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HYDROGEOLOGIC PROPERTIES OF THE BANDELIER TUFF AND GROUNDWATER OCCURRENCE AT DP MESA, TA-21, LOS ALAMOS NATIONAL LABORATORY, LOS ALAMOS, NM

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ABSTRACT

Hydrologic properties for the unsaturated zone are needed by the Los Alamos Environmental Restoration Project for site assessments. Three deep boreholes were drilled and sampled at TA-21 and two boreholes were drilled in DP Canyon to support characterization activities. Samples collected from the Bandelier Tuff from the deep boreholes were analyzed for saturated hydraulic conductivity, bulk density, and water content versus pressure head. These data were fitted the van Genuchten water retention function and the parameters were summarized by geologic unit. Two fitting approaches were used, one used the measured values for the saturated water content and the other used the saturated water content as a fitting parameter. Comparisons of the parameters revealed that on an individual sample there could be significant differences between the two fitting approaches, but for the mean parameter values by geologic unit, the largest difference was in the residual water content. Saturated conditions were found in DP Canyon, and this water is hypothesized as the source of DP Spring. The gravimetric water contents measured during drilling for the hole at MDA-V indicated no saturation in this region of DP Mesa which indicated that the perched zone found in the Guaje Pumice in Los Alamos Canyon does not penetrate laterally for this distance beneath TA-21.

INTRODUCTION

The Los Alamos National Laboratory Environmental Restoration (ER) Project is charged with characterizing, assessing, and, if necessary, remediating potentially contaminated sites throughout the Laboratory and surrounding areas impacted by past Laboratory operations. The ER Project has divided the Laboratory and surrounding area into Operable Units (OU) and Resource Recovery and Conservation Act (RCRA) Facility Investigations plans are prepared for each OU. OU 1106 is the TA-21 or DP Site at Los Alamos (Figure 1). The RCRA facility Investigation Plan was written for TA-21 in 1991 (LANL 1991). Field investigations have been ongoing since that time.

Understanding the groundwater pathway is part of the TA-21 characterization and assessment activities and is essential to make decisions relative to remediation. As part of the characterization activities, holes are drilled or augured to obtain samples for chemical and hydrologic characterization and/or to determine the occurrence of groundwater. The information and data from these samples are used in the pathways analyses to estimate risk to human health and the environment for the site.

This report will present the hydrologic data for the Bandelier Tuff from three boreholes at TA-21 and the occurrence of groundwater in these boreholes and in two boreholes in DP Canyon which forms the northern border to TA-21. The hydrologic data will be used in assessments at TA-21 by the ER Project. The occurrence of groundwater at TA-21 is important because it represents a potential

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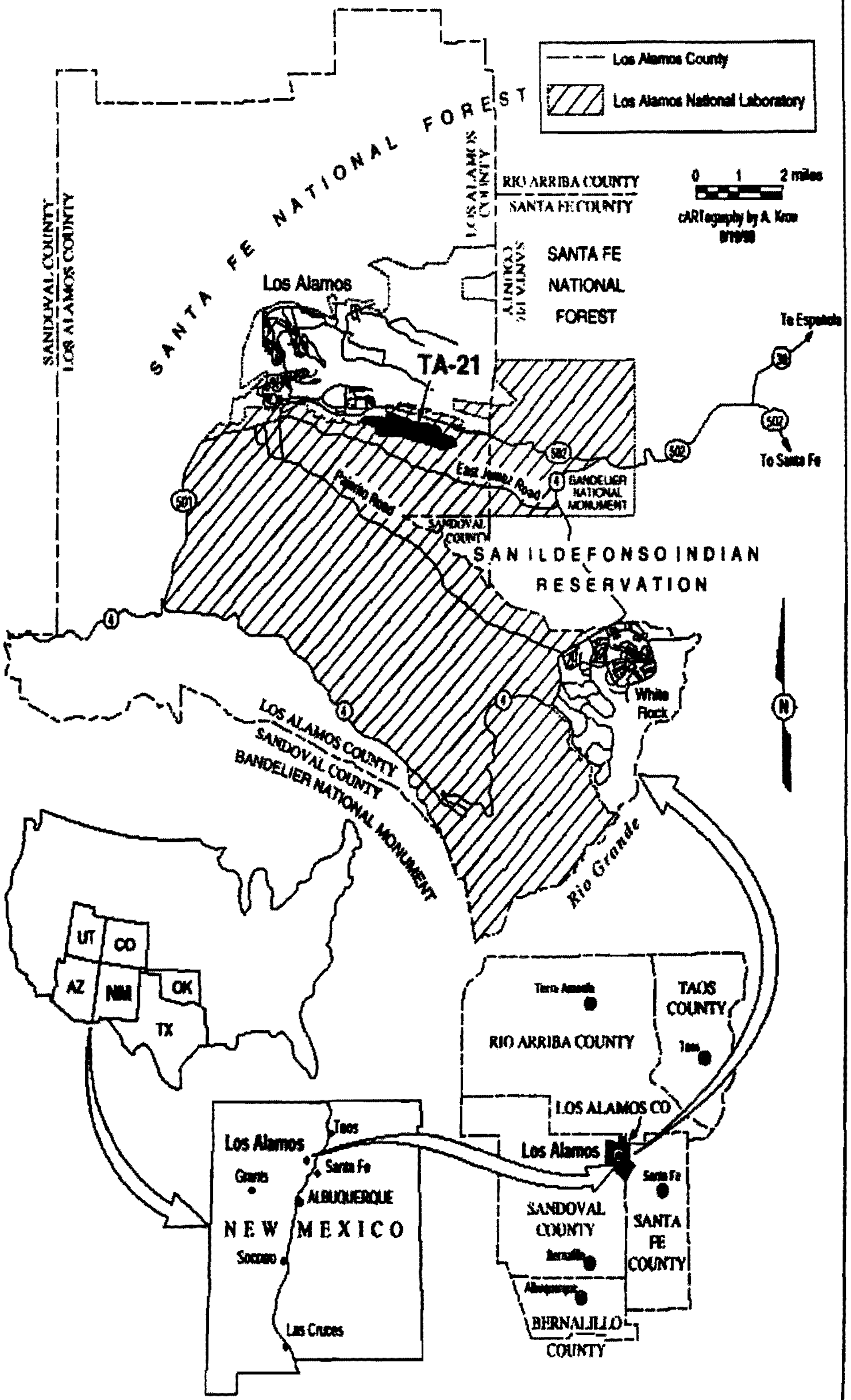

Figure 1. Location of TA-21.

pathway where saturated rather than unsaturated flow conditions exist. The groundwater in DP Canyon may also be the source of water for DP Spring (Broxton and Eller, 1995).

An excellent description and discussion of the geology of TA-21 are presented by Broxton and Eller (1995), and this hydrogeologic report should be viewed as an extension of their work.

The Bandelier Tuff comprises approximately the upper 183 m (600 ft.) of DP Mesa at TA-21. The tuff was deposited by a series of volcanic eruptions with the last eruption occurring approximately 1 million years ago. The stratigraphy of the Bandelier Tuff using the nomenclature of Broxton and Reneau (1995) is given in Figure 2. For this report, samples were collected from the Tshirege and Otowi Members of the Bandelier Tuff. Single samples were taken from the vapor phase notch unit and the Guaje Pumice. The intervening unit between the Tshirege and Otowi is the Cerro Toledo which is quite complicated because of its depositional history. The fine-scale bedding and large cobbles in the Cerro Toledo make hydrologic characterization of this unit difficult because of sample recovery problems and sufficient sampling to represent the large-scale variation of these types of depositional environments. Therefore, no hydrologic data or properties are presented for the Cerro Toledo interval in this report.

The conceptual hydrologic model for the Pajarito Plateau is given in reports by Davis et al. (1996) and the Los Alamos Hydrogeologic Workplan (LANL 1998). The conceptual model recognizes an unsaturated zone, groundwater in the alluvial channel material in some canyon bottoms, intermediate perched zones that may occur in any geologic unit, and the regional aquifer. At TA-21, the regional aquifer is located 305 m to 244 m (1000 ft to 800 ft) below the ground surface. That intermediate perched zones can occur in any geologic unit at TA-21 is demonstrated by DP Spring which emanates from the Tshirege Member of the Bandelier Tuff. Broxton and Eller (1995) reported the drilling results for LADP-3 where perched water was found in the Guaje Pumice Bed. Alluvial groundwater is found in Los Alamos Canyon which forms the southern border of TA-21. DP Canyon forms the northern border of TA-21, and results of investigations for alluvial groundwater in DP Canyon are given in this report.

METHODS

Boreholes

Data were obtained from three boreholes drilled at TA-21. The borehole logs for LADP-3 and LADP-4 were described in Broxton and Eller (1995). LADP-3 is located in Los Alamos Canyon (Figure 3), and begins in alluvium and then penetrates the Otowi Member of the Bandelier Tuff. All but one of the samples used in this report from LADP-3 were from the Otowi and the other sample is from the Guaje Pumice Bed. LADP-4 was located on a sideslope of DP Canyon (Figure 3). Samples were collected from units 2, 1v, and 1g of the Tshirege member, and the Otowi from LADP-4. LADP-4 did penetrate the Puye Formation, but no samples were taken from this unit. The third hole is the MDA-V Deep Hole (MDAVDH) which is located east of MDA-V (Figure 3). The borehole log for MDAVDH was done by Wohlentz (1996, personal comm.). MDAVDH was cored over its first 97.6 m (320 ft) and rotary drilled with air through the base of the Guaje Pumice Bed. Samples were collected from units 3, 2, 1v, and 1g of the Tshirege Member and one sample came from the vapor phase notch which is the boundary between units 1v and 1g.

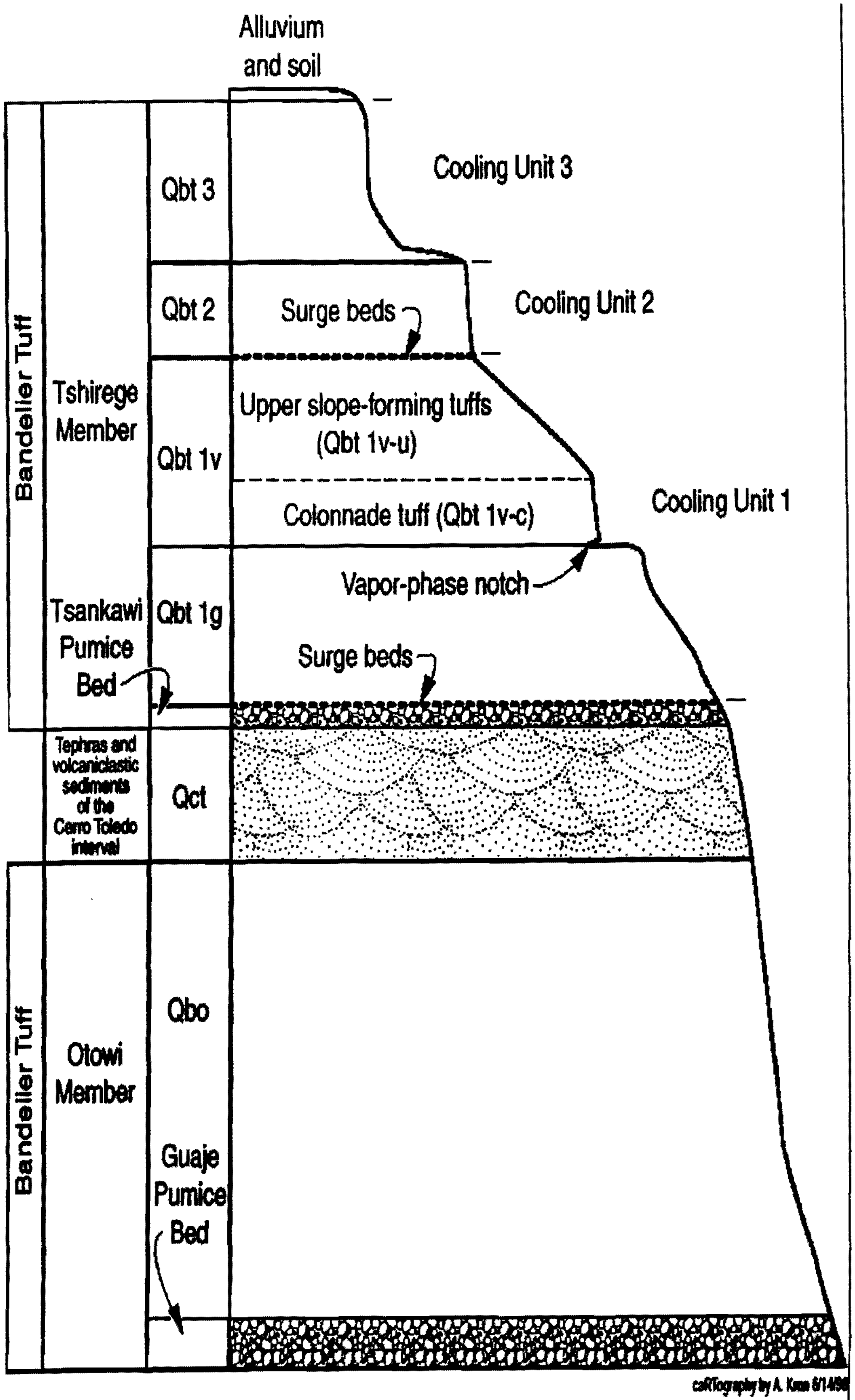

Figure 2. Stratigraphy at TA-21 from Broxton and Reneau (1995).

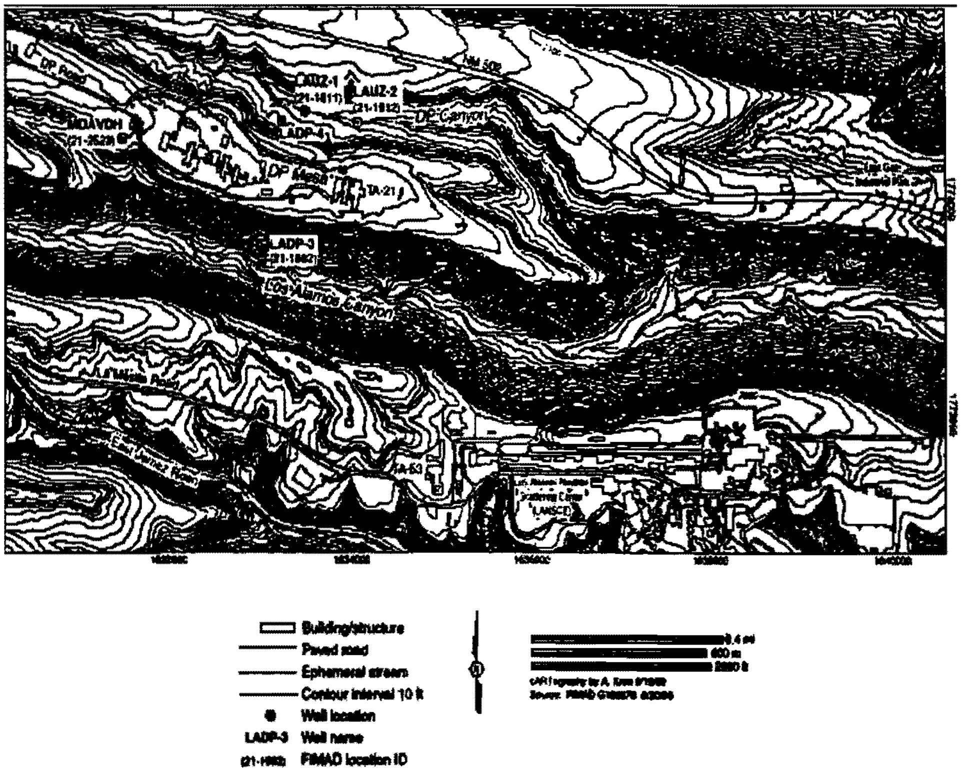

Figure 3. Location of boreholes at TA-21 that were used in this report.

Two boreholes, LAUZ-1 and LAUZ-2, were placed in DP Canyon (Figure 3) to investigate alluvial water. Two holes were drilled at the LAUZ-1 site. The first hole was outside the channel and did not intercept alluvial water. The second hole is the current LAUZ-1 hole which did intercept alluvial water. Only the current LAUZ-2 hole was drilled at that site. Neither LAUZ-1 or LAUZ-2 were cored so no samples for hydrologic parameters were taken. The only hydrologic test on these holes was measuring the recovery of the water after each hole was bailed.

Core samples from LADP-3, LADP-4, and MDAVDH were shipped to Daniel B. Stephens and Associates in Albuquerque, NM for characterization of hydrologic flow properties. The measured properties were saturated hydraulic conductivity using both constant and falling head techniques, bulk density (ρ_b), porosity (ϕ) from bulk density, water content versus pressure head using either hanging column, pressure plate or thermocouple psychrometer techniques depending on the magnitude of the pressure.

Data Analyses

The water content and pressure head data were fitted to the van Genuchten (1980) moisture characteristic equation using the computer code RETC (van Genuchten et al., 1991). The water retention relation is described by:

$$S_e = \theta - \theta_r / \theta_s - \theta_r = 1/\left[1 + (\alpha h)^n\right]^m \quad (1)$$

Where: S_e = the effective saturation;
θ = the volumetric water content (cm^3 / cm^3);
θ_r = the residual volumetric water content (cm^3 / cm^3);
θ_s = the saturated volumetric water content (cm^3 / cm^3);
h = pressure head (cm);
α = fitting parameter (cm^{-1}); and

n, m = fitting parameters with m= 1 – 1/n.

The change in hydraulic conductivity with water content is described by the following equation when m = 1-1/n:

$$k(S_e) = k_s S_e^{\ell}\left[1-(1-S_e^{1/m})^m\right]^2 \qquad (2)$$

Where: k_s = the saturated hydraulic conductivity (cm/s); and
ℓ = pore-connectivity parameter (set to 0.5 in this report).

Analyses of Bandelier Tuff hydraulic properties by Rogers and Gallaher (1995) used Equations 1 and 2. The limited number and difficulty of obtaining values for unsaturated hydraulic conductivity means that the parameters from Equation 1 are used to estimate the unsaturated conductivity curve using Equation 2 and a matching factor which is commonly k_s. van Genuchten and Nielsen (1985) demonstrated the importance that the slope of the water retention curve near saturation had on predicted hydraulic conductivity over the entire range of conductivity values. Subsurface transport calculations which are one of the products of a pathways analysis are very sensitive to the value used for hydraulic conductivity. Traditionally, θ_s has been fixed at the value of the porosity, and the remaining parameters θ_r, α, and n were estimated. van Genuchten and Nielsen (1985) presented a rationale that any model such as Equation 1 obscures the description of the water content at saturation leaving the definition of θ_s model dependent. To examine the effect of estimating θ_s on the Bandelier Tuff hydrologic properties, two parameter fittings were performed, one set estimated θ_s θ_r, α, and n, and the second set used the measured water content at a pressure head of 0.0 for θ_s and θ_r, α, and n were fitted. Comparisons of the parameters from the two fittings are made below.

The behavior of the air phase at Los Alamos is important because of the movement of organic vapors from waste sites and as suggested by Weeks (1987), airflow can evaporate water from rocks reducing the potential for liquid waste transport of contaminants with depth. Air phase permeability was estimated again using Equation 1 using the relationships from Parker et al. (1987). For a two-phase system consisting of air and water the relative hydraulic conductivity is:

$$k_{ra} = CS_a^{0.5}\left[1-S_w^{1/m}\right]^{2m} \qquad (3)$$

Where: k_{ra} = relative hydraulic conductivity of the air phase;
S_w = effective saturation of the water phase;
S_a = air phase saturation ($1-S_w$); and
C = gas slippage correction factor.

The value for C was set at 1.0 for the analyses reported here. Parameters were taken from Equation 1 fits to predict the k_{ra} curve for comparison to the water phase relative conductivity curve.

RESULTS

Data

Appendix 1 contains the values for bulk density (ρ_b), porosity, and k_s measured in the laboratory and the estimates for θ_s θ_r, α, and n obtained by the RETC fits to the θ versus h data for the samples in Appendix 2. Table 1-1 contains the parameters for the case where θ_s was estimated and Table 1-2 contains the estimated parameters when the measured value of θ_s is used. Sample identification information, depth, water content, and pressure head values are given in Appendix 2.

Data analyses

Statistics for the parameters are presented by geologic unit in Tables 1 – 5 for the parameter set where θ_s was fitted and in Tables 7 – 11 for the estimated parameters using the measured values for θ_s.

There are some general issues for both sets of parameters to be considered. Limited sample sizes for all units, but in particular Tshirege Member units 1v (n = 9) and 1g (n = 6) are a concern for application of these data. One possible solution is to pool data from Los Alamos such as those presented in Rogers and Gallaher (1995) with the data presented here to increase sample size. A statistical analysis is needed to determine if these samples are from the same population and if they can be pooled. One problem with pooling data is that changes in the depositional environment in the Bandelier Tuff as you move from west to east and perhaps north to south may introduce a deterministic trend in the hydrologic properties. For example, Griggs (1964) noted that the Tshirege Member of the Bandelier Tuff was more intensely welded on the western margin of the Pajarito Plateau. Welding can lead to decreases in porosity and matrix permeability. Crowe et al. (1978) discussed the importance of welding and cooling units on the hydrologic properties of the Bandelier Tuff and in particular depositional features which change with distance from the source. Different measurement techniques to determine Bandelier Tuff hydrologic properties curve also restrict pooling of data from different studies.

Table 1. Descriptive Statistics for hydrologic properties using fitted θ_s values from Unit 3, Tshirege Member Bandelier Tuff at TA-21, Los Alamos, NM (number of samples=12).

Variable	Mean	Standard Deviation	Median	Minimum	Maximum
ρ_b (g/cm**3)	1.30	0.08	1.28	1.17	1.45
θ_s	0.36	0.03	0.366	0.31	0.41
Porosity	0.51	0.03	0.52	0.45	0.56
k_s (cm/sec)	4.7*10**-4	9.0*10**-4	1.9*10**-4	2.0*10**-5	3.3*10**-3
Log(10) k_s	-3.67	0.50	-3.72	-4.62	-2.48
θ_r	0.01077	0.00668	0.011	0.0	0.02317
n	2.16	0.31	2.09	1.70	2.74
α (cm**-1)	0.00594	0.00172	0.00582	0.00281	0.00853

Table 2. Descriptive Statistics for hydrologic properties using fitted θ_s from Unit 2, Tshirege Member Bandelier Tuff at TA-21, Los Alamos, NM (number of samples=14).

Variable	Mean	Standard Deviation	Median	Minimum	Maximum
ρ_b (g/cm**3)	1.56	0.13	1.52	1.37	1.78
θ_s	0.32	0.048	0.31	0.26	0.39
Porosity	0.39	0.065	0.40	0.26	0.48
k_s (cm/sec)	9.0*10**-5	1.24*10**-4	3.0*10**-5	1.0*10**-5	4.6*10**-4
Log(10) k_s	-4.33	0.53	-4.50	-5.22	-3.34
θ_r	0.00664	0.00844	0.0031	0.0	0.02466
n	2.25	0.38	2.23	1.65	2.93
α (cm**-1)	0.00332	0.00217	0.00289	0.00068	0.00932

Table 3.Descriptive Statistics for hydrologic properties using fitted θ_s from Unit 1v, Tshirege Member Bandelier Tuff at TA-21, Los Alamos, NM (number of samples=9).

Variable	Mean	Standard Deviation	Median	Minimum	Maximum
ρ_b (g/cm**3)	1.30	0.16	1.28	1.09	1.55
θ_s	0.46	0.08	0.44	0.36	0.63
Porosity	0.50	0.06	0.49	0.41	0.59
k_s (cm/sec)	2.6*10**-4	2.6*10**-4	1.6*10**-4	5.0*10**-5	8.7*10**-4
Log(10) k_s	-3.73	0.37	-3.80	-4.29	-3.06
θ_r	0.00240	0.00514	0.0	0.0	0.01470
n	1.83	0.35	1.82	1.40	2.57
α (cm**-1)	0.00699	0.00382	0.00669	0.00072	0.01400

Table 4. Descriptive Statistics for hydrologic properties using fitted θ_s from Unit 1g, Tshirege Member Bandelier Tuff at TA-21, Los Alamos, NM (number of samples=6).

Variable	Mean	Standard Deviation	Median	Minimum	Maximum
ρ_b (g/cm**3)	1.18	0.06	1.20	1.08	1.26
θ_s	0.51	0.055	0.49	0.46	0.58
Porosity	0.53	0.04	0.52	0.48	0.59
k_s (cm/sec)	3.0*10**-4	1.9*10**-4	2.6*10**-4	1.3*10**-4	6.5*10**-4
Log(10) k_s	-3.59	0.26	-3.59	-3.89	-3.19
θ_r	0.0	0.0	0.0	0.0	0.0
n	1.57	0.10	1.60	1.43	1.66
α (cm**-1)	0.00818	0.00464	0.00559	0.00475	0.01528

Table 5. Descriptive Statistics for hydrologic properties using fitted θ_s from Otowi Member Bandelier Tuff at TA-21, Los Alamos, NM (number of samples=19).

Variable	Mean	Standard Deviation	Median	Minimum	Maximum
ρ_b (g/cm**3)	1.25	0.13	1.25	1.11	1.69
θ_s	0.38	0.05	0.38	0.24	0.44
Porosity	0.48	0.055	0.48	0.31	0.54
k_s (cm/sec)	3.0*10**-5	2.2*10**-5	3.0*10**-5	1.4*10**-7	9.0*10**-5
Log(10) k_s	-4.67	0.63	-4.51	-6.85	-4.04
θ_r	0.0	0.0	0.0	0.0	0.0
n	2.23	0.60	2.06	1.64	3.45
α (cm**-1)	0.00228	0.00142	0.00183	0.00057	0.00452

A logarithmic transformation (base 10) was used on the k_s values because this parameter is highly skewed and previous studies have shown k_s to be lognormally distributed (Nielsen et al., 1973).
Two unique samples were taken at TA-21 that are not represented in any existing database. One sample from the MDAVDH was from the vapor phase notch, which is a distinctive marker representing an abrupt transition from vitric tuffs beneath the notch to devitrified tuffs above the notch (interface between units 1v/1g) that occurs throughout the Pajarito Plateau (Broxton et al., 1995). The second unique sample from TA-21 that was hydrologically characterized was the Guaje Pumice from LADP-3. The data for these two samples are given in Table 6.

Table 6. Hydrologic parameters for single samples of vapor phase notch from borehole MDAVDH and Guaje Pumice from borehole LADP-3 at TA-21.

Variable	Vapor Phase Notch	Guaje Pumice
ρ_b (g/cm**3)	1.10	0.81
θ_s	0.454	0.557
Porosity	0.586	0.667
k_s (cm/sec)	2.9*10**-5	1.5*10**-4
Log(10) k_s	-4.538	-3.824
θ_r	0.0	0.0
n	1.46	4.0264
α (cm**-1)	0.00634	0.00081

The values for θ_s in Table 6 are fitted. These single samples of the vapor phase notch and the Guaje Pumice do not allow conclusions about the hydrologic properties of these units to be made. The vapor phase notch has consistently demonstrated higher water content compared to units above and below it throughout the Laboratory. From Table 6, k_s which is lower than either minimum for units 1v or 1g and higher values for porosity suggest low flux and more storage. Figure 4 compares the retention curve for the vapor phase notch from Table 6 with the units 1v and 1g retention curves using the mean parameters from Tables 3 and 4, respectively. The single Guaje Pumice sample was intact for measuring the hydraulic properties. From the values in Table 6, the Guaje Pumice appears to be a highly permeable unit with considerable storage.

Table 7. Descriptive Statistics for hydrologic properties using measured saturated water content from Unit 3, Tshirege Member Bandelier Tuff at TA-21, Los Alamos, NM (number of samples=12).

Variable	Mean	Standard Deviation	Median	Minimum	Maximum
ρ_b (g/cm**3)	1.30	0.08	1.28	1.17	1.45
θ_s	0.36	0.03	0.37	0.32	0.41
Porosity	0.51	0.03	0.52	0.45	0.56
k_s (cm/sec)	4.7*10**-4	9.0*10**-4	1.9*10**-4	2.0*10**-5	3.3*10**-3
Log(10) k_s	-3.67	0.50	-3.72	-4.62	-2.48
θ_r	0.01119	0.00671	0.011	0.0	0.02294
n	2.16	0.35	2.12	1.72	2.86
α (cm**-1)	0.00591	0.00128	0.00578	0.00423	0.00791

Table 8. Descriptive Statistics for hydrologic properties using measured saturated water content from Unit 2, Tshirege Member Bandelier Tuff at TA-21, Los Alamos, NM (number of samples=14).

Variable	Mean	Standard Deviation	Median	Minimum	Maximum
ρ_b (g/cm**3)	1.56	0.13	1.52	1.37	1.78
θ_s	0.33	0.051	0.33	0.26	0.41
Porosity	0.39	0.065	0.40	0.26	0.48
k_s (cm/sec)	9.0*10**-5	1.24*10**-4	3.0*10**-5	1.0*10**-5	4.6*10**-4
Log(10) k_s	-4.33	0.53	-4.50	-5.22	-3.34
θ_r	0.00835	0.00864	0.00797	0.0	0.02429
n	2.16	0.34	2.09	1.61	2.97
α (cm**-1)	0.0035	0.00192	0.00344	0.00081	0.00889

Table 9. Descriptive Statistics for hydrologic properties using measured saturated water content from Unit 1v, Tshirege Member Bandelier Tuff at TA-21, Los Alamos, NM (number of samples=9).

Variable	Mean	Standard Deviation	Median	Minimum	Maximum
ρ_b (g/cm**3)	1.30	0.16	1.28	1.09	1.55
θ_s	0.47	0.08	0.44	0.38	0.63
Porosity	0.50	0.06	0.49	0.41	0.59
k_s (cm/sec)	2.6*10**-4	2.6*10**-4	1.6*10**-4	5.0*10**-5	8.7*10**-4
Log(10) k_s	-3.73	0.37	-3.80	-4.29	-3.06
θ_r	0.00242	0.0052	0.0	0.0	0.01492
n	1.75	0.22	1.82	1.39	2.06
α (cm**-1)	0.00727	0.00346	0.00799	0.0015	0.01352

Table 10. Descriptive Statistics for hydrologic properties using measured saturated water content from Unit 1g, Tshirege Member Bandelier Tuff at TA-21, Los Alamos, NM (number of samples=6).

Variable	Mean	Standard Deviation	Median	Minimum	Maximum
ρ_b (g/cm**3)	1.18	0.06	1.20	1.08	1.26
θ_s	0.52	0.064	0.50	0.47	0.62
Porosity	0.53	0.04	0.52	0.48	0.59
k_s (cm/sec)	3.0*10**-4	1.9*10**-4	2.6*10**-4	1.3*10**-4	6.5*10**-4
Log(10) k_s	-3.59	0.26	-3.59	-3.89	-3.19
θ_r	0.0	0.0	0.0	0.0	0.0
n	1.54	0.09	1.56	1.43	1.66
α (cm**-1)	0.0090	0.00427	0.00710	0.00555	0.01564

Table 11. Descriptive Statistics for hydrologic properties using measured saturated water content from Otowi Member Bandelier Tuff at TA-21, Los Alamos, NM (number of samples=19).

Variable	Mean	Standard Deviation	Median	Minimum	Maximum
ρ_b (g/cm**3)	1.25	0.13	1.25	1.11	1.69
θ_s	0.39	0.04	0.40	0.26	0.46
Porosity	0.48	0.055	0.48	0.31	0.54
k_s (cm/sec)	3.0*10**-5	2.2*10**-5	3.0*10**-5	1.4*10**-7	9.0*10**-5
Log(10) k_s	-4.67	0.63	-4.51	-6.85	-4.04
θ_r	0.00429	0.0104	0.0	0.0	0.0419
n	2.21	0.57	2.07	1.64	3.38
α (cm**-1)	0.00242	0.00143	0.00215	0.00068	0.00468

More samples from vapor phase notch and the Guaje Pumice are needed before any conclusions about the hydrologic performance of these units can be ascertained.

Parameter comparisons

The fitting of θ_s appeared to have minimal effect on the means and standard deviations of the values for θ_r, α, and n (Figures 4 – 6). For both θ_r and α, the measured θ_s fits give a slightly higher value than when θ_s is fitted (Figures 4–5). The greatest difference is the estimate for θ_r in the Otowi Member in Figure 4. The opposite effect occurred for n with the n values when θ_s is fitted being higher (Figure 6). On an individual sample basis, the effects on parameter values are more substantial. Figure 7 compares the relative conductivity curves for the sample from the 185 ft. depth in LADP-3. This demonstrates in terms of an individual sample the impact that the different parameter estimates can have on flux rates.

The divergence at the dry end has implications for conditions at Los Alamos because the effective saturation is approximately 10 percent, and flux estimates could differ by an order of magnitude or more depending on the fitting parameters.

Comparisons of θ_r, α, and n for each sample are presented in Figures 8 – 10. The values for n appear to have more scatter about the 1:1 line than the values for either θ_r or α. Statistical tests were performed for regression lines fitted to the data in Figures 8 – 10. Hypotheses tested were that the intercept was equal to 0 and the slope was equal to 1. The only parameter that tested statistically significant was the slope for the θ_r line (Figure 8) which is most likely due to the number of zeros for the fitted values. These hypothesis tests again show that the mean values are not significantly different, but as with the example presented for LADP-3, any one sample can significantly affect vadose flow calculations.

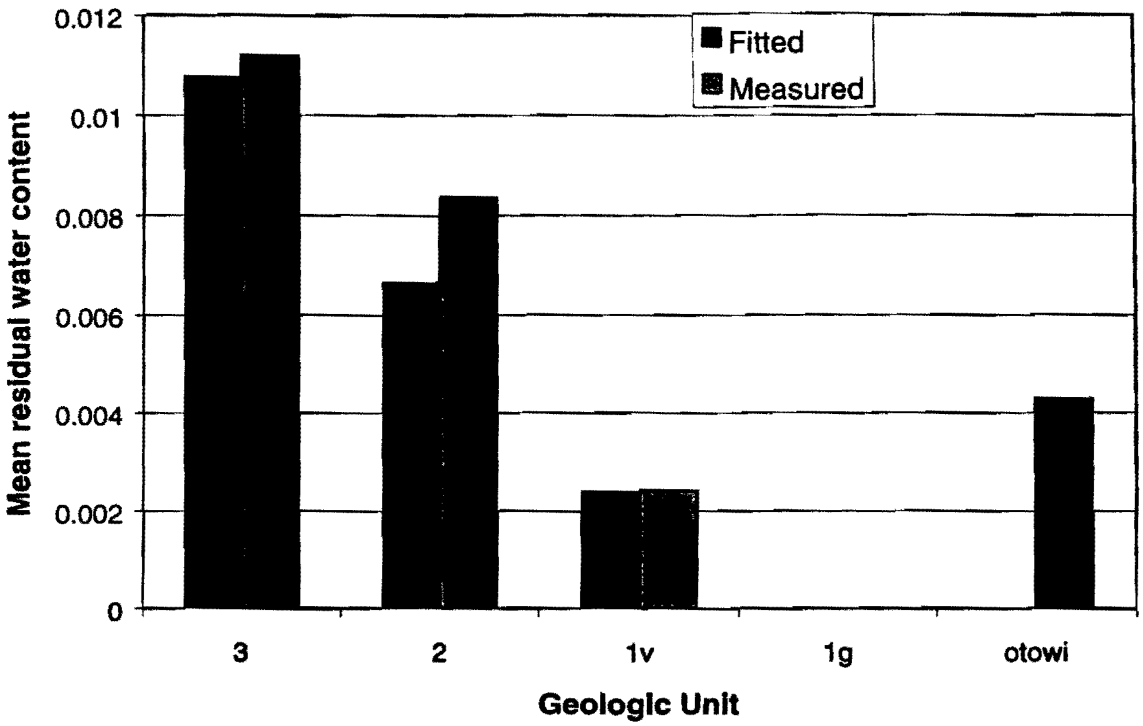

Figure 4. Comparison by Bandelier Tuff geologic unit of mean θ_r estimated by fitting θ_s versus the θ_r estimated using measured θ_s for boreholes LADP-3, LADP-4, and MDAVDH.

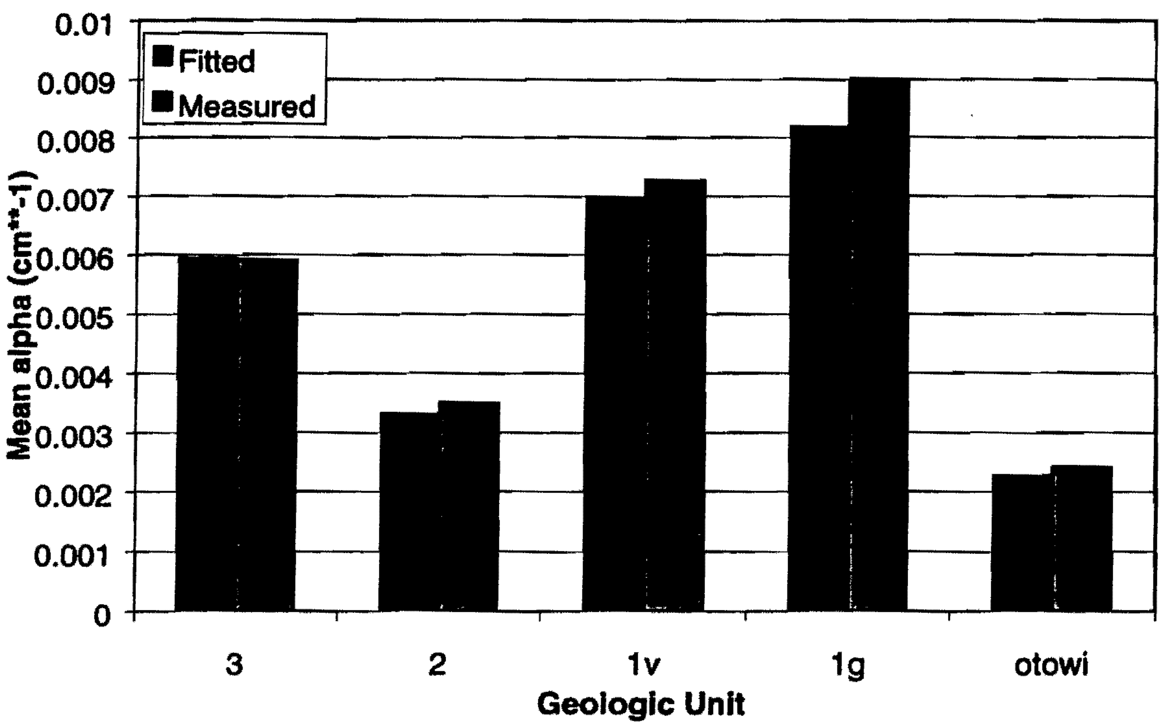

Figure 5. Comparison by Bandelier Tuff geologic unit of mean α estimated by fitting θ_s versus the α estimated using measured θ_s for boreholes LADP-3, LADP-4, and MDAVDH.

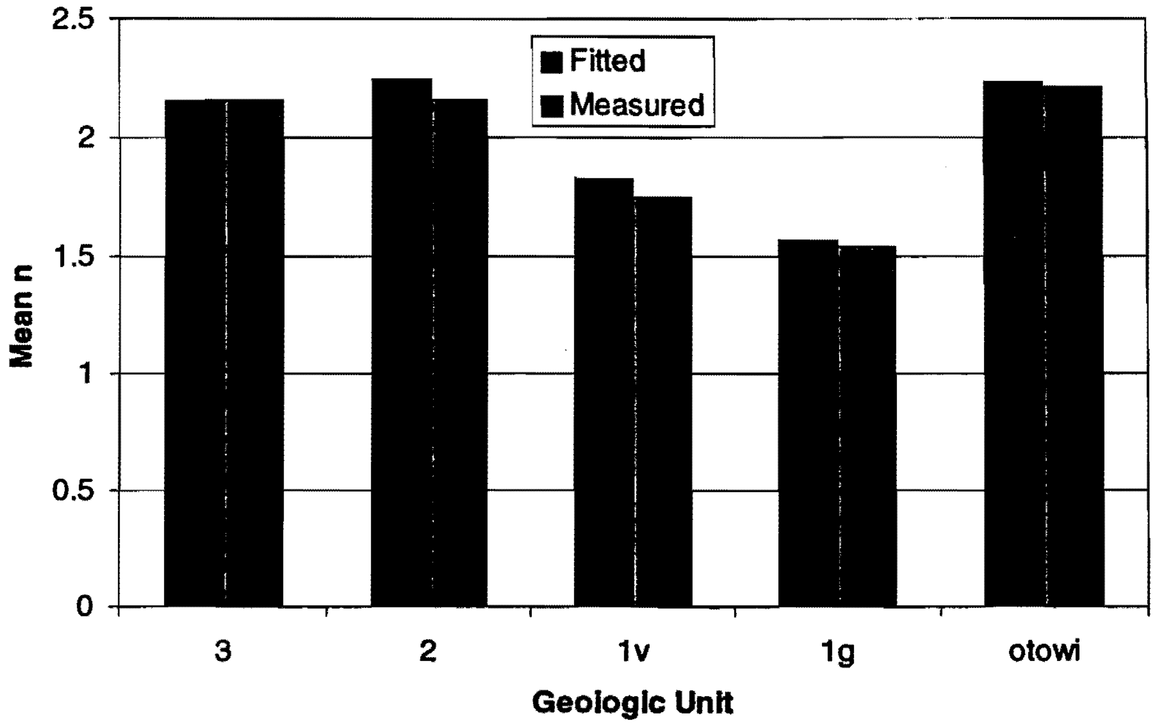

Figure 6. Comparison by Bandelier Tuff geologic unit of mean n estimated by fitting θ_s versus the n estimated using measured θ_s for boreholes LADP-3, LADP-4, and MDAVDH.

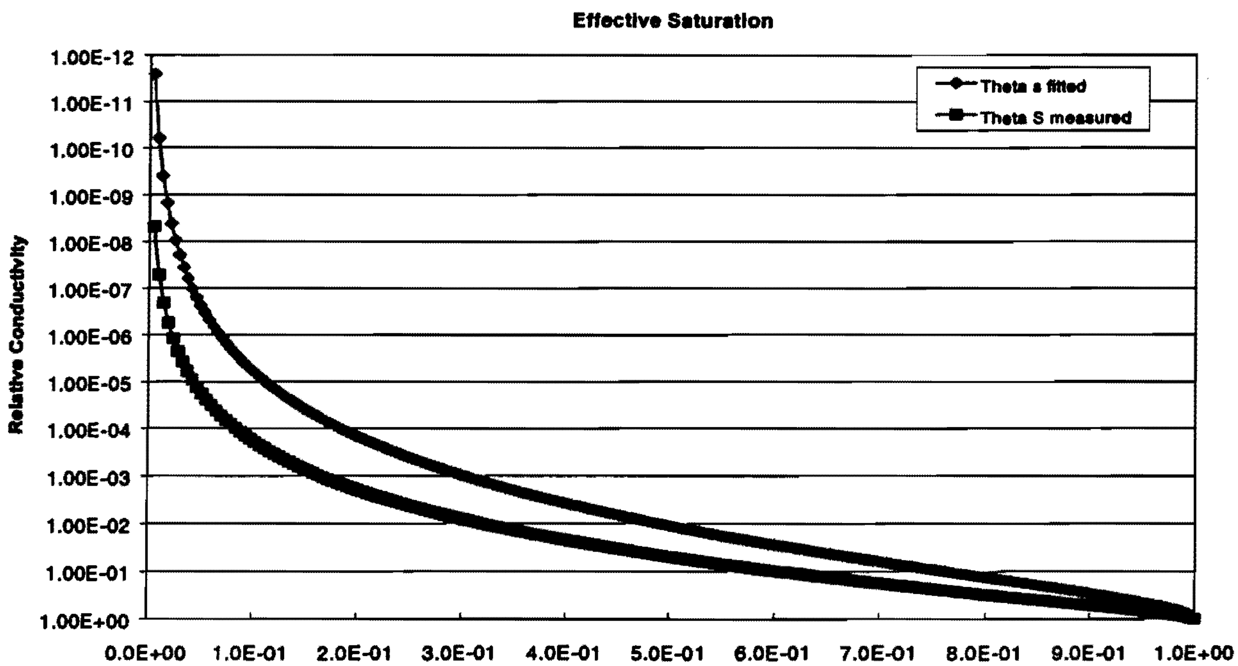

Figure 7. Relative conductivity curves for the sample from the 185 ft depth in LADP-3 for the van Genuchten parameters derived from fitting θ_s and using a measured θ_s.

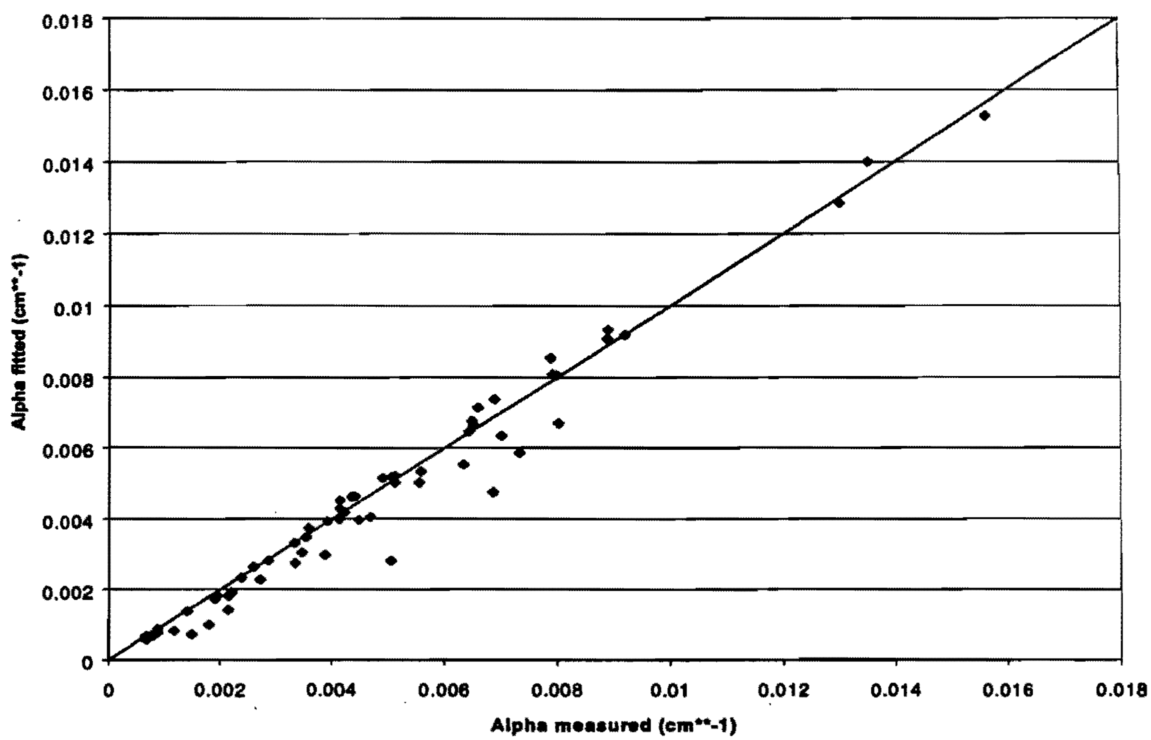

Figure 8. Comparison of residual water contents estimated from fitting θ_s and those using a measured θ_s for samples from LADP-3, LADP-4, and MDAVDH.

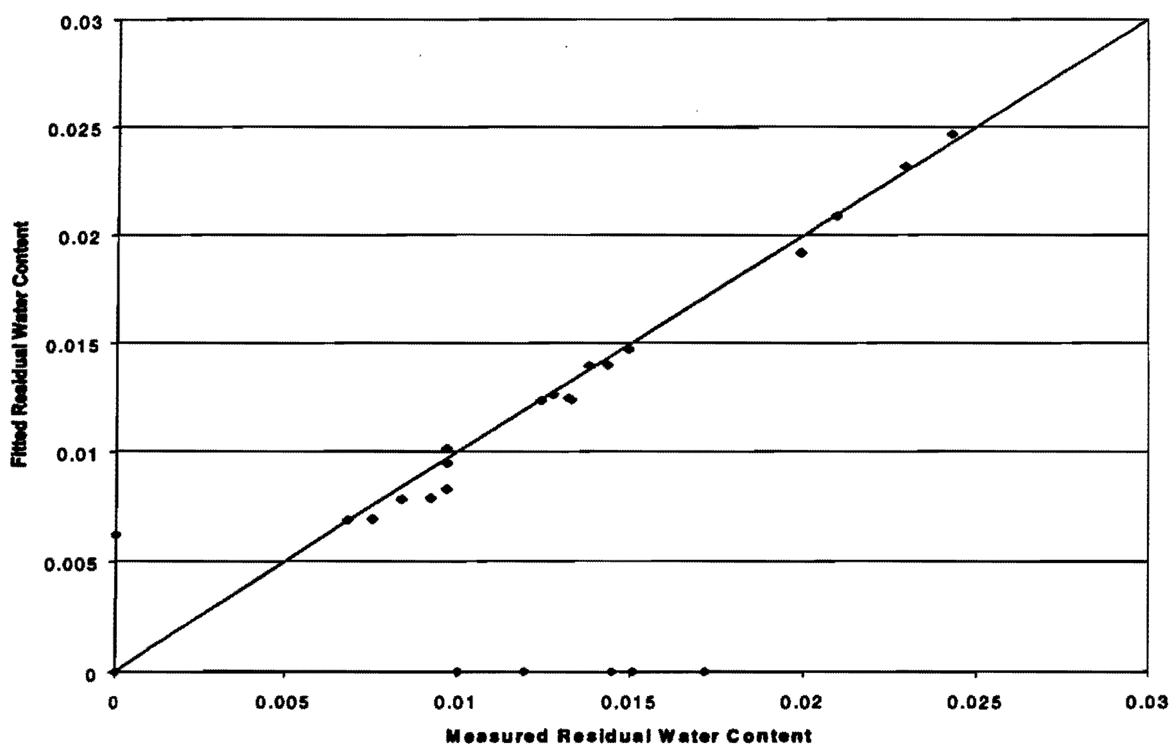

Figure 9. Comparison of alpha values estimated from fitting θ_s and those using a measured θ_s for samples from LADP-3, LADP-4, and MDAVDH.

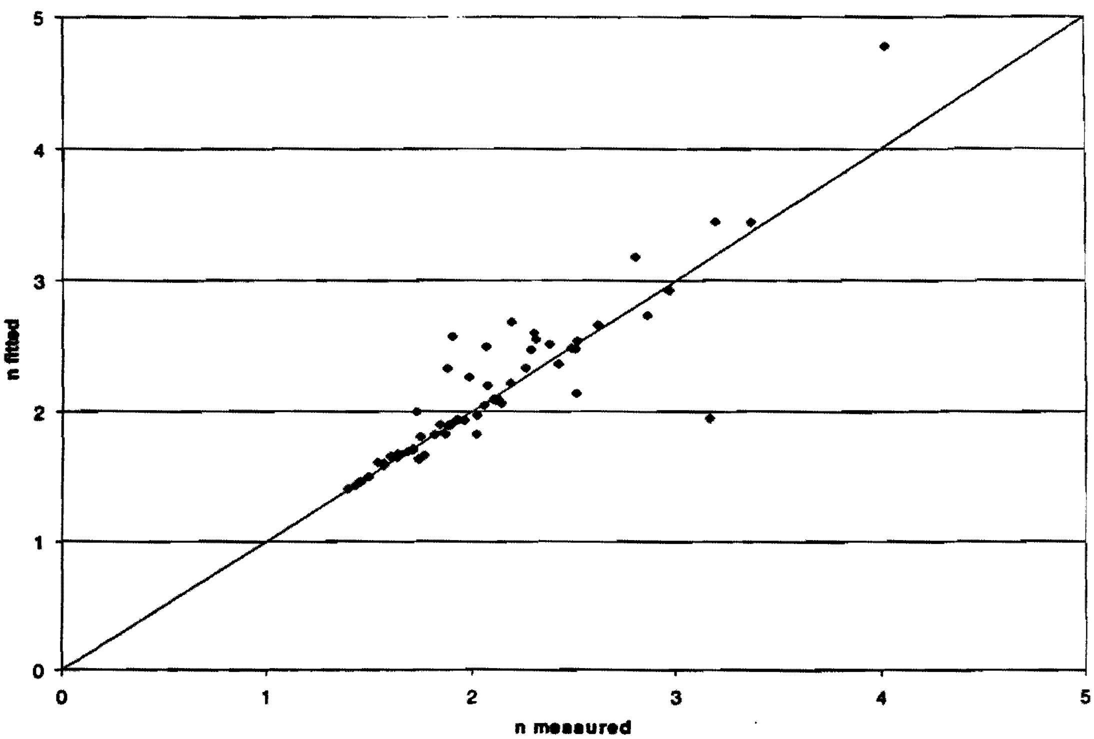

Figure 10. Comparison of alpha values estimated from fitting θ_s and those using a measured θ_s for samples from LADP-3, LADP-4, and MDAVDH.

One last issue is the fitting of four parameters, θ_s θ_r, α, and n with limited data points. From Appendix 1, there were seven pressure head – water content measurements made on each sample. The number is limited by the costs per measurement and the ability to make measurements. The estimation of four parameters though not over-determining the system reduces the degrees of freedom and may not be considered parsimonious. One solution is to increase the number of pressure head and water content measurements particularly in the region near saturation. This region is important to predict the movement of water and chemicals, and the behavior of the Bandelier Tuff near saturation has not been investigated. Durner (1992, 1994) has proposed a multicomponent model for water retention and hydraulic conductivity estimation to account for multimodal pore distributions such as macropores in soils or fractures in rocks. Durner demonstrated the importance of the region near saturation on the prediction of hydraulic conductivity. Modeling uses approaches such as composite curves to represent hydrologic rock properties. The alternative to the modeling approach is for more measurements near saturation and considering alternative models of hydraulic properties of the Bandelier Tuff rather than accepting an assumed simulated condition.

Air phase conductivity

Using the mean parameter values from Tables 1 –5 and Equation 3 from Parker et al. (1987), the air phase relative conductivity for the units 3, 2, 1v, 1g, and Otowi are compared to the water phase relative conductivity in Figures 11 – 15. The nearly linear air phase relative conductivity curves are a function of the mean values for n in Tables 1 – 5 and the exponent in Equation 3. The approximation reveals that for the Bandelier Tuff the air phase conductivity is less sensitive to changes in water content near saturation than the liquid phase. Qualitatively, these results reveal that an air phase flux is present even at relatively high water contents. The relative magnitude of water transported in each phase depends on the pressure gradients as well as the conductivity values. Simulations with computer codes using the relationship in Equation 3 can provide information on the flux of water in the air phase. Andraski (1997) performed very simple calculations for a desert site in Nevada and found that the vapor flux was greater than or equal to the liquid flux for most conditions.

Moisture Distribution

Contaminant transport predictions require data on the moisture staus of the porous media as well as the water retention and conductivity properties dicussed in this report. Ideally, the pressure head is measured so the water flux can be calculated using the pressure gradient and hydraulic conductivity. Pressure measurements particularly insitu are difficult to obtain so water content is measured and then the pressure head is estimated using the water retention curve. Water contents were measured with depth for the LADP-3, LADP-4, and MDAVDH using a microwave drying technique for radiation screening. The water content values that are given are gravimetric θ_g or weight basis water contents, and these are related to by the following relationship

$$\theta_g = \frac{\theta \rho_w}{\rho_b} \qquad (4)$$

where ρ_w is the density of water.

Broxton et al. (1995) presented the gravimetric water content distributions for both LADP-3 and LADP-4. The water contents for LADP-3 were generally less than 15% by weight except for the alluvium near the surface and the Guaje Pumice Bed which was saturated at the bottom. LADP-4 had water contents that ranged between 5 – 10% by weight except at the interface between Bandelier Tuff units 1v and 1g where a water content spike between 20 – 25% occurred and near the Tsankawi Pumice bed (unit 1g and Cerro Toledo interface) where the values where near 20% by weight.

The water contents from field screening for MDAVDH are given in Figure 16. From

Figure 16 there appears to be a trend of increasing water content with depth. The spike at approximately 170 feet below the surface is in unit 1v below the contact with unit 2. The spike at 320 feet is at the interface between unit 1g and the Cerro Toledo above Tsankawi Pumice Bed similar to the moisture spike observed in LADP-4.

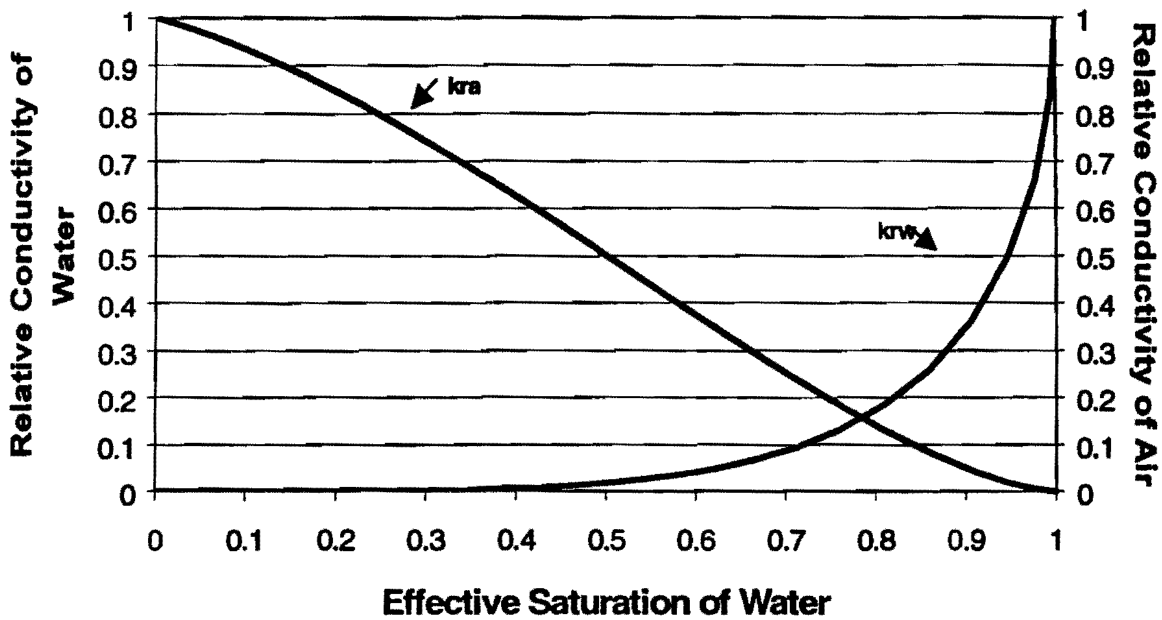

Figure 11. Air and water relative conductivity for Bandelier Tuff Unit 3 at TA-21 using mean van Genuchten parameters for the case where θ_s was fitted.

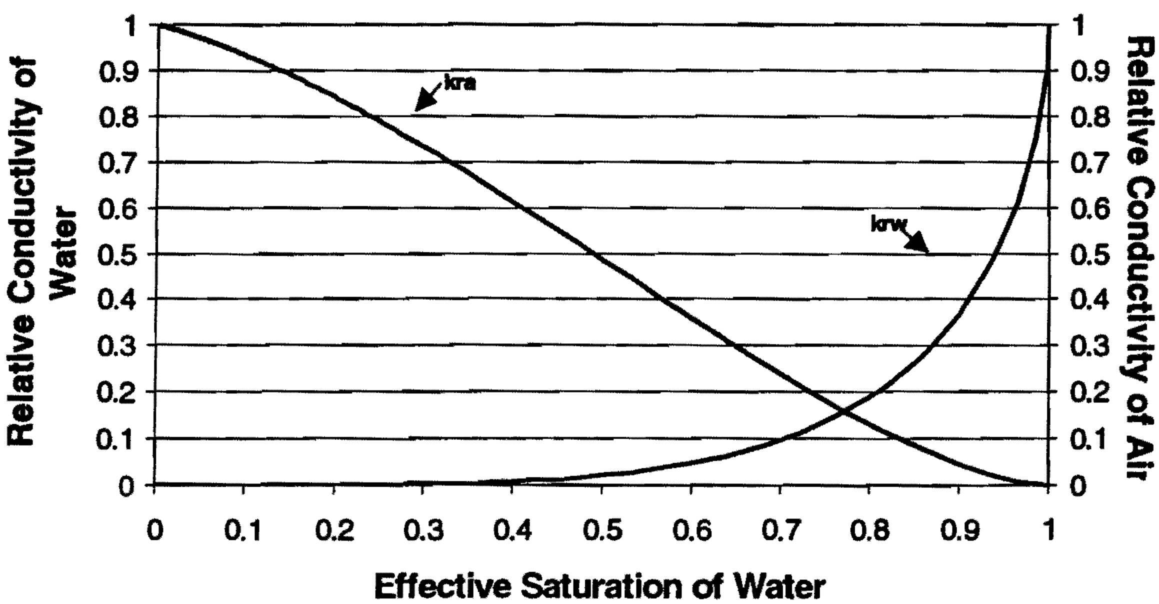

Figure 12. Air and water relative conductivity for Bandelier Tuff Unit 2 at TA-21 using mean van Genuchten parameters for the case where θ_s was fitted.

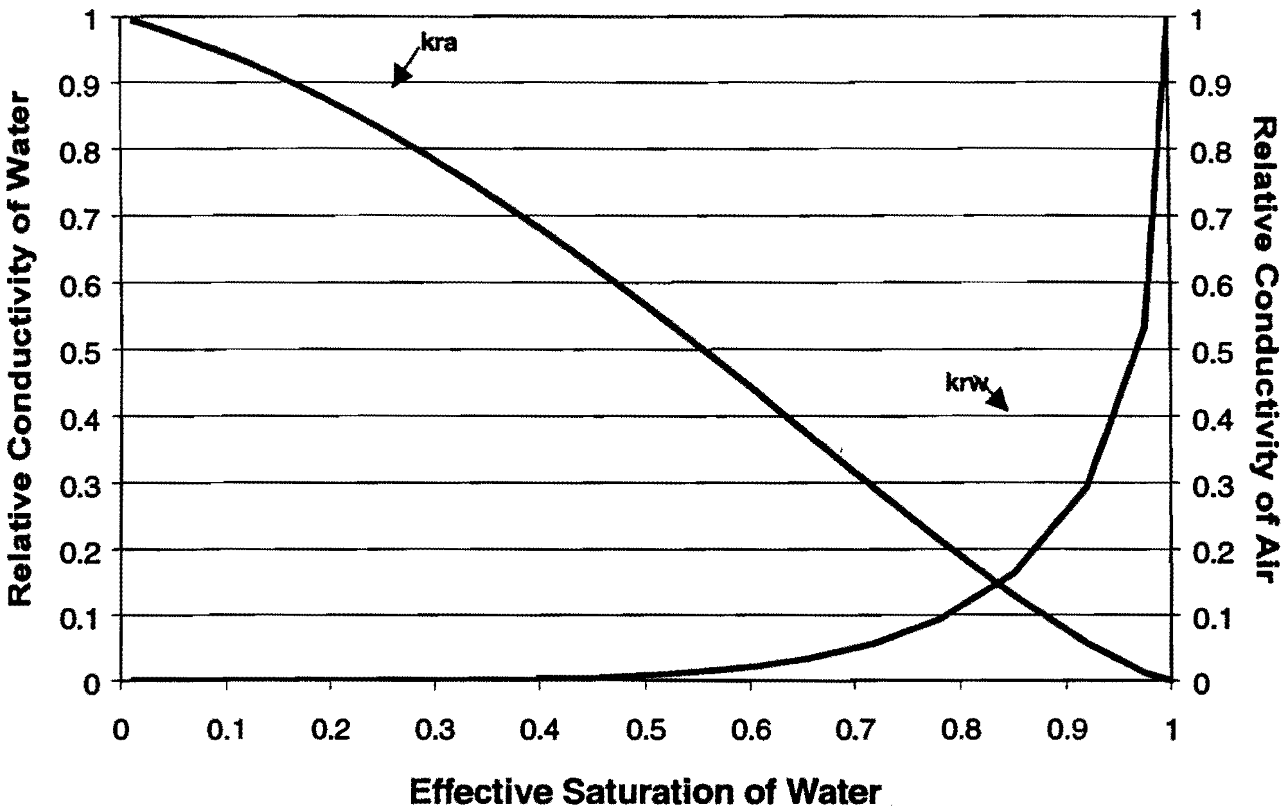

Figure 13. Air and water relative conductivity for Bandelier Tuff Unit 1v at TA-21 using mean van Genuchten parameters for the case where θ_s was fitted.

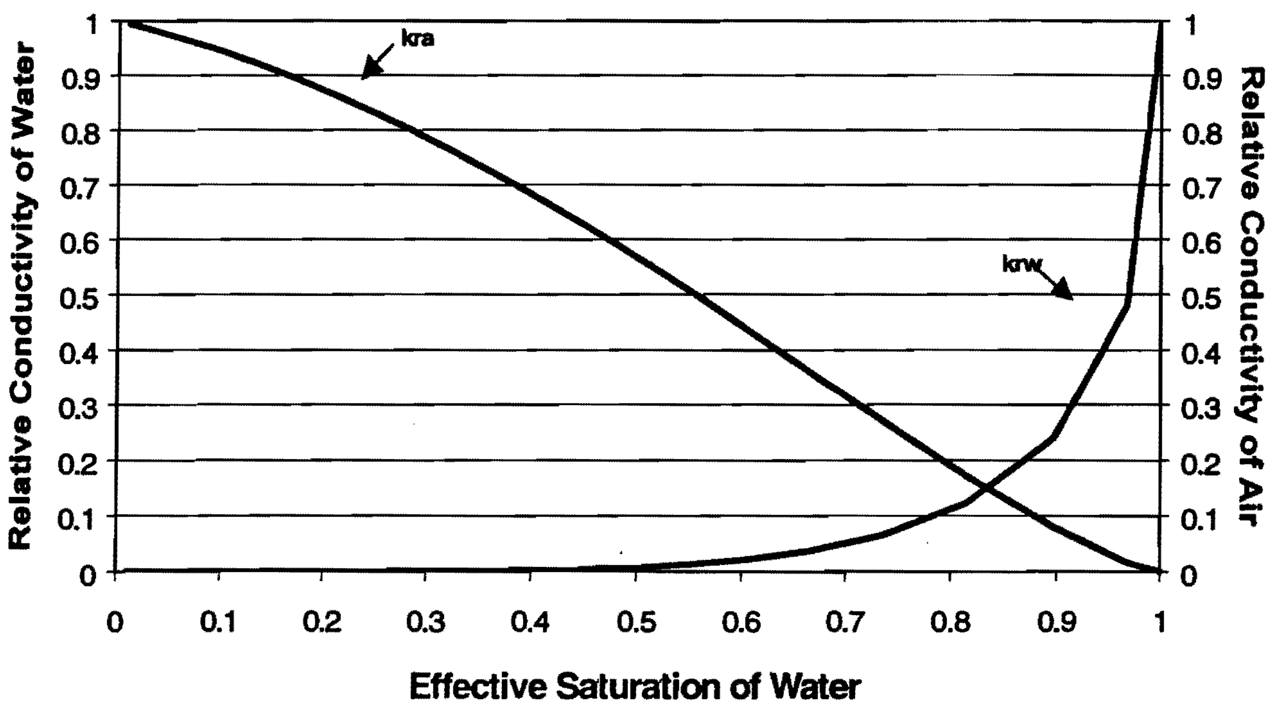

Figure 14. Air and water relative conductivity for Bandelier Tuff Unit 1g at TA-21 using mean van Genuchten parameters for the case where θ_s was fitted.

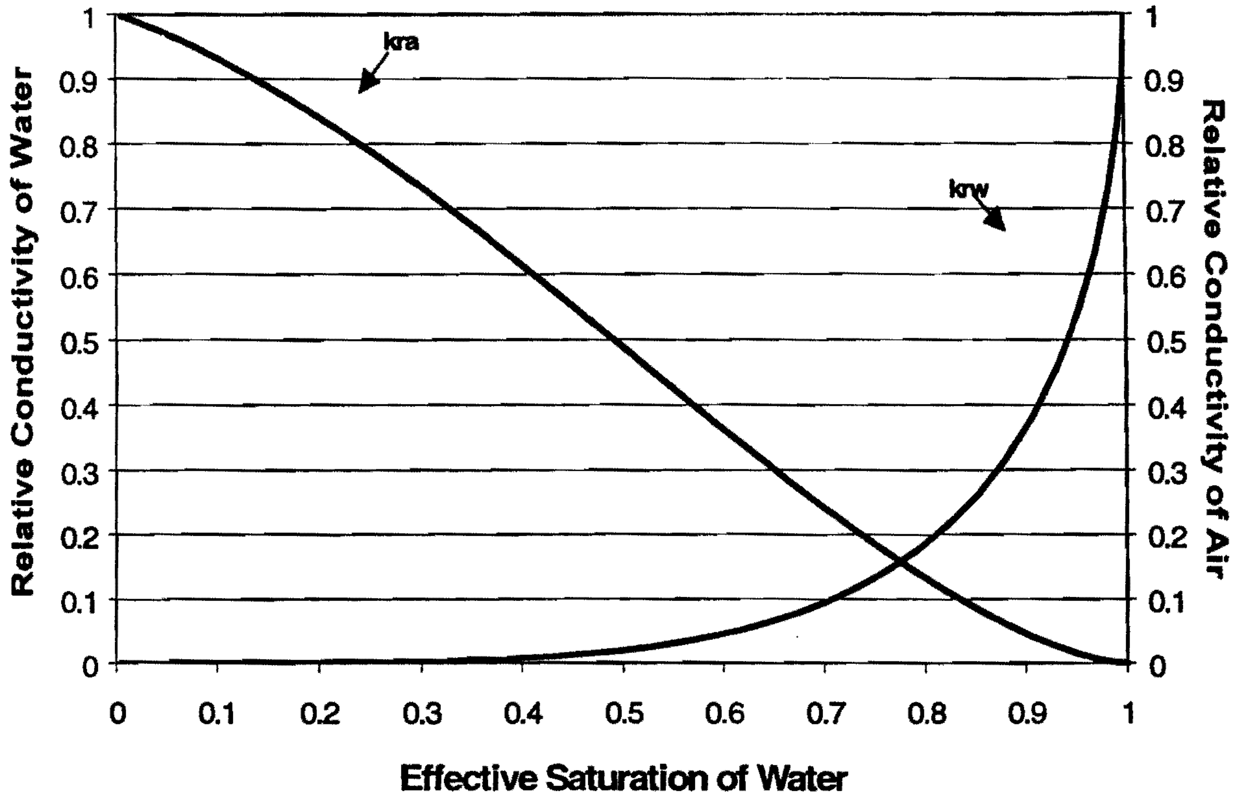

Figure 15. Air and water relative conductivity for the Otowi Member of the Bandelier Tuff at TA-21 using mean van Genuchten parameters for the case where θ_s was fitted.

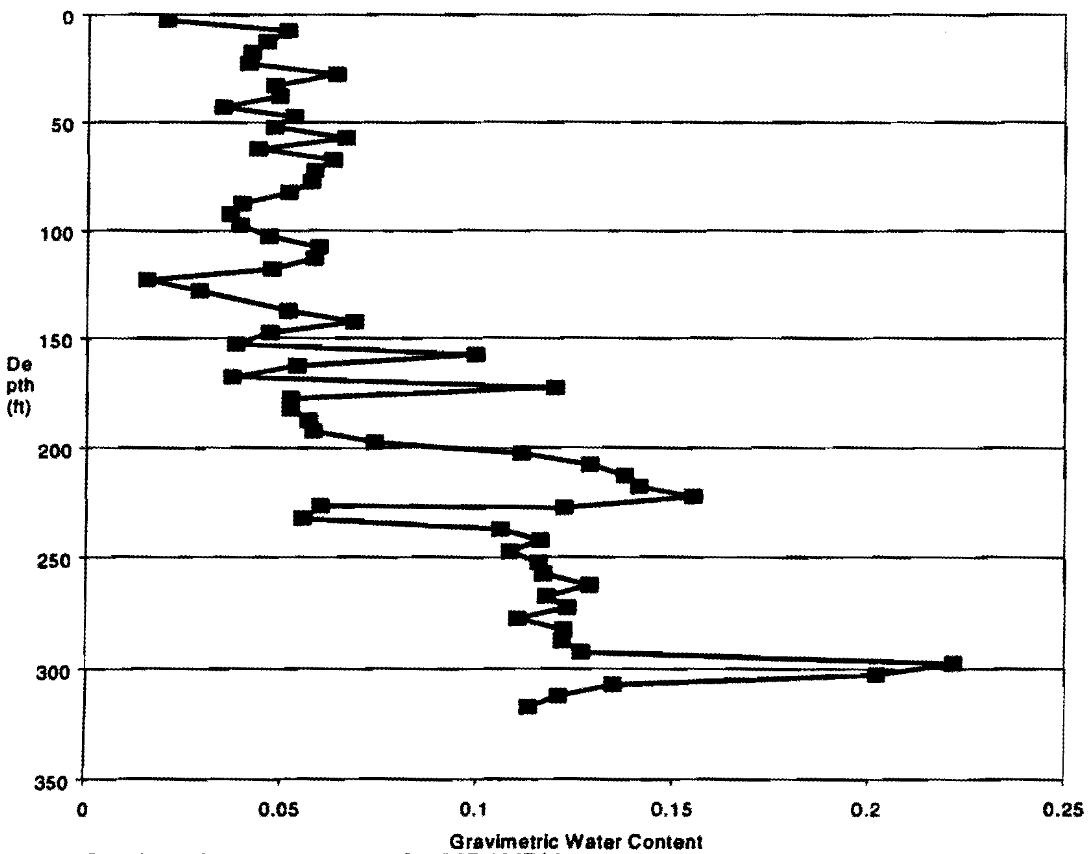

Figure 16. Gravimetric water content for MDAVDH.

DP Canyon Wells

Water contents were measured at the LAUZ sites. There were two holes drilled at the LAUZ-1 site. The first hole was outside the channel and did not intercept alluvial water. The water content distribution for that hole is presented in Figure 17. The second hole is the current LAUZ-1 hole which did intercept alluvial water.

The water contents in Figure 17 reveal a high water content near the surface that is consistent with wet conditions found in DP Canyon alluvium. Spikes in water content occur at 150 ft and 250 ft below ground surface with the 250 ft spike approaching a gravimetric water content of 0.26. There is no geologic log for the initial borehole at LAUZ-1, but extrapolation from LADP-4 which is in DP Canyon at a higher elevation suggests that the water content spike at 150 ft corresponds to interface between units 1v and 1g and the value at 250 ft is near the unit 1v and Cerro Toledo interface. Broxton et al. (1995) suggested flow along the units 1v/1g boundary as a supply of water for DP Spring, and these data support that hypothesis. The increased water content near the upper Cerro Toledo boundary indicates a potential source of water for seeps observed in the Cerro Toledo at the outcrop in DP Canyon below DP Spring.

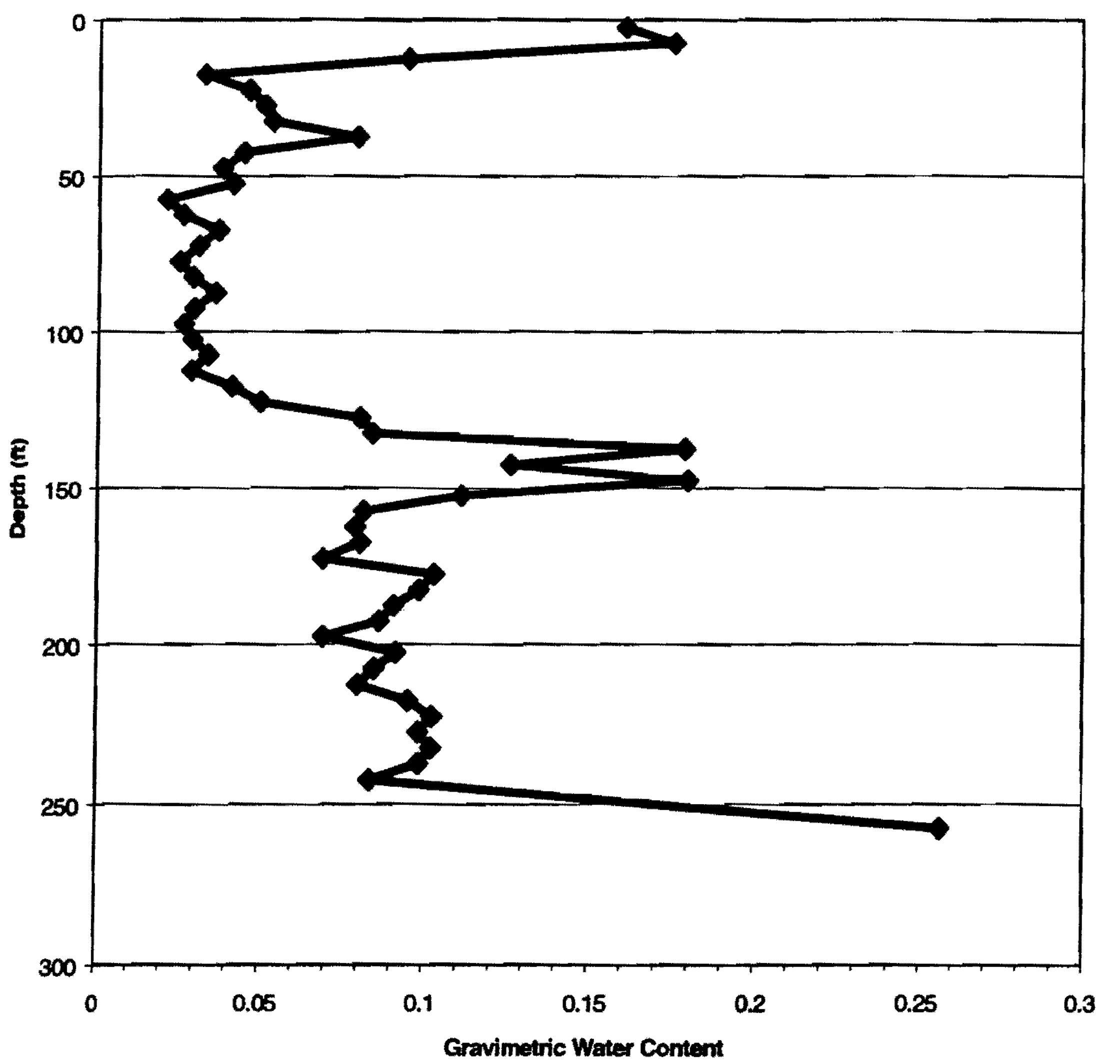

Figure 17 Gravimetric water content distribution for LAUZ-1 outside the channel.

Hydrologic data and chemical characterization of DP Spring have not been conclusive on the source of DP Spring. Tracer tests performed by injecting tracers into LAUZ-1 and LAUZ-2 will identify if the alluvial groundwater in DP Canyon is the source and simultaneously provide travel time data if the alluvial water is the source.

SUMMARY AND CONCLUSIONS

Bandelier Tuff hydrologic properties for core samples from three boreholes on DP Mesa were determined. Analyses included fitting of retention data to the van Genuchten formula, estimating the unsaturated hydraulic conductivity using the retention parameters, and estimating the air phase permeability. The statistics of the hydrologic properties were calculated by geologic unit. Lateral sampling was insufficient to estimate any statistical relationships such as spatial correlation for the geological units. The lowest saturated hydraulic conductivities were observed in Tshirege unit 2 and the Otowi Member.

Moisture profiles for the MDAVDH indicated that no saturated zones occurred over its depth. Alluvial groundwater was found in the DP Canyon boreholes, but unsaturated conditions were present beneath the alluvium. This alluvial groundwater is hypothesized as a source for DP Spring. .

The results presented in this report provide estimates for the means and variances for Bandelier Tuff hydrologic properties for TA-21. The fitting of θ_s in the van Genuchten water retention function rather than fixing this parameter with the porosity or measured θ_s can lead to differences in estimated hydraulic conductivity. In terms of the mean parameters for each geologic unit, fitting of θ_s had a significant effect only on θ_r. This study is the first to investigate the fitting of θ_s on the water retention and hydraulic conductivity curves for Bandelier Tuff. It appears that if a measured θ_s is available, then there is no advantage in fitting θ_s, and issues such as limited sample size and parsimony suggest using the measured θ_s. If there are concerns about different flux estimates from fitting versus measured, then both the fitted and measured θ_s curves must be evaluated for a site, and decisions about the appropriate flux rate made.

Analyses were performed to estimate air permeability data for the Bandelier Tuff at TA-21 using relationships derived by Parker et al. (1987). The potential for evaporation processes to be occurring at depth in the Bandelier Tuff, because of the topography of the mesas and the relatively high permeability, make having data on air permeability with water content important for simulation of moisture flux.

Data in this report are matrix properties and issues such as fractures and macropores must be treated differently. A major data gap is the Cerro Toledo interval which is important hydrologically because of its complex structure and bedding. The lateral variability in hydrologic properties is not well defined with three sampling points, and some effort needs to be made to look at pooling the Bandelier Tuff from across the Pajarito Plateau for better understanding issues such as spatial correlation and connectivity. Finally, these are core-scale parameters (approximately 15 cm), and scale issues must be considered when they are used to represent hydrologic properties of a larger system for example a 1-m block in a numerical simulation model.

The occurrence of water at TA-21 is well known from the results of Broxton et al. (1995). MDAVDH showed that the Guaje Pumice was not saturated indicating that at least the perched groundwater system found in LADP-3 does not reach below the mesa. LADP-4 did not contain any saturated zones. The alluvial groundwater in DP Canyon is an obvious source for DP Spring, and a tracer test will test this hypothesis.

TA-21 is an important site for the ER Project and contains many areas that will require simulation and analysis in order to propose a remedial action. The data presented in this report are fundamental in supporting the ER Project in its goal of restoring the Los Alamos site.

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Appendix 1. Parameter fitting results for each sample from boreholes LADP-3, LADP-4, and MDAVDH.

Table 1-1. Borehole locations, data, and van Genuchten parameters for the case where θ_s is fitted for LADP-3, LADP-4, and MDAVDH.

Borehole	Unit	East	North	Elev	Depth	PB	Theta S	Porosity	Ksat	Log Ksat	Theta R	N	Alpha	Log Alpha
				(ft.)	(ft.)	(g/cm**3)			(cm/sec)				(cm**-1)	
MDAVDH	vpn	1631442.9	1774550.0	7159.0	223.4	1.10	0.4541	0.586	2.9E-05	-4.5376	0	1.4616	0.00634	-2.197
MDAVDH	1v	1631442.9	1774550.0	7159.0	162.2	1.44	0.36201	0.456	0.00014	-3.8539	0	1.60277	0.00669	-2.174
MDAVDH	1v	1631442.9	1774550.0	7159.0	163.9	1.40	0.41744	0.472	0.00043	-3.3665	0.0147	2.04749	0.00662	-2.179
MDAVDH	1v	1631442.9	1774550.0	7159.0	167.0	1.40	0.40743	0.473	0.00022	-3.6576	0	1.71153	0.00907	-2.042
MDAVDH	1v	1631442.9	1774550.0	7159.0	183.8	1.09	0.43553	0.589	0.00087	-3.0605	0.00686	1.90294	0.00917	-2.037
MDAVDH	1v	1631442.9	1774550.0	7159.0	193.7	1.55	0.62998	0.413	0.0003	-3.5229	0	1.81775	0.00805	-2.094
MDAVDH	1v	1631442.9	1774550.0	7159.0	214.2	1.21	0.45037	0.544	0.00012	-3.9208	0	2.56985	0.00072	-3.142
MDAVDH	1v	1631442.9	1774550.0	7159.0	218.7	1.09	0.49231	0.589	8.3E-05	-4.0809	0	1.49708	0.014	-1.853
MDAVDH	1g	1631442.9	1774550.0	7159.0	233.8	1.26	0.58346	0.524	0.00065	-3.1871	0	1.60791	0.00475	-2.323
MDAVDH	1g	1631442.9	1774550.0	7159.0	253.8	1.08	0.45607	0.591	0.00015	-3.8239	0	1.6562	0.00585	-2.232
MDAVDH	1g	1631442.9	1774550.0	7159.0	268.7	1.14	0.46592	0.568	0.0003	-3.5229	0	1.43125	0.01285	-1.891
MDAVDH	3	1631442.9	1774550.0	7159.0	6.7	1.35	0.31208	0.489	2.4E-05	-4.6198	0.02317	1.93412	0.00418	-2.378
MDAVDH	3	1631442.9	1774550.0	7159.0	12.4	1.36	0.3249	0.487	0.00013	-3.8861	0.00827	1.82672	0.00738	-2.131
MDAVDH	3	1631442.9	1774550.0	7159.0	14.5	1.27	0.34329	0.522	0.0033	-2.4815	0	1.69989	0.00853	-2.069
MDAVDH	3	1631442.9	1774550.0	7159.0	25.2	1.27	0.32996	0.522	0.00018	-3.7447	0.00787	1.96451	0.00714	-2.146
MDAVDH	3	1631442.9	1774550.0	7159.0	32.2	1.24	0.35367	0.532	0.0002	-3.699	0.00945	2.0885	0.00808	-2.092
MDAVDH	3	1631442.9	1774550.0	7159.0	38.5	1.33	0.38784	0.498	0.00024	-3.6198	0.01012	2.21286	0.00501	-2.300
MDAVDH	3	1631442.9	1774550.0	7159.0	41.3	1.45	0.41296	0.454	0.00018	-3.7447	0.01246	2.08929	0.00676	-2.170
MDAVDH	3	1631442.9	1774550.0	7159.0	44.7	1.36	0.37732	0.485	9.8E-05	-4.0088	0.01916	2.36366	0.00515	-2.288
MDAVDH	3	1631442.9	1774550.0	7159.0	47.3	1.28	0.39954	0.518	0.00015	-3.8239	0.01399	2.47734	0.00518	-2.285
MDAVDH	3	1631442.9	1774550.0	7159.0	49.6	1.24	0.39221	0.534	0.00021	-3.6778	0.01239	2.73742	0.00463	-2.334
MDAVDH	3	1631442.9	1774550.0	7159.0	56.2	1.23	0.38077	0.535	0.0003	-3.5229	0.01235	2.48476	0.00646	-2.189
MDAVDH	3	1631442.9	1774550.0	7159.0	63.7	1.17	0.32961	0.558	0.00059	-3.2291	0	1.99597	0.00281	-2.551
MDAVDH	2	1631442.9	1774550.0	7159.0	91.4	1.39	0.3574	0.477	0.00024	-3.6198	0.0062	2.68193	0.00297	-2.527
MDAVDH	2	1631442.9	1774550.0	7159.0	93.3	1.37	0.39336	0.484	0.00046	-3.3372	0.0078	1.93134	0.00932	-2.030

Borehole	Unit	East	North	Elev	Depth	PB	Theta S	Porosity	Ksat	Log Ksat	Theta R	N	Alpha	Log Alpha
				(ft.)	(ft.)	(g/cm**3)			(cm/sec)				(cm**-1)	
MDAVDH	2	1631442.9	1774550.0	7159.0	96.7	1.49	0.34004	0.439	9.5E-05	-4.0223	0.01262	2.92766	0.0052	-2.284
MDAVDH	2	1631442.9	1774550.0	7159.0	98.3	1.46	0.27557	0.448	0.00009	-4.0458	0	2.49694	0.00142	-2.847
MDAVDH	2	1631442.9	1774550.0	7159.0	104.7	1.64	0.26731	0.381	2.1E-05	-4.6778	0.01396	2.54196	0.00281	-2.551
MDAVDH	2	1631442.9	1774550.0	7159.0	109.6	1.61	0.28388	0.394	3.4E-05	-4.4685	0.0069	2.0837	0.00373	-2.428
MDAVDH	2	1631442.9	1774550.0	7159.0	144.0	1.67	0.28431	0.369	0.00003	-4.5229	0.02086	1.89268	0.00393	-2.405
MDAVDH	2	1631442.9	1774550.0	7159.0	159.6	1.51	0.32578	0.429	0.00013	-3.8861	0	2.32286	0.00099	-3.004
LADP-4	Otowi	1633175.6	1774718.1	6740.2	309.55	1.16	0.44124	0.512	3.3E-05	-4.4815	0	2.19292	0.00228	-2.642
LADP-4	Otowi	1633175.6	1774718.1	6732.3	317.40	1.18	0.37914	0.512	3.2E-05	-4.4949	0	3.44993	0.0007	-3.154
LADP-4	Otowi	1633175.6	1774718.1	6729.6	320.15	1.14	0.44364	0.522	4.6E-05	-4.3372	0	1.89067	0.00348	-2.458
LADP-4	Otowi	1633175.6	1774718.1	6719.3	330.40	1.14	0.41295	0.528	3.8E-05	-4.4202	0	2.05862	0.00233	-2.632
LADP-4	Otowi	1633175.6	1774718.1	6711.5	338.20	1.11	0.40187	0.541	0.00006	-4.2218	0	3.44399	0.00088	-3.055
LADP-4	Otowi	1633175.6	1774718.1	6706.9	342.85	1.16	0.40306	0.514	1.8E-05	-4.7447	0	2.51349	0.00173	-2.762
LADP-4	Otowi	1633175.6	1774718.1	6702.2	347.55	1.16	0.40055	0.513	2.9E-05	-4.5376	0	2.32939	0.00183	-2.737
LADP-4	Otowi	1633175.6	1774718.1	6697.4	352.30	1.15	0.40332	0.526	3.2E-05	-4.4949	0	2.66236	0.00138	-2.860
LADP-4	Otowi	1633175.6	1774718.1	6638.3	411.45	1.44	0.39443	0.406	7.1E-05	-4.1487	0	1.66556	0.00429	-2.367
LADP-4	Otowi	1633175.6	1774718.1	6566.8	482.95	1.27	0.39076	0.475	9.1E-05	-4.041	0	1.66382	0.00396	-2.402
LADP-4	Otowi	1633175.6	1774718.1	6552.1	497.65	1.29	0.34704	0.467	0.00004	-4.3979	0	1.64907	0.00398	-2.400
LADP-4	Otowi	1633175.6	1774718.1	6549.7	500.05	1.23	0.3834	0.478	2.9E-05	-4.5376	0	1.63561	0.00452	-2.344
LADP-4	Otowi	1633175.6	1774718.1	6522.3	527.40	1.34	0.33632	0.425	1.4E-07	-6.8539	0	2.55142	0.00077	-3.113
LADP-4	1v	1633175.6	1774718.1	6946.8	102.95	1.28	0.39562	0.504	0.00016	-3.7959	0	1.89653	0.00304	-2.517
LADP-4	1v	1633175.6	1774718.1	6898.5	151.20	1.23	0.53494	0.49	5.1E-05	-4.2924	0	1.40437	0.00553	-2.257
LADP-4	1g	1633175.6	1774718.1	6888.7	161.00	1.19	0.55973	0.51	0.00013	-3.8861	0	1.5871	0.00502	-2.299
LADP-4	1g	1633175.6	1774718.1	6844.6	205.15	1.22	0.4627	0.495	0.00022	-3.6576	0	1.66458	0.00533	-2.273
LADP-4	1g	1633175.6	1774718.1	6804.1	245.65	1.2	0.51858	0.484	0.00033	-3.4815	0	1.46248	0.01528	-1.815
LADP-4	2	1633175.6	1774718.1	7033.7	16.05	1.49	0.3346	0.42	2.2E-05	-4.6576	0.02466	1.93826	0.00347	-2.459
LADP-4	2	1633175.6	1774718.1	7022.5	27.20	1.78	0.26114	0.264	2.5E-05	-4.6021	0	1.82596	0.00462	-2.335
LADP-4	2	1633175.6	1774718.1	7019.4	30.35	1.78	0.27802	0.308	1.8E-05	-4.7447	0	2.13911	0.00264	-2.578
LADP-4	2	1633175.6	1774718.1	6993.1	56.60	1.67	0.27158	0.31	6E-06	-5.2218	0	2.60362	0.00068	-3.167

Borehole	Unit	East	North	Elev	Depth	PB	Theta S	Porosity	Ksat	Log Ksat	Theta R	N	Alpha	Log Alpha
				(ft.)	(ft.)	(g/cm**3)			(cm/sec)				(cm**-1)	
LADP-4	2	1633175.6	1774718.1	6979.9	69.80	1.51	0.37072	0.412	1.4E-05	-4.8539	0	1.64974	0.00274	-2.562
LADP-4	2	1633175.6	1774718.1	6969.2	80.50	1.52	0.38781	0.373	0.00012	-3.9208	0	2.47014	0.00192	-2.716
LADP-3	Otowi	1632989	1773469.1	6570.2	185.4	1.69	0.2418	0.309	2.2E-06	-5.6576	0	1.95074	0.00068	-3.167
LADP-3	Otowi	1632989	1773469.1	6515.4	240.3	1.25	0.36592	0.485	3.1E-05	-4.5086	0	2.2649	0.00082	-3.086
LADP-3	Otowi	1632989	1773469.1	6483.4	272.2	1.3	0.33732	0.448	0.00002	-4.699	0	1.80749	0.00182	-2.739
LADP-3	Otowi	1632989	1773469.1	6480	275.6	1.29	0.36456	0.468	2.3E-05	-4.6383	0	3.18143	0.00057	-3.244
LADP-3	Otowi	1632989	1773469.1	6462.5	293.2	1.25	0.36746	0.465	1.5E-05	-4.8239	0	1.68935	0.00331	-2.480
LADP-3	Otowi	1632989	1773469.1	6454.2	301.5	1.28	0.3353	0.471	2.2E-05	-4.6576	0	1.67534	0.00405	-2.392
LADP-3	Guaje	1632989	1773469.1	6431.8	323.9	0.81	0.48633	0.667	1.5E-04	-3.824	0	4.77629	0.0007	-3.154

Table 1-2. Borehole locations, data, and van Genuchten parameters for the case where θ_s is measured for LADP-3, LADP-4, and MDAVDH.

Borehole	Unit	East	North	Elev (ft.)	Depth (ft.)	PB (g/cm**3)	Theta S	Porosity	Ksat (cm/sec)	Log Ksat	Theta R	N	Alpha (cm**-1)	Log Alpha
MDAVDH	vpn	1631442.9	1774550.0	7159.0	223.4	1.10	0.464	0.586	2.90E-05	-4.5376	0	1.4519	0.007	-2.1542
MDAVDH	1v	1631442.9	1774550.0	7159.0	162.2	1.44	0.377	0.456	1.40E-04	-3.8539	0	1.5718	0.008	-2.0958
MDAVDH	1v	1631442.9	1774550.0	7159.0	163.9	1.40	0.415	0.472	4.30E-04	-3.3665	0.0149	2.0581	0.0065	-2.1864
MDAVDH	1v	1631442.9	1774550.0	7159.0	167.0	1.40	0.404	0.473	2.20E-04	-3.6576	0	1.7144	0.0089	-2.0515
MDAVDH	1v	1631442.9	1774550.0	7159.0	183.8	1.09	0.436	0.589	8.70E-04	-3.0605	0.0068	1.9019	0.0092	-2.0366
MDAVDH	1v	1631442.9	1774550.0	7159.0	193.7	1.55	0.628	0.413	3.00E-04	-3.5229	0	1.8197	0.008	-2.0974
MDAVDH	1v	1631442.9	1774550.0	7159.0	214.2	1.21	0.525	0.544	1.20E-04	-3.9208	0	1.9011	0.0015	-2.8239
MDAVDH	1v	1631442.9	1774550.0	7159.0	218.7	1.09	0.486	0.589	8.30E-05	-4.0809	0	1.4984	0.0135	-1.8690
MDAVDH	1g	1631442.9	1774550.0	7159.0	233.8	1.26	0.62	0.524	6.50E-04	-3.1871	0	1.5431	0.0069	-2.1636
MDAVDH	1g	1631442.9	1774550.0	7159.0	253.8	1.08	0.475	0.591	1.50E-04	-3.8239	0	1.6074	0.0073	-2.134
MDAVDH	1g	1631442.9	1774550.0	7159.0	268.7	1.14	0.467	0.568	3.00E-04	-3.5229	0	1.4302	0.013	-1.8857
MDAVDH	3	1631442.9	1774550.0	7159.0	6.7	1.35		0.489	2.40E-05	-4.6198	0.0229	1.9264	0.0042	-2.3736
MDAVDH	3	1631442.9	1774550.0	7159.0	12.4	1.36	0.32	0.487	1.30E-04	-3.8861	0.0097	1.8657	0.0069	-2.1617
MDAVDH	3	1631442.9	1774550.0	7159.0	14.5	1.27	0.336	0.522	3.30E-03	-2.4815	0	1.7173	0.0079	-2.1034
MDAVDH	3	1631442.9	1774550.0	7159.0	25.2	1.27	0.323	0.522	1.80E-04	-3.7447	0.0092	2.0202	0.0066	-2.1811
MDAVDH	3	1631442.9	1774550.0	7159.0	32.2	1.24	0.352	0.532	2.00E-04	-3.699	0.0097	2.1044	0.0079	-2.1018
MDAVDH	3	1631442.9	1774550.0	7159.0	38.5	1.33	0.39	0.498	2.40E-04	-3.6198	0.0097	2.1861	0.0051	-2.2907
MDAVDH	3	1631442.9	1774550.0	7159.0	41.3	1.45	0.409	0.454	1.80E-04	-3.7447	0.0132	2.1266	0.0065	-2.1884
MDAVDH	3	1631442.9	1774550.0	7159.0	44.7	1.36	0.37	0.485	9.80E-05	-4.0088	0.0199	2.4288	0.0049	-2.309
MDAVDH	3	1631442.9	1774550.0	7159.0	47.3	1.28	0.396	0.518	1.50E-04	-3.8239	0.0143	2.5127	0.0051	-2.2958
MDAVDH	3	1631442.9	1774550.0	7159.0	49.6	1.24	0.384	0.534	2.10E-04	-3.6778	0.0133	2.8635	0.0044	-2.3555
MDAVDH	3	1631442.9	1774550.0	7159.0	56.2	1.23	0.38	0.535	3.00E-04	-3.5229	0.0124	2.4905	0.0064	-2.1917
MDAVDH	3	1631442.9	1774550.0	7159.0	63.7	1.17	0.367	0.558	5.90E-04	-3.2291	0	1.7329	0.0051	-2.2967
MDAVDH	2	1631442.9	1774550.0	7159.0	91.4	1.39	0.383	0.477	2.40E-04	-3.6198	0	2.1917	0.0039	-2.4122
MDAVDH	2	1631442.9	1774550.0	7159.0	93.3	1.37	0.389	0.484	4.60E-04	-3.3372	0.0084	1.9582	0.0089	-2.051
MDAVDH	2	1631442.9	1774550.0	7159.0	96.7	1.49	0.338	0.439	9.50E-05	-4.0223	0.0128	2.967	0.0051	-2.2907
MDAVDH	2	1631442.9	1774550.0	7159.0	98.3	1.46	0.317	0.448	9.00E-05	-4.0458	0	2.0666	0.0021	-2.6695

Borehole	Unit	East	North	Elev (ft.)	Depth (ft.)	PB (g/cm**3)	Theta S	Porosity	Ksat (cm/sec)	Log Ksat	Theta R	N	Alpha (cm**-1)	Log Alph
MDAVDH	2	1631442.9	1774550.0	7159.0	104.7	1.64	0.269	0.381	2.10E-05	-4.6778	0.0138	2.5215	0.0029	-2.5451
MDAVDH	2	1631442.9	1774550.0	7159.0	109.6	1.61	0.28	0.394	3.40E-05	-4.4685	0.0076	2.1169	0.0036	-2.4461
MDAVDH	2	1631442.9	1774550.0	7159.0	144.0	1.67	0.284	0.369	3.00E-05	-4.5229	0.0209	1.8948	0.0039	-2.4067
MDAVDH	2	1631442.9	1774550.0	7159.0	159.6	1.51	0.364	0.429	1.30E-04	-3.8861	0	1.8791	0.0018	-2.7447
LADP-4	Otowi	1633175.6	1774718	6740.2	309.55	1.16	0.464	0.512	3.30E-05	-4.4815	0	2.0705	0.0027	-2.5670
LADP-4	Otowi	1633175.6	1774718	6732.3	317.40	1.18	0.4	0.512	3.20E-05	-4.4949	0	3.1988	0.0008	-3.1135
LADP-4	Otowi	1633175.6	1774718	6729.6	320.15	1.14	0.446	0.522	4.60E-05	-4.3372	0	1.8835	0.0035	-2.45
LADP-4	Otowi	1633175.6	1774718	6719.3	330.40	1.14	0.418	0.528	3.80E-05	-4.4202	0.01	2.1415	0.0024	-2.6252
LADP-4	Otowi	1633175.6	1774718	6711.5	338.20	1.11	0.408	0.541	6.00E-05	-4.2218	0	3.3755	0.0009	-3.0506
LADP-4	Otowi	1633175.6	1774718	6706.9	342.85	1.16	0.416	0.514	1.80E-05	-4.7447	0	2.3811	0.0019	-2.7189
LADP-4	Otowi	1633175.6	1774718	6702.2	347.55	1.16	0.408	0.513	2.90E-05	-4.5376	0	2.2625	0.0019	-2.712
LADP-4	Otowi	1633175.6	1774718	6697.4	352.30	1.15	0.406	0.526	3.20E-05	-4.4949	0	2.6222	0.0014	-2.8507
LADP-4	Otowi	1633175.6	1774718	6638.3	411.45	1.44	0.398	0.406	7.10E-05	-4.1487	0.0145	1.7677	0.0041	-2.38
LADP-4	Otowi	1633175.6	1774718	6566.8	482.95	1.27	0.401	0.475	9.10E-05	-4.041	0	1.6368	0.0045	-2.3487
LADP-4	Otowi	1633175.6	1774718	6552.1	497.65	1.29	0.35	0.467	4.00E-05	-4.3979	0	1.6421	0.0041	-2.3840
LADP-4	Otowi	1633175.6	1774718	6549.7	500.05	1.23	0.381	0.478	2.90E-05	-4.5376	0.0151	1.7429	0.0041	-2.38
LADP-4	Otowi	1633175.6	1774718	6522.3	527.40	1.34	0.353	0.425	1.40E-07	-6.8539	0	2.3134	0.0009	-3.0506
LADP-4	1v	1633175.6	1774718	6946.8	102.95	1.28	0.409	0.504	1.60E-04	-3.7959	0	1.8463	0.0035	-2.4609
LADP-4	1v	1633175.6	1774718	6898.5	151.20	1.23	0.547	0.49	5.10E-05	-4.2924	0	1.3938	0.0063	-2.198
LADP-4	1g	1633175.6	1774718	6888.7	161.00	1.19	0.572	0.51	1.30E-04	-3.8861	0	1.5712	0.0056	-2.2557
LADP-4	1g	1633175.6	1774718	6844.6	205.15	1.22	0.468	0.495	2.20E-04	-3.6576	0	1.6556	0.0056	-2.2533
LADP-4	1g	1633175.6	1774718	6804.1	245.65	1.2	0.522	0.484	3.30E-04	-3.4815	0	1.4612	0.0156	-1.8057
LADP-4	2	1633175.6	1774718	7033.7	16.05	1.49	0.336	0.42	2.20E-05	-4.6576	0.0243	1.9272	0.0035	-2.4522
LADP-4	2	1633175.6	1774718	7022.5	27.20	1.78	0.264	0.264	2.50E-05	-4.6021	0.012	2.0162	0.0044	-2.361
LADP-4	2	1633175.6	1774718	7019.4	30.35	1.78	0.282	0.308	1.80E-05	-4.7447	0.0172	2.5176	0.0026	-2.58
LADP-4	2	1633175.6	1774718	6993.1	56.60	1.67	0.286	0.31	6.00E-06	-5.2218	0	2.3058	0.0008	-3.091
LADP-4	2	1633175.6	1774718	6979.9	69.80	1.51	0.384	0.412	1.40E-05	-4.8539	0	1.6076	0.0033	-2.476
LADP-4	2	1633175.6	1774718	6969.2	80.50	1.52	0.406	0.373	1.20E-04	-3.9208	0	2.2886	0.0022	-2.657
LADP-3	Otowi	1632989	1773469	6570.2	185.4	1.69	0.257	0.309	2.20E-06	-5.6576	0.0419	3.1668	0.0007	-3.167
LADP-3	Otowi	1632989	1773469	6515.4	240.25	1.25	0.398	0.485	3.10E-05	-4.5086	0	1.9818	0.0012	-2.928
LADP-3	Otowi	1632989	1773469	6483.4	272.2	1.3	0.349	0.448	2.00E-05	-4.699	0	1.7494	0.0022	-2.667

Borehole	Unit	East	North	Elev	Depth	PB	Theta S	Porosity	Ksat	Log Ksat	Theta R	N	Alpha	Log Alpha
				(ft.)	(ft.)	(g/cm**3)			(cm/sec)				(cm**-1)	
LADP-3	Otowi	1632989	1773469	6480	275.6	1.29	0.392	0.468	2.30E-05	-4.6383	0	2.8065	0.0007	-3.1674
LADP-3	Otowi	1632989	1773469	6462.5	293.15	1.25	0.368	0.465	1.50E-05	-4.8239	0	1.688	0.0033	-2.4775
LADP-3	Otowi	1632989	1773469	6454.2	301.45	1.28	0.346	0.471	2.20E-05	-4.6576	0	1.6437	0.0047	-2.3297
LADP-3	Guaje	1632989	1773469	6431.8	323.9	0.81	0.557	0.667	1.5E-04	-3.824	0	4.0258	0.0008	-3.0915

Appendix 2 Soil water content and pressure data for boreholes LADP-3, LADP-4, and MDAVDH.

SAMPLE ID 1748 LADP-3 185.3-185.5	
h	θ
(cm)	
0.0	0.257
102.0	0.225
316.0	0.225
1030.0	0.222
3335.0	0.073
9474.0	0.056
20590.0	0.035

SAMPLE ID 1749 LADP-3 240.0-240.5	
h	θ
(cm)	
0.0	0.398
102.0	0.364
337.0	0.316
1020.0	0.286
5395.0	0.039
10045.0	0.031
30268.0	0.024

SAMPLE ID 1750 LADP-3 271.9-272.5	
h	θ
(cm)	
0.0	0.349
92.0	0.325
311.0	0.283
1020.0	0.194
4813.0	0.036
12452.0	0.033
24169.0	0.028

SAMPLE ID 1751 LADP-3 275.3-275.9	
h	θ
(cm)	
0.0	0.392
102.0	0.359
337.0	0.337
1020.0	0.332
4253.0	0.042
9800.0	0.032
21161.0	0.024

SAMPLE ID 1752 LADP-3 292.8-923.5	
h	θ
(cm)	
0.0	0.368
102.0	0.349
316.0	0.262
1030.0	0.167
4283.0	0.046
8566.0	0.029
22354.0	0.027

SAMPLE ID 1753 LADP-3 301.2-301.7	
h	θ
(cm)	
0.0	0.346
92.0	0.299
316.0	0.229
1020.0	0.141
4314.0	0.033
8505.0	0.027
19682.0	0.015

SAMPLE ID 1755 LADP-3 323.6-324.2	
h	θ
(cm)	
0.0	0.557
102.0	0.456
337.0	0.445
1020.0	0.422
2825.0	0.035
11116.0	0.031
18785.0	0.024

SAMPLE ID 1758 LADP-4 15.8-16.3	
h	θ
(cm)	
0.0	0.336
102.0	0.315
337.0	0.228
1020.0	0.121
3651.0	0.043
12136.0	0.037
15746.0	0.035

SAMPLE ID 1759 LADP-4 27.0-27.4	
h	θ
(cm)	
0.0	0.264
112.0	0.225
337.0	0.165
1020.0	0.053
3386.0	0.034
10300.0	0.019
30410.0	0.013

SAMPLE ID 1760 LADP-4 30.0-30.7	
h	θ
(cm)	
0.0	0.282
92.0	0.263
311.0	0.221
1020.0	0.073
4467.0	0.024
8260.0	0.022
29819.0	0.016

SAMPLE ID 1761 LADP-4 56.0-57.2	
h	θ
(cm)	
0.0	0.286
102.0	0.278
337.0	0.239
1020.0	0.234
3478.0	0.046
10626.0	0.036
20314.0	0.032

SAMPLE ID 1762 LADP-4 69.5-70.1	
h	θ
(cm)	
0.0	0.384
102.0	0.348
306.0	0.275
1020.0	0.211
4844.0	0.046
9464.0	0.034
30257.0	0.028

SAMPLE ID 1763 LADP-4 80.4-80.6	
h	θ
(cm)	
0.0	0.406
102.0	0.359
337.0	0.336
1020.0	0.122
4487.0	0.026
9280.0	0.019
21834.0	0.014

SAMPLE ID 1764 LADP-4 102.8-103.1	
h	θ
(cm)	
0.0	0.409
102.0	0.362
337.0	0.278
1020.0	0.154
3396.0	0.027
8628.0	0.017
16613.0	0.013

SAMPLE ID 1765 LADP-4 160.9-161.1	
h	θ
(cm)	
0.0	0.572
102.0	0.483
316.0	0.366
1030.0	0.24
4253.0	0.065
9515.0	0.051
17571.0	0.038

SAMPLE ID 1766 LADP-4 204.9-205.4	
h	θ
(cm)	
0.0	0.468
102.0	0.404
306.0	0.273
1020.0	0.202
2611.0	0.035
8281.0	0.025
28788.0	0.019

SAMPLE ID 1769 LADP-4 245.5-245.8	
h	θ
(cm)	
0.0	0.522
112.0	0.34
337.0	0.252
1020.0	0.176
4212.0	0.046
11728.0	0.035
19733.0	0.029

SAMPLE ID 1771 LADP-4 309.3-309.8	
h	θ
(cm)	
0.0	0.464
92.0	0.408
316.0	0.358
1020.0	0.153
2917.0	0.031
9576.0	0.019
15817.0	0.016

SAMPLE ID 1772 LADP-4 317.0-317.8	
h	θ
(cm)	
0.0	0.4
102.0	0.368
337.0	0.366
1020.0	0.314
3202.0	0.045
12319.0	0.043
31981.0	0.025

SAMPLE ID 1773 LADP-4 319.8-320.5	
h	θ
(cm)	
0.0	0.446
102.0	0.415
316.0	0.303
1030.0	0.149
3080.0	0.034
11911.0	0.02
17296.0	0.019

SAMPLE ID 1774 LADP-4 330.0-330.8	
h	θ
(cm)	
0.0	0.418
92.0	0.397
311.0	0.337
1020.0	0.151
3304.0	0.04
8475.0	0.028
26464.0	0.015

SAMPLE ID 1775 LADP-4 342.5-343.2	
h	θ
(cm)	
0.0	0.416
92.0	0.384
311.0	0.364
1020.0	0.147
3202.0	0.029
11412.0	0.018
26199.0	0.015

SAMPLE ID 1776 LADP-4 338.0-338.4	
h	θ
(cm)	
0.0	0.408
102.0	0.398
337.0	0.395
1020.0	0.279
3396.0	0.024
9474.0	0.02
28320.0	0.011

SAMPLE ID 1777 LADP-4 347.0-348.1	
h	θ
(cm)	
0.0	0.408
92.0	0.382
311.0	0.361
1020.0	0.147
4793.0	0.025
9239.0	0.023
16235.0	0.023

SAMPLE ID 1778 LADP-4 352.0-352.6	
h	θ
(cm)	
0.0	0.406
102.0	0.399
306.0	0.38
1020.0	0.187
2437.0	0.046
10993.0	0.022
21426.0	0.019

SAMPLE ID 1779 LADP-4 411.4-411.5	
h	θ
(cm)	
0.0	0.398
102.0	0.353
306.0	0.278
1020.0	0.139
4263.0	0.047
12136.0	0.032
29784.0	0.032

SAMPLE ID 1780 LADP-4 482.8-483.1	
h	θ
(cm)	
0.0	0.401
92.0	0.351
316.0	0.274
1020.0	0.165
3019.0	0.051
8179.0	0.039
23435.0	0.03

SAMPLE ID 1781 LADP-4 499.9-500.2	
h	θ
(cm)	
0.0	0.381
102.0	0.353
316.0	0.252
1030.0	0.151
3212.0	0.049
9392.0	0.041
17388.0	0.037

SAMPLE ID 1782 LADP-4 497.3-498.0	
h	θ
(cm)	
0.0	0.35
92.0	0.321
316.0	0.24
1020.0	0.146
3814.0	0.046
9821.0	0.044
5878.0	0.037

SAMPLE ID 1783 LADP-4 527.2-527.6	
h	θ
(cm)	
0.0	0.353
102.0	0.337
306.0	0.307
1020.0	0.271
3335.0	0.052
9851.0	0.044
20345.0	0.038

SAMPLE ID 1784 LADP-4 151.0-151.4	
h	θ
(cm)	
0.0	0.547
102.0	0.461
306.0	0.384
1020.0	0.282
4589.0	0.148
11422.0	0.086
17653.0	0.073

SAMPLE ID 7366 MDAVDH 12.0-12.7	
h	θ
(cm)	
1.0	0.32
51.0	0.31
326.0	0.144
1020.0	0.073
4385.0	0.029
7343.0	0.018
17031.0	0.011

SAMPLE ID 7365 MDAVDH 6.4-7.0	
h	θ
(cm)	
1.0	0.313
102.0	0.287
331.0	0.198
1020.0	0.094
3467.0	0.047
8158.0	0.036
29064.0	0.025

SAMPLE ID 7368 MDAVDH 25.0-25.4	
h	θ
(cm)	
1.0	0.323
56.0	0.316
342.0	0.125
999.0	0.068
3263.0	0.023
9484.0	0.012
16725.0	0.007

SAMPLE ID 7367 MDAVDH 14.2-14.8	
h	θ
(cm)	
1.0	0.336
51.0	0.325
326.0	0.142
1020.0	0.097
5507.0	0.013
14481.0	0.008
43443.0	0.003

SAMPLE ID 7369 MDAVDH 31.9-32.5	
h	θ
(cm)	
1.0	0.352
56.0	0.326
342.0	0.114
999.0	0.049
3875.0	0.018
8158.0	0.013
23965.0	0.008

SAMPLE ID 7370 MDAVDH 38.2-38.8	
h	θ
(cm)	
1.0	0.39
57.0	0.373
326.0	0.189
1122.0	0.053
5507.0	0.024
8362.0	0.012
45891.0	0.008

SAMPLE ID 7371 MDAVDH 41.1-41.5	
h	θ
(cm)	
1.0	0.409
56.0	0.393
342.0	0.157
999.0	0.065
3977.0	0.031
11830.0	0.013
21620.0	0.009

SAMPLE ID 7372 MDAVDH 44.4-45.0	
h	θ
(cm)	
1.0	0.37
102.0	0.35
337.0	0.156
989.0	0.072
4793.0	0.028
12034.0	0.018
20192.0	0.01

SAMPLE ID 7373 MDAVDH 47.0-47.5	
h	θ
(cm)	
1.0	0.396
102.0	0.364
337.0	0.157
989.0	0.056
6221.0	0.021
9994.0	0.011
21926.0	0.009

SAMPLE ID 7374 MDAVDH 49.2-50.0	
h	θ
(cm)	
1.0	0.384
102.0	0.375
331.0	0.158
1020.0	0.052
5711.0	0.017
10810.0	0.009
21518.0	0.003

SAMPLE ID 7375 MDAVDH 56.0-56.3	
h	θ
(cm)	
1.0	0.38
102.0	0.321
331.0	0.12
1020.0	0.037
4283.0	0.025
8464.0	0.009
16623.0	0.006

SAMPLE ID 7376 MDAVDH 63.4-64.0	
h	θ
(cm)	
1.0	0.367
102.0	0.27
331.0	0.252
1020.0	0.114
4079.0	0.016
7954.0	0.008
21008.0	0.003

SAMPLE ID 7377 MDAVDH 91.2-91.5	
h	θ
(cm)	
1.0	0.383
102.0	0.319
326.0	0.246
1020.0	0.052
6221.0	0.011
11524.0	0.009
16113.0	0.007

SAMPLE ID 7378 MDAVDH 93.0-93.6	
h	θ
(cm)	
1.0	0.389
51.0	0.362
326.0	0.129
1020.0	0.068
6425.0	0.014
13869.0	0.011
24577.0	0.007

SAMPLE ID 7379 MDAVDH 96.4-97.0	
h	θ
(cm)	
1.0	0.338
102.0	0.313
331.0	0.112
1020.0	0.033
5201.0	0.014
12136.0	0.009
17439.0	0.01

SAMPLE ID 7380 MDAVDH 98.0-98.5	
h	θ
(cm)	
1.0	0.317
102.0	0.295
326.0	0.264
1020.0	0.124
5405.0	0.023
9994.0	0.011
14379.0	0.011

SAMPLE ID 7381 MDAVDH 104.4-105.0	
h	θ
(cm)	
1.0	0.269
96.0	0.26
331.0	0.19
1010.0	0.062
3263.0	0.023
10198.0	0.017
13257.0	0.013

SAMPLE ID 7382 MDAVDH 109.4-109.7	
h	θ
(cm)	
1.0	0.28
102.0	0.272
331.0	0.174
1020.0	0.073
3875.0	0.021
8362.0	0.014
18560.0	0.009

SAMPLE ID 7383 MDAVDH 143.7-144.2	
h	θ
(cm)	
1.0	0.284
54.0	0.278
326.0	0.19
1122.0	0.082
2651.0	0.071
4079.0	0.031
35591.0	0.024

SAMPLE ID 7384 MDAVDH 153.3-153.7	
h	θ
(cm)	
1.0	1.184
112.0	1.072
347.0	0.948
1020.0	0.761
5201.0	0.091
11320.0	0.042
17948.0	0.035

SAMPLE ID 7385 MDAVDH 159.2-159.9	
h	θ
(cm)	
1.0	0.364
112.0	0.32
347.0	0.268
1020.0	0.233
5201.0	0.025
7139.0	0.019
14379.0	0.015

SAMPLE ID 7386 MDAVDH 161.8-162.5	
h	θ
(cm)	
1.0	0.377
102.0	0.275
347.0	0.26
377.0	0.149
1020.0	0.132
6425.0	0.02
7343.0	0.016
15093.0	0.014

SAMPLE ID 7387 MDAVDH 163.6-164.2	
h	θ
(cm)	
1.0	0.415
102.0	0.353
337.0	0.167
989.0	0.075
3365.0	0.038
13971.0	0.015
32328.0	0.011

SAMPLE ID 7388 MDAVDH 166.8-167.2	
h	
(cm)	θ
1.0	0.404
112.0	0.317
306.0	0.16
1020.0	0.107
5405.0	0.024
9382.0	0.01
22028.0	0.006

SAMPLE ID 7389 MDAVDH 183.6-184.0	
h	θ
(cm)	
1.0	0.436
102.0	0.323
337.0	0.157
989.0	0.062
3875.0	0.021
10708.0	0.017
29064.0	0.01

SAMPLE ID 7390 MDAVDH 193.5-193.8	
h	θ
(cm)	
1.0	0.628
112.0	0.486
347.0	0.245
1020.0	0.117
3671.0	0.052
8260.0	0.013
15297.0	0.008

SAMPLE ID 7391 MDAVDH 214.0-214.3	
h	θ
(cm)	
1.0	0.525
112.0	0.417
347.0	0.394
1020.0	0.367
4487.0	0.064
7852.0	0.028
23863.0	0.008

SAMPLE ID 7392 MDAVDH 218.3-219.0	
h	θ
(cm)	
1	0.486
102	0.385
347	0.304
377	0.0253
1020	0.229
5507	0.057
10606	0.032
12849	0.019

SAMPLE ID 7393 MDAVDH 223.2-223.5	
h	θ
(cm)	
1	0.464
102	0.374
347	0.343
377	0.245
1020	0.186
6323	0.086
11320	0.065
16215	0.04

SAMPLE ID 7394 MDAVDH 233.5-234.0	
h	θ
(cm)	
1.0	0.62
48.0	0.528
326.0	0.355
1122.0	0.288
3161.0	0.089
7649.0	0.009
36203.0	0.009

SAMPLE ID 7395 MDAVDH 253.6-254.0	
h	θ
(cm)	
1.0	0.475
51.0	0.411
326.0	0.264
1020.0	0.161
5201.0	0.027
8668.0	0.022
24781.0	0.016

SAMPLE ID 7396 MDAVDH 268.4-269.0	
h	θ
(cm)	
1.0	0.467
48.0	0.411
326.0	0.229
1122.0	0.17
2957.0	0.12
7445.0	0.041
16623.0	0.024