow rates. The hydraulic conductivity for the upper screened section is calculated at 2.8 m/d and for the lower screened section at 14.8 m/d.

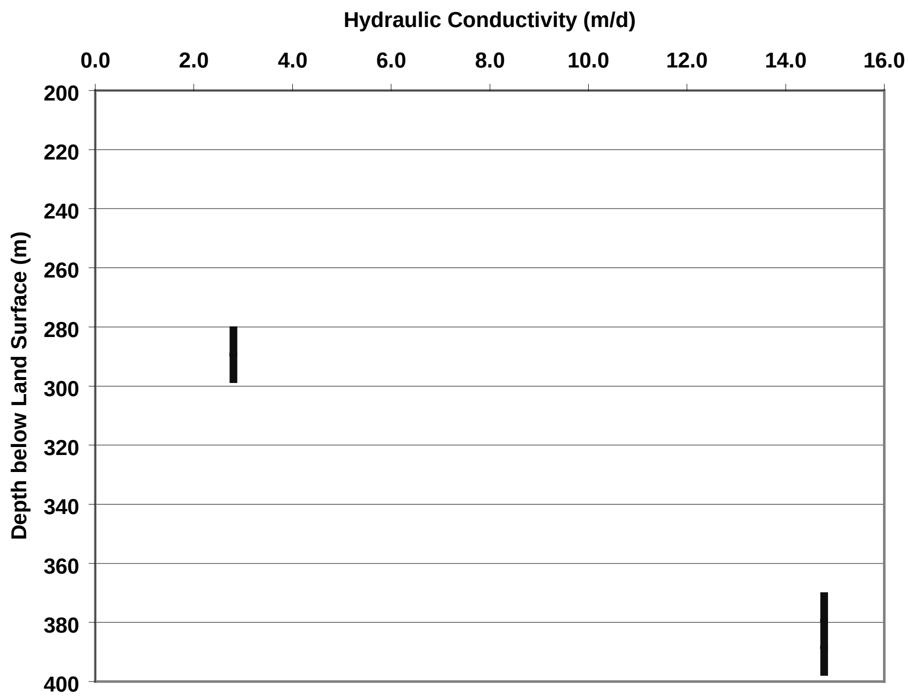

Figure 34. Hydraulic conductivity with depth in well ER-EC-7.

6.1.7 ER-EC-8

The average hydraulic conductivity considering all pumping rates in well ER-EC-8 is illustrated in Figure 35. The three uppermost screen joints of the upper screened section contain most of the detected permeability. Calculated hydraulic conductivities in the upper screened section have a highest value of 36.2 m/d. The middle and lower screened sections have average calculated hydraulic conductivities generally less than the minimum quantification limit of about 4.0 m/d.

The statistical frequency of the average log hydraulic conductivities calculated for all pumping rates is presented in Figure 36. Low values of hydraulic conductivity have been removed from the analysis by the application of the minimum quantification limit. The figure also represents only 38 of the 130 hydraulic conductivity calculation intervals to be above the minimum quantification limit of about 4.0 m/d.

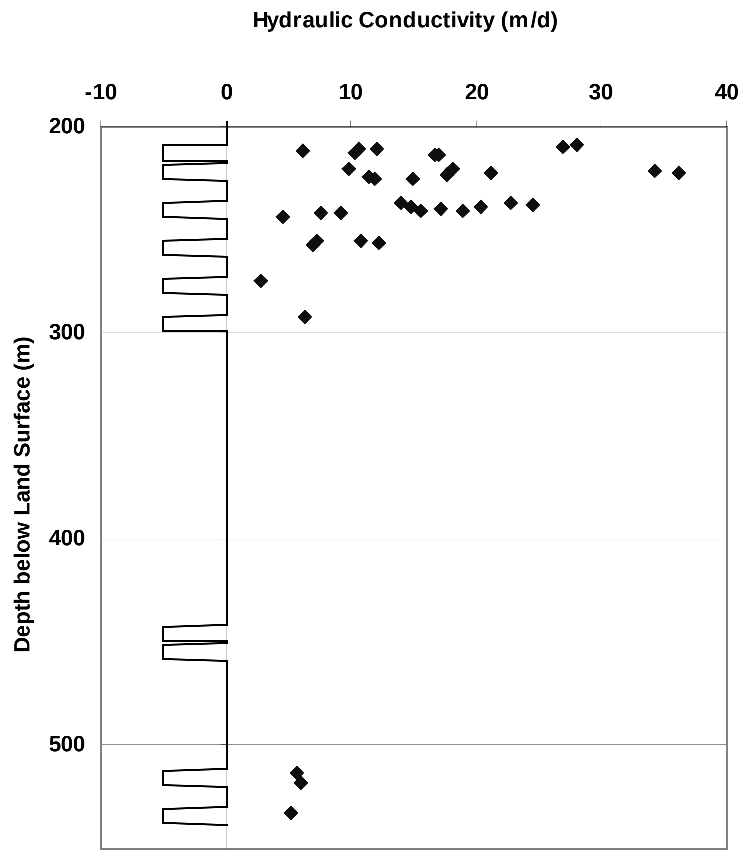

Figure 35. Hydraulic conductivity with depth in well ER-EC-8.

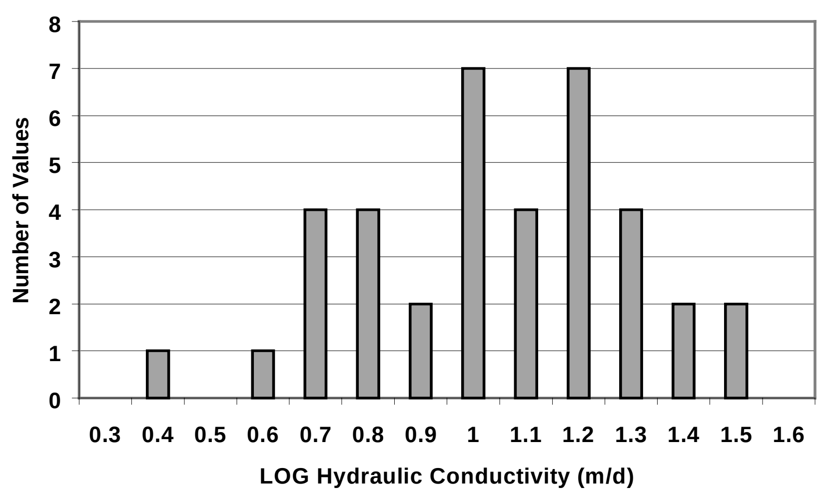

Figure 36. Histogram of ER-EC-8 log hydraulic conductivity.

6.2 Association of Hydraulic Conductivity and Lithology

The hydraulic conductivity values presented above are sorted by lithology. The lithology types and depths were provided by IT Corporation (Jeffery Wurtz, personal communication, 4-30-01). Table 10 provides the length of detectable hydraulic conductivity placed into lithologic bins for each well.

Table 10. Occurrence of detectable hydraulic conductivity by lithology.

Well	Tuff (m)	Lava (m)	Flow Breccia (m)
ER-EC-1	0.6	14.0	1.8
ER-EC-2a	40.2	-	-
ER-EC-4	0.6	11.0	-
ER-EC-5	32.3	-	-
ER-EC-6	-	4.9	-
ER-EC-7	-	7.9	23.2
ER-EC-8	23.2	-	-

The frequency of occurrence for hydraulic conductivity sorted by lithology is presented below. These figures do not represent the entire spectrum of hydraulic conductivities that actually occur in the ER-EC wells for the following reasons:

- the minimum value that is quantifiable is a function of flowmeter performance and the lag time for the borehole flowmeter response, which varies as a function of borehole flow rate and also spatially within each screen joint, and
- the minimum quantifiable value is also a function of discharge rate that varies widely for each well and the fluid pressure change during pumping, which is estimated based on flow and temperature conditions within the well,

Therefore, for each well, the range of hydraulic conductivity represents the maximum values downward to variable minimum values. In composite, given the different pumping rates and fluid pressure changes during pumping, detected portions of the full statistical frequency of hydraulic conductivities may be illustrated. Well ER-EC-7 is screened across several lithologies in the upper and lower screened sections. The apparent borehole flow diversion outside of the casing prevented calculation of hydraulic conductivities for intervals smaller than an entire screened section. Therefore, hydraulic conductivity cannot be assigned to a specific lithology for well ER-EC-7.

The hydraulic conductivities for tuff lithology are presented in Figures 37 and 38. Figure 37 illustrates that each well has hydraulic conductivity values that range over a portion of the range of values detected for tuff. The number of occurrences for well ER-EC-2a is truncated at 10 in the figure to allow visualization of the other values. Figure 38 presents these data in composite. The figure indicates that there are only a few occurrences of hydraulic conductivity above 40 m/d with many occurrences between 10 and 20 m/d. Only well ER-EC-2a was able to detect hydraulic conductivities at the low end of the range because of the well's large amount of drawdown.

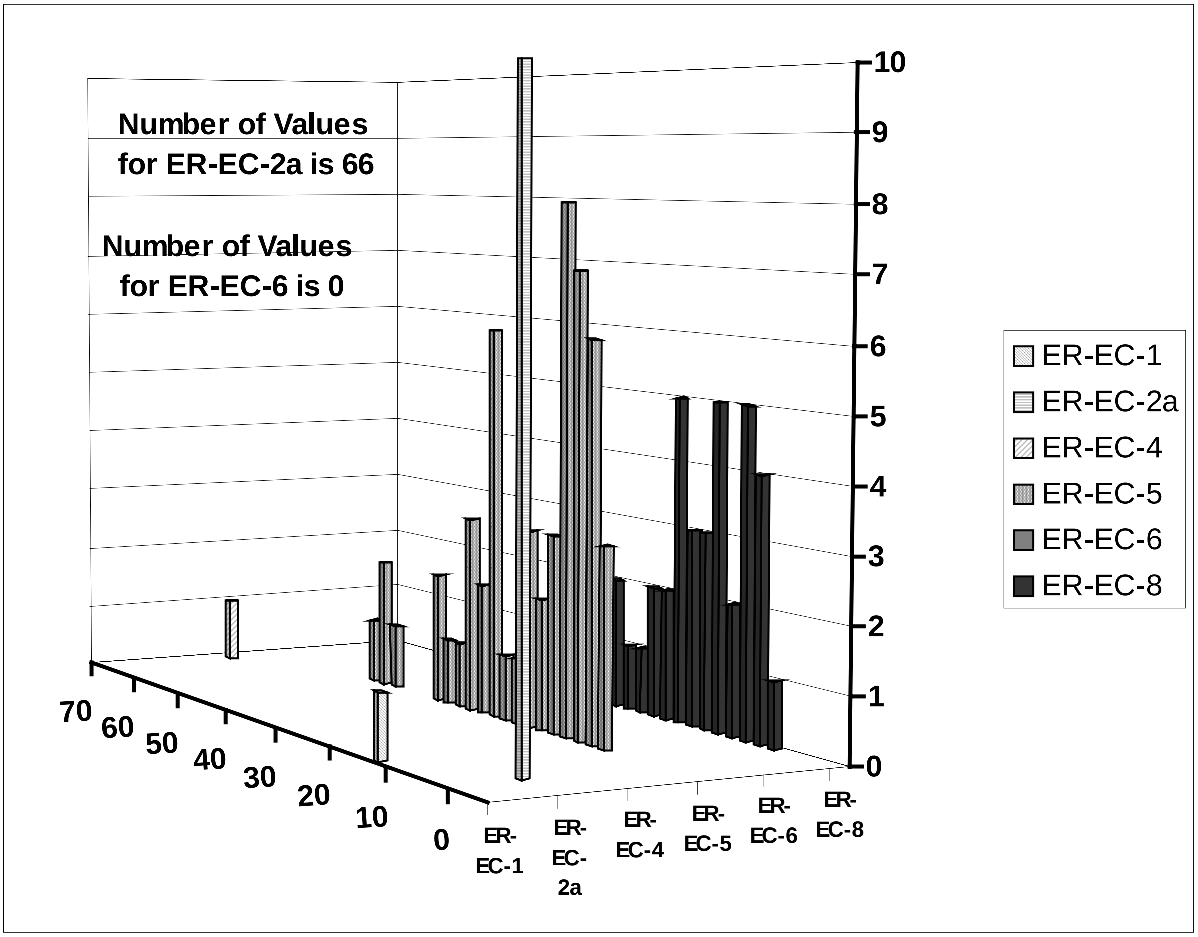

Figure 37. Histogram of log hydraulic conductivity for tuff lithology showing individual wells.

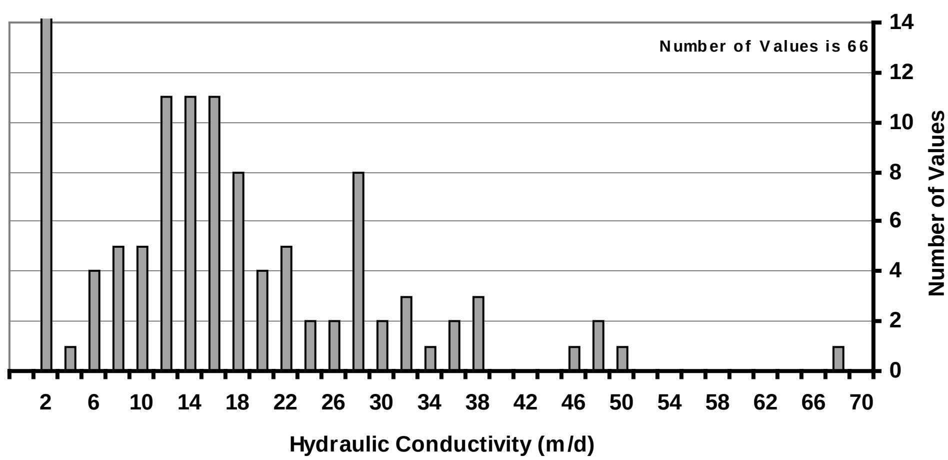

Figure 38. Summary histogram of log hydraulic conductivity for tuff lithology.

The hydraulic conductivities for lava lithology are presented in Figures 39 and 40. The figures include only the three wells where there are quantifiable hydraulic conductivities for this lithology. The values for lava are higher than for tuff and reach a maximum of over 183.3 m/d with most of the values between 100 and 10 m/d. Again, it should be noted that the number of values at the low end of the hydraulic conductivity range is under-represented because values less than the quantification limit are omitted. There are only three values of hydraulic conductivity that can be assigned to flow breccia. These values occur in well ER-EC-1 and are 30.2, 20.0, and 16.6 m/d.

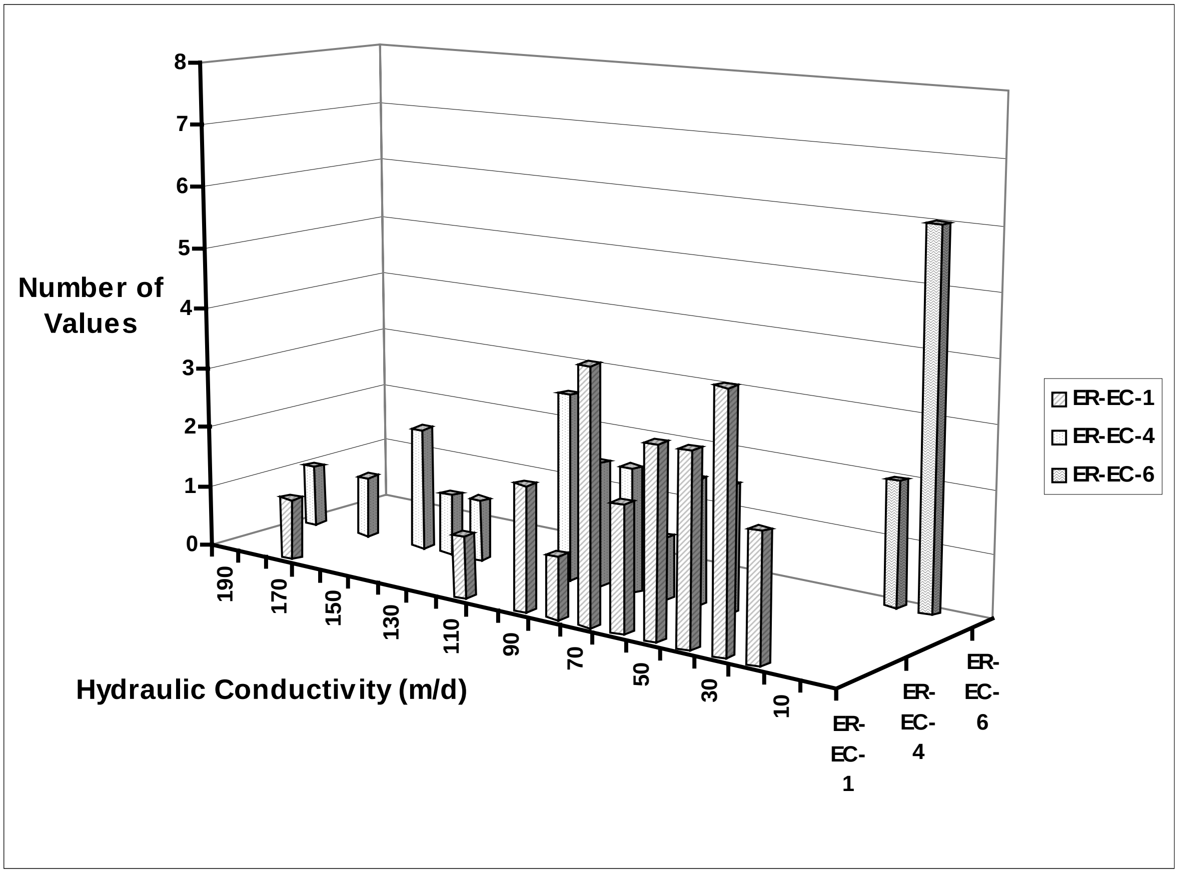

Figure 39. Histogram of log hydraulic conductivity for lava lithology showing individual wells.

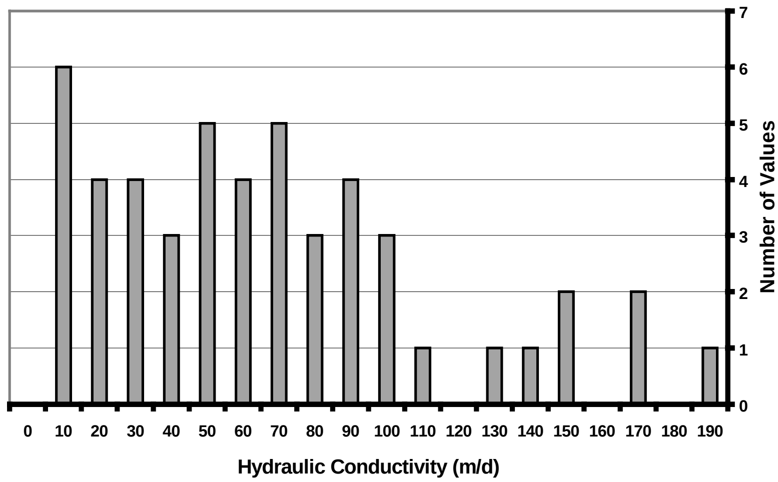

Figure 40. Histogram of log hydraulic conductivity for lava lithology.

7.0 SUMMARY AND CONCLUSIONS

Borehole flow logging contributes a greater understanding of subsurface conditions than measuring well discharge only at land surface. Combining the results of up to nine borehole flow logs to estimate hydraulic conductivity with depth includes data averaging over vertical intervals and averaging of calculated hydraulic conductivities among the various flow logs. Data filtering is also necessary to aid in differentiating between changes in borehole flow rate due to flow turbulence (and other causes) and those associated with groundwater inflow. The results provided are believed to be an appropriate balance between predictive accuracy and preserving spatial resolution. Indeed, there is a continuum between calculating the average hydraulic conductivity for an entire well (i.e., high degree of certainty and low spatial resolution), and attempting to assign a hydraulic conductivity to small intervals based on small changes in flow (i.e., rate low degree of certainty and high spatial resolution). Considering long intervals for hydraulic conductivity estimation loses the resolution contained in the borehole flow data. The ER-EC wells demonstrate that the majority of groundwater inflow occurs over intervals much smaller than individual screen joints. This report has strived to preserve this information and assign hydraulic conductivities to these discrete features. A benefit to this approach is that a more complete statistical distribution is provided of hydraulic conductivities within a well and for various lithologies.

Borehole flow logging during well pumping has provided the quantity of groundwater inflow and hydraulic conductivity at depth for seven ER-EC wells. The groundwater inflow zones that contribute the most groundwater and that have the highest hydraulic conductivity can be found in the upper, middle, and lower screened sections. No discernible relationship is demonstrated between hydraulic conductivity and depth. The upper screened section produced the largest portion of groundwater inflow for four of the seven wells ER-EC-1, ER-EC-4, ER-EC-6, and ER-EC-8. The upper screened section contributed at least some of the groundwater inflow for wells ER-EC-2A, ER-EC-5, and ER-EC-7. The middle and lower screened sections produced little or no groundwater inflow except for wells ER-EC-5 and ER-EC-7, which produced most of their water from the middle and lower screened sections, respectively.

Most of the 61-cm test intervals within the screened casing have hydraulic conductivities below the detection threshold. Groundwater inflow measurements within 974 m (3,194 ft) of screened casing contained only 160 m (784 ft) where the hydraulic conductivity was sufficiently large to be quantifiable. Most of the detected hydraulic conductivity occurred in a tuff lithology with a composite vertical length of 97 m (318 ft) having a maximum hydraulic conductivity of 66 m/d (217 ft/d). Testing in a lava lithology produced detectable hydraulic conductivities over a composite vertical interval of 38 m (124 ft) having a maximum hydraulic conductivity of 183 m/d (600 ft/d). There were only 1.8 m (6 ft) of flow breccia having detectable hydraulic conductivity and these averaged 22 m/d (72 ft/d).

8.0 REFERENCES

CRC, 1987, Handbook of Chemistry and Physics, The Chemical Rubber Company, Cleveland, Ohio.

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

Freeze, R.A. and J.A. Cherry, 1979, Groundwater, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

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.

IT (International Technology Corp.), 1999, Well Development and Hydraulic Testing Plan for Western Pahute Mesa - Oasis Valley Wells, ITLV/13052-086.

IT (International Technology Corp.), 2000a, Western Pahute Mesa - Oasis Valley Well ER-EC-1 Data Report for Development and Hydraulic Testing, April 2000.

IT (International Technology Corp.), 2000b, Western Pahute Mesa - Oasis Valley Well ER-EC-6 Data Report for Development and Hydraulic Testing, April 2000.

IT (International Technology Corp.), 2000c, Western Pahute Mesa - Oasis Valley Well ER-EC-7 Data Report for Development and Hydraulic Testing, July 2000.

IT (International Technology Corp.), 2000d, Western Pahute Mesa - Oasis Valley Well ER-EC-5 Data Report for Development and Hydraulic Testing, August 2000.

IT (International Technology Corp.), 2000e, Western Pahute Mesa - Oasis Valley Well ER-EC-8 Data Report for Development and Hydraulic Testing, August 2000.

IT (International Technology Corp.), 2000f, Western Pahute Mesa - Oasis Valley Well ER-EC-2a Data Report for Development and Hydraulic Testing, September 2000.

IT (International Technology Corp.), 2000g, Western Pahute Mesa - Oasis Valley Well ER-EC-4 Data Report for Development and Hydraulic Testing, September 2000.

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.

Lyles, B. F., 1994, Increased thermal-pulse flowmeter resolution by adding a packer and computer. *Ground Water Monitoring and Remediation*, Fall Issue.

Molz, F.J., R.H. Morin, A.E. Hess, J.G. Melville and O. Guven, 1989, The impeller meter for measuring aquifer permeability variations: Evaluation and comparison with other tests, *Water Resources Research*, 25(7):1677-1683.

Oberlander, P.L., 1989, Fluid density and gravitational variations in deep boreholes and their effect on fluid potential, *Ground Water*, 27(3):341-350.

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.

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