WM2008 Conference, February 24-28, 2008, Phoenix, AZ
Abstract #8403

Development of Vadose-Zone Hydraulic-Parameter Values

P. M. Rogers, Fluor Hanford, Soil & Groundwater Remediation Project,
1200 Jadwin, Richland, WA 99352

Zane P. Walton, QinetiQ North America,
1180 N. Town Center Drive, Las Vegas, NV 89144

Gerald H. Nieder-Westermann, Bechtel SAIC Company, LLC,
1180 N. Town Center Drive, Las Vegas, NV 89144

ABSTRACT

Several approaches have been developed to establish a relation between the soil-moisture retention curve and readily available soil properties. Those relationships are referred to as pedotransfer functions. Described in this paper are the rationale, approach, and corroboration for use of a nonparametric pedotransfer function for the estimation of soil hydraulic-parameter values at the Yucca Mountain area in Nevada for simulations of net infiltration. This approach, shown to be applicable for use at Yucca Mountain, is also applicable for use at the Hanford Site where the underlying data were collected.

INTRODUCTION

A pedotransfer function (PTF) approach is developed and used to estimate soil hydraulic parameters needed for infiltration modeling, because site-specific soils information in the Yucca Mountain area are generally limited to grain-size distribution with some measurements of bulk density and saturated hydraulic conductivity. The Yucca Mountain infiltration model requires soil hydraulic parameters that include saturated hydraulic conductivity (K_{sat}), field capacity (FC) commonly defined as the soil-moisture content (MC) at −0.33 bar (−336.6 cm water) and alternatively the MC at −0.10 bar (−102 cm water), permanent wilting point (PWP) defined as the soil-moisture content at −60 bar (−61,200 cm water), and saturation (θ_s). Site-specific measurements of these parameters are not available or are scarce. Additionally, the PTF approach described herein can be used to estimate residual saturation (θ_r) and the moisture-retention curve-fitting parameters, α and n.

ALTERNATIVE PEDOTRANSFER FUNCTIONS

Of the several published relationships between the soil-moisture retention curve and readily available soil properties (Cornelis et al., 2001 [1]) there are at least three general approaches (Nemes et al., 2006 [2], p. 327). Two of the approaches are parametric approaches that rely on equations with parameters found from fitting those equations to data. Examples are regression techniques such as those outlined by Rawls and Brakensiek (1985 [3]) and later implemented by Carsel and Parrish (1988 [4]) and artificial neural networks such as those developed for the U.S. Department of Agriculture (USDA) program ROSETTA (Schaap et al., 2001 [5]). Parametric approaches have drawbacks that include identifying the correct equation and determining that the probability distributions of errors are similar across the data space

(Nemes et al., 2006 [2], p. 327). A third approach is a nonparametric approach. A nonparametric approach can be beneficial when the form of the relationship between the inputs and outputs in not known in advance, such as is the case with soil hydraulic properties (Nemes et al., 2006 [2], p. 327).

Both the ROSETTA and Rawls and Brakensiek regression techniques require the fraction of sand, silt, and clay in a soil that can be an effective predictor of hydraulic-parameter values. The ROSETTA program database (Schaap et al., 2001 [5]) contains 2,134 samples for water retention, 1,306 samples for K_{sat}, and 235 samples for unsaturated hydraulic conductivity. Samples were obtained from a large number of sources that involve agricultural and nonagricultural soils in temperate-climate zones of the northern hemisphere, mainly from the USA and some from Europe. The advantages of ROSETTA include its ease of use, its highly respected developers, and the fact that it was developed by the USDA.

Another approach considered was documented in Carsel and Parrish (1988 [4]) and in Rawls and Brakensiek (1985 [3]). Joint multivariate-density functions were developed for various USDA textural classes (Carsel and Parrish 1988 [4], p. 755) based on a database of soil samples from 42 states (Carsel and Parrish 1988 [4], p. 758). The advantages of the Carsel and Parrish approach include its ease of use, that it is a published approach, and that its developers are highly respected.

A disadvantage to both parametric approaches for use at Yucca Mountain is that soils are collected from many types of climatic and depositional settings in the USA and Europe, and mostly from agricultural areas, in contrast to the desert environment at Yucca Mountain. Soils from temperate and subtropical climates and agricultural soils generally have larger holding capacities compared to desert soils, and the PTFs of the Rawls and Brakensiek method and of ROSETTA are largely based on such soils. Additionally, the collection methods and laboratory procedures, especially those related to the ROSETTA program database, are not documented for every sample. Finally, the U.S. Geological Survey (USGS) found that ROSETTA leads to unreasonably high recharge estimates in a recharge study at the Glassboro Study Area, New Jersey (USGS 2003 [6], p. 2). The unreasonably high recharge estimates primarily were caused by the over-prediction of saturated hydraulic conductivity (USGS 2003 [6], p. 2). The study used data from six locations in southern New Jersey that appear to have steady-state flow conditions, and five hydraulic-property prediction and parameterization techniques were evaluated for recharge estimation. The unsaturated zone at the Glassboro Study Area is mainly sand to sandy loam in texture. It is not clear why ROSETTA may be over-predicting K_{sat}; the same study found that water retention was predicted relatively well by ROSETTA (USGS 2003 [6], p. 2).

Considering the factors above, it is reasoned that a nonparametric approach might provide reasonable soil hydraulic-parameter estimates and overcome or reduce some of the uncertainties associated with parametric approaches if a site(s) were available that had (1) similar soil characteristics and (2) well-documented soil sampling/testing. Ideally, such a site would be at or adjacent to Yucca Mountain, but such is not the case. However, there is a substantial database of soil characteristics associated with the Hanford Site, located in the semiarid region of Eastern Washington. This database is documented in Khaleel and Freeman (1995 [7], Appendices A and B) and is relatively complete. In the report and database by Khaleel and Freeman (1995 [7], Appendices A and B,) grain-size distributions, moisture-retention measurements, and saturated hydraulic-conductivity values from the laboratory analysis of 183 soil samples are used to develop the following hydraulic parameters values: residual saturation (θ_r), saturation (θ_s), saturated hydraulic conductivity (K_{sat}), and the moisture-retention curve-fitting parameters, α and n. Also, this Hanford Site database includes moisture-retention curves developed by fitting the curves to the data using *The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils* (van Genuchten et al., 1991 [8]). These curves can be used to estimate the FC and PWP. The FC is defined as the soil-moisture content at −0.33 bar (–336.6 cm water) and at –0.10 bar (−102 cm water). The PWP is defined as the soil-moisture content at −60 bar (−61,200 cm water). Note that the Hanford Site database does not contain other parameters useful for the development of PTFs, such as bulk density, porosity, organic content, and plasticity index. The soils and sediments identified in the Hanford Site database have developed under semiarid climatic conditions similar to those at Yucca Mountain. The average annual precipitation at the Hanford Site is about 17.3 cm/yr (Truex et al., 2001b [9], Section 3.2) compared to about 18 cm/yr for Yucca Mountain (SNL 2006 [10], Section 6.1.5.1, Table 6.1-4). Hanford Site sediments have organic-carbon content below 0.5 wt% (Truex et al., 2001a [11], Section 2.3.1.2). Organic-carbon content in agricultural areas of Nye County, Nevada, range from about 0.006% to 0.70% (USDA 2006 [12]).

The soils at the Hanford Site contain less organic material than soils developed under wetter conditions, which also is true of the soils at Yucca Mountain. The soil depositional processes at Yucca Mountain, compared to those at the Hanford Site, include some differences that can contribute to differences in grain shape and soil structure. Large-scale fluvial processes dominate Hanford Site soil and sediments, resulting in more-rounded particles and single-grain structure. Small-scale fluvial processes and eolian (Soil Unit 6)[1] processes are the dominant processes at Yucca Mountain, resulting in less-rounded particles with more angular fragments. Soils of fluvial origin associated with stream and alluvial fan material (Soil Units 1 through 4) cover over 40% of the infiltration-model area. An eolian component has accumulated on these surfaces through time, which is concentrated in the upper 0.5 to 1 m of the soil profile. Deposits representing eolian source material are mapped over only 4.8% of the area (Soil Unit 6).

The dominant surficial deposit (54% of the model area; Soil Units 5, 7, and 9) is colluvium. The colluvium consists of rock fragments of parent material that have been separated from the underlying intact bedrock through weathering processes. Colluvium by definition, however, does not remain in situ, but moves or has moved, downslope through gravitational processes. The fine-grained component of colluvial soils is interpreted to be the result of the influx of eolian material. There are depositional-mode differences between the Yucca Mountain soils and Hanford Site soils and sediments; the differences in the associated hydraulic parameters are not quantified, however, because the Yucca Mountain hydraulic data are too limited.
Such differences contribute to an overall uncertainty, captured by the development of descriptive statistics for each hydraulic parameter, which include the parameter mean and standard deviations. The identification and evaluation of the Hanford Site database leads to the assumption that an adequate analogous data set exists from which a nonparametric PTF can be implemented and tested. Subsequent sections of this paper describe the implementation of the

---

[1] See Table II for a description of the soil units.

PTF matching approach and corroboration of the results with PTF methods outlined by Rawls and Brakensiek (1985 [3]), the PTF program called ROSETTA (Schaap et al., 2001 [5]), and limited data from nearby Nye County, Nevada.

NONPARAMETRIC PEDOTRANSFER-FUNCTION MATCHING APPROACH

On the basis of soil texture, Yucca Mountain soil samples were matched to the analogous Hanford Site sediment and soil samples. Both the Yucca Mountain soil-sample texture information and the Hanford Site information are provided as fraction sand, silt, and clay. Also, both Yucca Mountain data and Hanford Site data contain a percent of rock fragments (or gravel) that, if present, must be accounted with appropriate corrections. The soil hydraulic parameters associated with the Hanford Site sample then are assumed for the Yucca Mountain sample once a best match is determined. In a few cases, exact texture matches have been identified. Generally, however, there is no exact soil-texture match; for these cases, therefore, best matches were selected based on those closely matching the percent of sand, silt, and clay and, secondarily, on those closely matching the sum of the silt and clay fractions.

The Euclidean distance (D_e) is an indicator of how good the soil-texture match is between any two samples, with the smaller D_e values indicating better matches. An exact match has a D_e of zero. The D_e is applied to the sand, silt, and clay values by determining the difference between sand, silt, and clay fractions of any two soil samples. Because three parameters are considered, this application of D_e represents the three-dimensional distance between the three parameters. The expression used to calculate D_e between sand, silt, and clay for a pair of Yucca Mountain and analogous site samples is as follows:

$$D_e\ (3D) = [(Sand_{ymp}-Sand_{Hanford})^2 + (Silt_{ymp}-Silt_{Hanford})^2 + (Clay_{ymp}-Clay_{Hanford})^2]^{1/2}.$$

The use of D_e removes some subjectivity for the matching process and also allows for numerical quantification of match quality. Table I provides a summary of the match quality, as expressed by the D_e, in terms of mean D_e, standard deviation, minimum value, maximum value, and count of the number of matches for samples collected within the Yucca Mountain infiltration model area of interest.

The matching approach is applied to the range of soils observed in the Yucca Mountain area. Soils at Yucca Mountain have been grouped into soil units based on the classification of soils established by the USDA (1999 [13]). The key factors for applying the soil taxonomic principles to the soil groupings are the amount of clay accumulation in the deposits, the extent of pedogenic calcium carbonate accumulated in the deposits, and the variation in the particle-size distribution. The grouping defined in BSC (2006, Section 6.2.3.1 [14]) uses these pedogenic characteristics, which effectively reflect the age of a deposit. This approach for defining soil units applicable to an infiltration model is corroborated by Young et al. (2004 [15]), which demonstrates that infiltration properties are directly related to the age of surficial deposits, and by Duniway et al. (2004 [16]), which demonstrates that the buildup of pedogenic carbonate in a soil increases the water holding capability of the soil.

Table I. Summary of Soil-Sample Match Quality Based on Euclidean Distance.

Soil Unit	Mean D_e[a]	Standard Deviation	Minimum D_e[a]	Maximum D_e[a]	Count
1	0.0454	0.0362	0	0.1700	83
2	0.0357	0.0253	0	0.1338	105
3	0.0370	0.0257	0	0.1393	124
4	0.0219	0.0156	0	0.0566	24
5	0.0336	0.0193	0	0.1068	80
6	NA[b]	NA[b]	NA[b]	NA[b]	NA[b]
7	0.0290	0.0130	0.0141	0.0510	14
9	0.0323	0.0143	0.01	0.0648	24

Source: *Data Analysis for Infiltration Modeling: Development of Soil Units and Associated Hydraulic Parameter Values*, (BSC 2006 [14]), Table 6-6.

[a] D_e = Euclidean distance for matches between the analogous site samples and the Yucca Mountain soil samples, based on fraction of sand, silt, and clay.

[b] NA = The value is not available because Soil Unit 6 was sampled once, the sample was divided into five fractions, and sand sieve analysis tests were performed on the five fractions. The results are reported as fraction sand and fraction silt plus clay. This precludes calculating the three-dimensional D_e for Soil Unit 6.

As summarized from BSC (2006, [14] Section 6.2.2), several soil groupings are considered plus an alternative soil grouping that is the aggregation of all the soils into one group to test the effect of various binning schemes on PTF performance. The highest level of the systematic USDA soil classification is the soil order. A soils map of the United States (USDA 1999 [13], Dominant Soil Orders) shows that only three of 12 soil orders are mapped in southern Nevada:

- Aridisols
- Entisols
- Mollisols.

The other nine soil orders reflect one or more of the following: higher rainfall, colder climate, higher organic carbon, extreme weathering of minerals, or higher clay content than soils observed at Yucca Mountain. Mollisols occur in isolated areas of southern Nevada; generally, these soils are characterized by a relatively thick, dark-colored, humus-rich surface horizon, such as the soils common to grasslands. These soils do not reflect the soils observed at Yucca Mountain and, thus, are, considered not applicable to the infiltration classification. The presence of only aridisols and entisols at Yucca Mountain also has been reported in Resource Concepts (1989 [17]).

Aridisols are soils that do not have water available to mesophytic plants, which are plants that grow under medium conditions of moisture for long periods. The central concept of entisols is that there is little or no evidence of the development of pedogenic horizons, because the deposits are too young for soils to have begun forming; or new material is introduced each year; or the soils are on steep, actively eroding slopes; or the deposits consist of minerals, such as quartz, that do not degrade to form soil horizons. Entisols may overlie buried soils that are greater than 1 m in depth and that demonstrate either clay or carbonate accumulation (USDA 1999 [13], Chapters 11 and 12). The soil groupings in the Yucca Mountain area are summarized as follows.

Soil Unit 1 is an aridisol that contains the oldest Quaternary deposits that have been mapped in the Yucca Mountain area and are interpreted to be fluvial deposits of early to middle Pleistocene age. Their age is indicated by the extent of accumulation of silica and carbonate in the soil horizons, which have become cemented and effectively limit downward migration of infiltrating water, and by a well-packed desert pavement on the surface. Soil Unit 1 encompasses 8% of the mapped area (Table II).

Table II. Calculated Areas and Deposition Type for Each Soil Unit.

Soil Unit, (Type of Deposit)	Soil Taxonomic Name	Number of 30 × 30 m Cells	Calculated Area (%)
1 (Fluvial)	Typic Argidurids	19,900	7.85
2(Fluvial)	Typic Haplicalcids	44,065	17.38
3(Fluvial)	Typic Haplocambids	33,115	13.06
4(Fluvial)	Typic Torriothents	4,630	1.83
5 (Colluvium)	Lithic Haplocambids	116,813	46.06
6 (Eolian)	Typic Torripsamments	12,205	4.81
7(Colluvium)	Lithic Haplargids	3,154	1.24
8 (Bedrock)	Rock	795	0.31
9(Colluvium)	Typic Calciargids	16,441	6.48
10 (Disturbed)	Disturbed Ground	2,479	0.98

Source: *Data Analysis for Infiltration Modeling: Development of Soil Units and Associated Hydraulic Parameter Values*, (BSC 2006 [14]), Tables 6-2 and 6-3.

NOTE: Total number of cells in area of interest = 253,597.

Soil Unit 2 is an aridisol and consists of fluvial deposits that exhibit some argillic (clay) accumulation, as well as noticeable carbonate accumulation. Although the carbonate may be sufficient to almost encompass the horizon, it has not developed a cemented character. The desert pavement developed on the surface of these deposits is moderately-to-tightly packed. Eolian deposits, consisting of a sandy, silty material, have accumulated in the upper 0.5 m underneath the pavement and above the parent fluvial deposits. Soil Unit 2 comprises about 17% of the infiltration model area (Table II).

Soil Unit 3, is an aridisol that has no-to-minor clay accumulation and visible but minor carbonate accumulation in the soil horizons. Desert pavement is not present or is weakly developed where present on these deposits. The addition of some eolian material is evident in the upper 30 cm of the deposits. This deposit covers about 13% of the model area (Table II).

Soil Unit 4 is an entisol with an apparent lack of soil development of clay, or of carbonate accumulation, in any horizon in the recent appearance of these fluvial deposits. They are confined to the modern stream channels and are subject to reworking in runoff events.
The deposits have not been stable for a sufficient time for desert pavement to develop and are found over less than 2% of the infiltration model area (Table II).

Soil Unit 5 is an aridisol and is the most extensive of the model units, covering 46% of the infiltration model area (Table II), and comprises colluvial and debris flow deposits that mantle the hill slopes throughout the Yucca Mountain area. This colluvial unit is typified by a thin mantle of angular rock rubble having lithologies of the underlying bedrock. The colluvium generally is less than 1 m thick. The clast-supported deposit lacks fine-grained material at the surface, but silt and sand of inferred eolian origin occur beneath the surface and increase with depth. The unit is poorly vegetated and occurs in various hill-slope positions. Some deposits are estimated to be of early to mid-Pleistocene age, based on desert varnish development on rock clasts.

Soil Unit 6 is an entisol and occurs in about 5% of the mapped area (Table II). The most prominent units are the sand ramps that are preserved on the flanks of bedrock highs, such as Busted Butte. Some deposits are up to 22 m thick and exhibit multiple buried soil horizons, suggesting an episodic depositional history. The unit is primarily gravelly sand, with 5% to 50% gravel; soil development is evidenced by argillic and carbonate horizons. The angular gravel observed in exposures is interpreted to indicate substantial colluvial and possibly sheetwash processes during deposition.

Soil Unit 7 is an aridisol that occurs in about 1% of the Yucca Mountain area (Table II) and is confined to vegetated ridgetops in the northernmost part of the infiltration model area. It is a thin mantle, generally less than 1 m thick, of an angular gravel diamicton composed of tabular slabs of the underlying Tiva Canyon bedrock mixed with a sandy clay loam soil matrix. The fine-grained matrix is attributed to an eolian origin. A tightly packed desert pavement has developed on the relatively level surfaces.

Soil Unit 8 is assumed in those areas where bedrock is exposed at the surface.

Soil Unit 9 is an aridisol and is the group of vegetated colluvial deposits at the toes of hillsides (USDA 1999 [13], Table 6-2). This unit defines about 6% of the model area (Table II) and consists of interbedded colluvium and debris flow deposits, grading to and interbedded with alluvium on upper fan surfaces. The reported thickness ranges from 0.5 to 3 m, and the extent of soil development observed is comparable to that of Soil Units 3 and 4.

Soil Unit 10 is disturbed ground consisting of less than 1% of the Yucca Mountain area and is not included in this analysis.

CORROBORATION OF THE MATCHING APPROACH

The matching approach discussed above is corroborated by comparison to Rawls and Brakensiek (1985 [3]), implemented by Carsel and Parrish (1988 [4]), the ROSETTA program and database, a neural network-based model; a description of the algorithms and neural network methodology is provided by Schaap et al. (1998 [18] and 2001 [5]), and to limited Nye County, Nevada, data collect by the USDA.

The method outlined by Rawls and Brakensiek (1985 [3]) is performed with a multiple regression model of the form:

$$\begin{aligned}
&\ln(K_{sat}),\ \theta_r,\ \ln(\alpha^{-1}),\ \ln(n-1) = \\
&[c_0 + c_1S + c_2C + c_3\theta_s + c_{11}S^2 + c_{22}C^2 + c_{33}\theta_s^2 + c_{12}S\%C + c_{13}S\theta_s + c_{23}C\theta_s + \\
&c_{112}S^2C + c_{223}C^2\theta_s + c_{113}S^2\theta_s + c_{122}SC^2 + c_{233}C\theta_s^2 + c_{1133}S^2\theta_s^2 + c_{2233}C^2\theta_s^2],
\end{aligned}$$

where

K_{sat} = Saturated hydraulic conductivity (cm/h)
θ_r = Residual water content (cm^3/cm^3)
α = Empirical van Genuchten et al. (1991 [8]) curve fitting constant (1/cm)
n = Empirical van Genuchten et al. (1991 [8]) curve fitting constant (unitless)
c = Coefficients
S = Percent sand, by weight ($5<S<70$)
C = Percent clay, by weight ($5<C<60$)
θ_s = Total saturated water content (cm^3/cm^3).

The coefficient, c, values (Table III) originally were taken from Carsel and Parrish (1988 [4], Figure 1). Several errors were identified, however, associated with θ_r and ln(α-1) (Carsel and Parrish 1988 [4], Figure 1). Thus, the errors were replaced with correct coefficients from Meyer et al. (1997 [19], p. 5). Soil parameters calculated using the Rawls and Brakensiek (1985 [3]) regression equation are limited to a percent sand range of 5% to 70%. Soil samples with sand ranges greater than 70% must be corrected using the method outlined by Cronican and Gribb (2004 [20]).

Following the derivation of soil properties (Rawls and Brakensiek 1985 [3]) and, as applicable, the correction by Cronican and Gribb (2004 [20]), soil properties were corrected for Yucca Mountain gravel content as was done with the Hanford Site data used in the matching approach (BSC 2006, Section 6.3.3). The mean, standard error, standard deviation, median, minimum, maximum, and number of values (count) were calculated and are presented in BSC (2006, [14] Section 6.3.4).

The analysis using ROSETTA was performed by entering Yucca Mountain soil textures and bulk densities, when available, into the software program through a text input file for each Yucca Mountain sample used in the base case analysis (BSC 2006, Appendix B). Output from ROSETTA consisted of the saturated hydraulic conductivity (K_{sat}), and van Genuchten parameters α and n, θ_r, and θ_s (van Genuchten et al., 1991 [8]). The gravel corrections were performed for K_{sat}, θ_r, and θ_s in the same manner as the analogous site data (BSC 2006, [14] Section 6.3.3). The mean, standard error, standard deviation, median, minimum, maximum, and number of values (count) were calculated and are presented in BSC (2006, [14] Section 6.3.4).

Table III. Rawls and Brakensiek (1985) Regression Constants. (2 Pages)

Term	Natural Log Saturated Hydraulic Conductivity (K_{sat}) ln[cm/h]	Residual Water Content (θ_r) [cm^3/cm^3]	Natural Log (1/α) ln[cm]	Natural Log N −dimensionless
(Constant)	−8.96847	−0.0182482	5.3396738	−0.7842831
S	0	0.00087269	0	0.0177544
C	−0.028212	0.00513488	0.1845038	0
θs	19.52348	0.02939286	−2.48394546	−1.062498
S^2	0.00018107	0	0	−5.30 E-05
C^2	−0.0094125	−0.00015395	−0.00213853	−0.00273493
θ_s^2	−8.395215	0	0	1.11134946

Table III. Rawls and Brakensiek (1985) Regression Constants. (2 Pages)

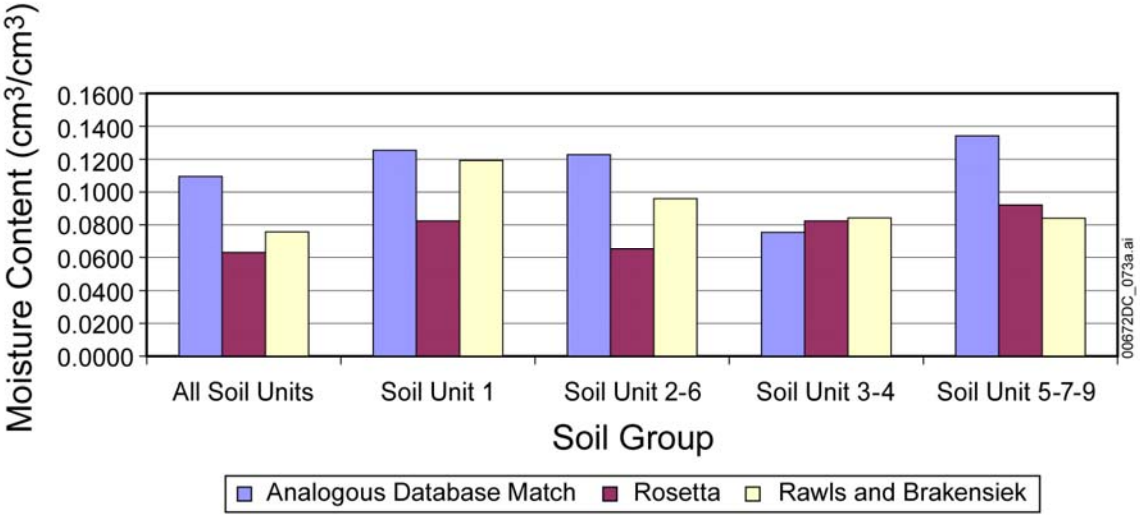
Term	Natural Log Saturated Hydraulic Conductivity (K_{sat}) ln[cm/h]	Residual Water Content (θ_r) [cm^3/cm^3]	Natural Log ($1/\alpha$) ln[cm]	Natural Log N −dimensionless
SC	0	0	0	0
$S\theta_s$	0.077718	−0.0010827	−0.0435649	−0.03088295
$C\theta_s$	0	0	−0.61745089	0
S^2C	0.0000173	0	−1.282 E-05	−2.35 E-06
$C^2\theta_s$	0.02733	0.00030703	0.00895359	0.00798746
$S^2\theta_s$	0.001434	0	−7.2472 E-04	0
SC^2	−0.0000035	0	5.40 E-06	0
$C\theta_s^2$	0	−0.0023584	0.5002806	−0.00674491
$S^2\theta_s^2$	−0.00298	0	0.00143598	2.6587 E-04
$C^2\theta_s^2$	−0.019492	−0.00018233	−0.00855375	−0.00610522

Source: *Data Analysis for Infiltration Modeling: Development of Soil Units and Associated Hydraulic Parameter Values*, (BSC 2006, [14] Table 6-14), after Carsel and Parrish (1988 [4], Figure 1).

NOTE: Corrected coefficients for θ_r and $1/\alpha$ are from Meyer (1997 [19], p. 5).

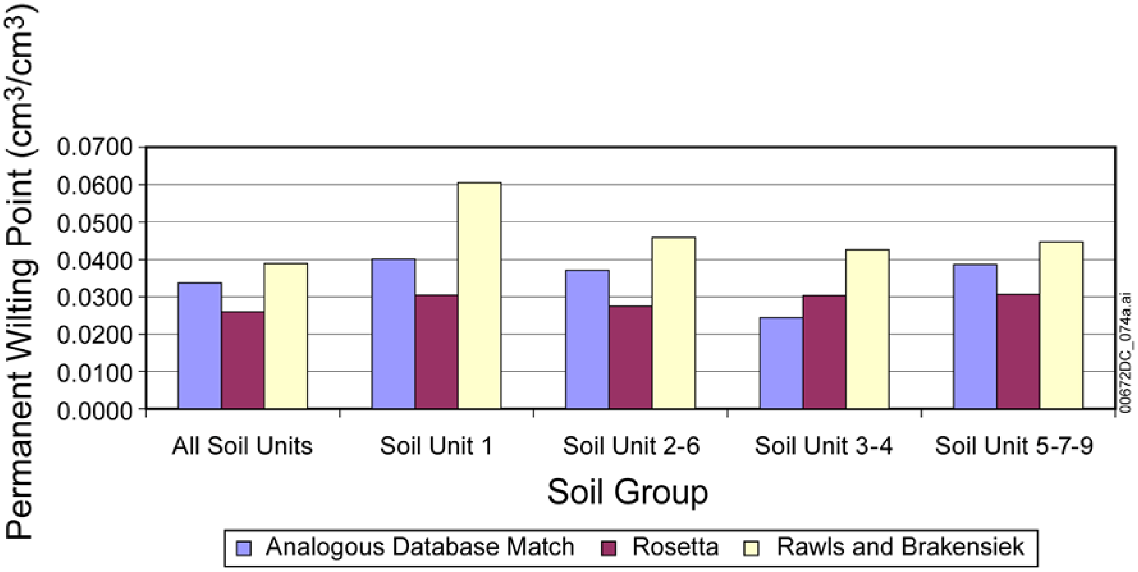
The results of the corroboration are shown below in a series of histograms for moisture contents corresponding to various matric potentials and for K_{sat}. Generally, the corroboration considers groups of soil units: Soil Unit 1; Soil Units 2 and 6; Soil Units 3 and 4; Soil Units 5, 7, and 9; and a group consisting of all soil units. Figures 1 and 2 show that FC moisture content at -0.33 bar (-336.6 cm) and the PWP moisture content at -60 bar (-61,200 cm) for the matching approach are slightly larger than the other two methods. Moisture contents calculated with ROSETTA generally are lower than those calculated with the other two methods.

Figure 3 provides a comparison of the three methods, based on the geometric mean values of K_{sat}. Small K_{sat} values dominate in comparison with the geometric mean. This comparison reveals that the analogous site method (based on the Hanford Site data) and the Rawls and Brakensiek (1985 [3]) method have good agreement and that the ROSETTA results are consistently larger; the smaller the bar, the large the K_{sat} value. This result is consistent with a recharge study at the Glassboro Study Area, New Jersey, by the USGS in which it found that the ROSETTA program led to unreasonably high recharge estimates, primarily because of the over-prediction of K_{sat} (USGS 2003 [6], p. 2).



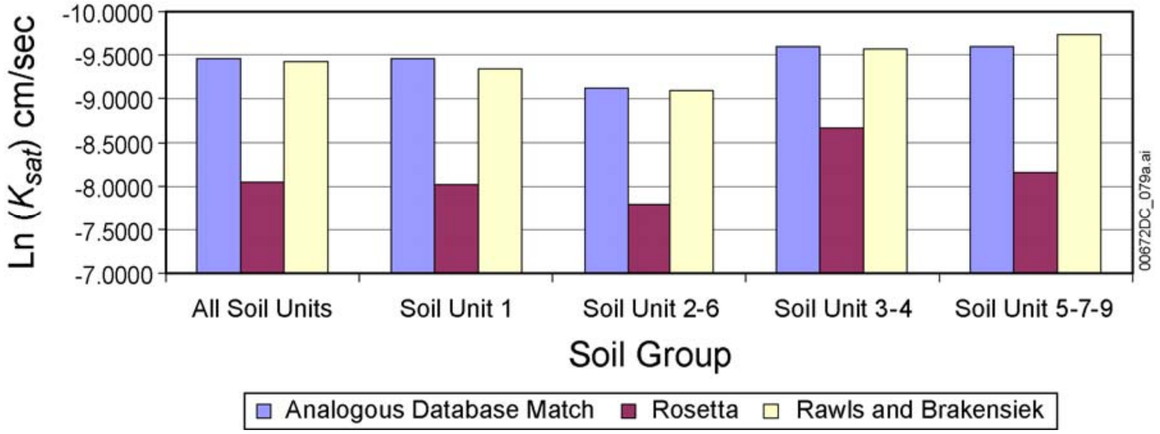
Source: *Data Analysis for Infiltration Modeling: Development of Soil Units and Associated Hydraulic Parameter Values*, (BSC 2006, [14] Figure 6-13).

Fig. 1. Mean Moisture Content Values at –0.33 bar (–336.6 cm) for Three Pedotransfer Function Methods Using Yucca Mountain Data.



Source: *Data Analysis for Infiltration Modeling: Development of Soil Units and Associated Hydraulic Parameter Values*, (BSC 2006, [14] Figure 6-14).

Fig. 2. Mean Permanent Wilting Point at –60 bar (-61,200 cm) for Three Pedotransfer Function Methods Using Yucca Mountain Data.

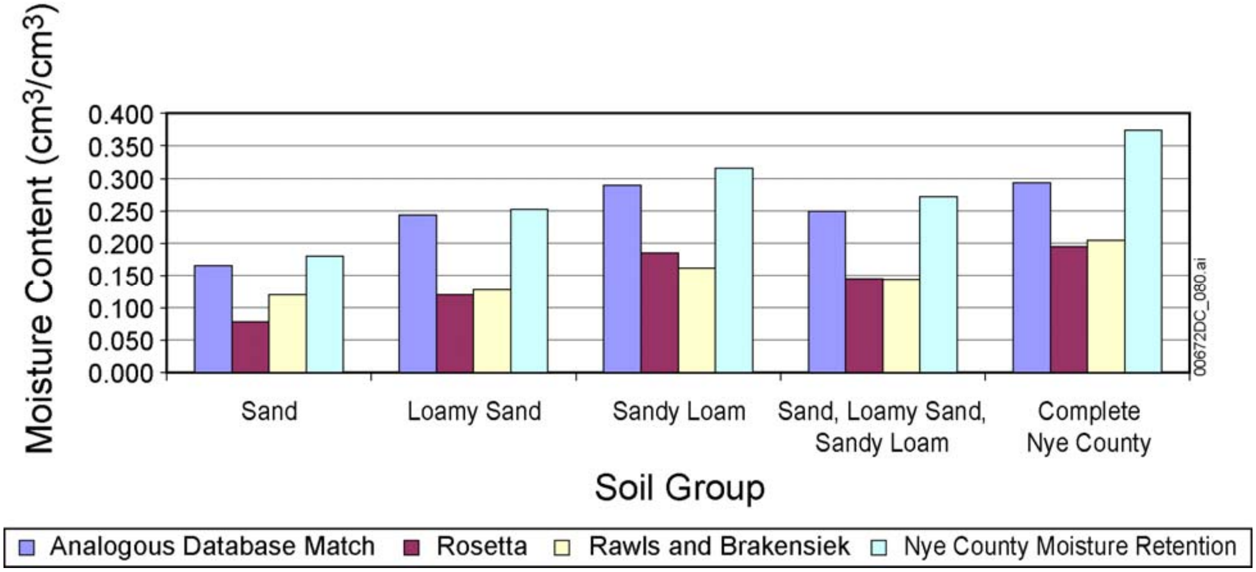


Source: *Data Analysis for Infiltration Modeling: Development of Soil Units and Associated Hydraulic Parameter Values*, (BSC 2006, [14] Figure 6-19).

NOTES: The y-axis is inverted such that the smaller values are at the top of the figure. Means are based on the geometric means, which emphasizes any small values in the data set.

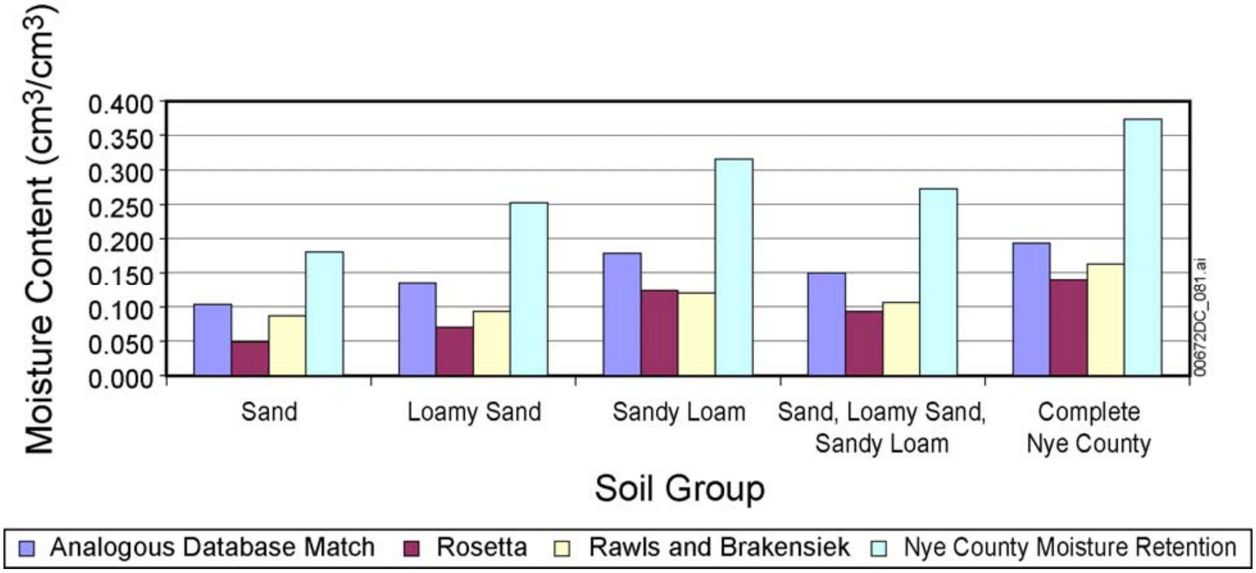
Fig. 3. Mean Ln (K_{sat}) for Three Pedotransfer Function Methods Using Yucca Mountain Data.

The matching approach also was applied to Nye County data, and the results were compared to soil hydraulic properties developed from the two alternative PTFs: the Rawls and Brakensiek (1985 [3]) method and the ROSETTA program (Schaap 2001 [5]), in the same manner as described above. Additionally, soil-moisture-retention data at 10 kPa (–0.10 bar) and 33 kPa (–0.33 bar) were available in the Nye County data set, which were compared with the derived moisture contents at –0.10 and –0.33 bar. The results of the comparison are shown graphically, with the mean values estimated with the matching approach for the Nye County data parameters plotted with the resulting mean values from the two alternative PTF methods (Rawls and Brakensiek 1985 [3]; Schaap et al., 2001 [5]). The Nye County moisture data for FC at –0.10 bar show a good match to the moisture contents estimated with the matching approach (Figure 4). Likewise, the moisture data developed by Rawls and Brakensiek (1985 [3]) and by using the ROSETTA program at –0.10 bar agree well with each other and are consistently lower than both the Nye County moisture data and the analogous database-developed moisture data. At –0.33 bar matric potential, the analogous database-developed moisture data more closely match the data developed by Rawls and Brakensiek (1985 [3]) and by using the ROSETTA program, while the Nye County moisture data are consistently higher than the other three PTFs (Figure 5).



Source: *Data Analysis for Infiltration Modeling: Development of Soil Units and Associated Hydraulic Parameter Values*, (BSC 2006, [14] Figure 6-20).

Fig. 4. Mean Moisture Content Values at −0.10 bar (−102 cm) for Three Pedotransfer Function Methods Using Nye County Data and Measured Moisture-Retention Data from Nye County.



Source: *Data Analysis for Infiltration Modeling: Development of Soil Units and Associated Hydraulic Parameter Values*, (BSC 2006, [14] Figure 6-21).

Fig. 5. Mean Moisture Content Values at −0.33 bar (−336.6 cm) for Three Pedotransfer Function Methods Using Nye County Data and Measured Moisture-Retention Data from Nye County.

CONCLUSIONS

Method corroboration performed by (1) comparing the analogous site matching approach to two other PTFs (Rawls and Brakensiek 1985 [3]) and that of ROSETTA, (Schaap et al., 2001 [5], pp. 163 to 176) and (2) comparing the analogous site matching approach to Nye County data indicate that the matching approach provides reasonable estimates of soil hydraulic parameters for the Yucca Mountain area in Nevada. When compared to nearby Nye County data, estimates of moisture content using the matching approach showed good agreement, especially at the wet end of the moisture retention curve (Figure 4). The other two PTFs consistently under-predicted MC when compared to Nye County data. The good agreement when matching methods with local Nye County data is attributed to strong similarities between local soils in Nye County and Hanford Site soils and sediments.

Proving the applicability of this matching approach for use in estimating soil hydraulic parameters at Yucca Mountain strengthens its credibility for similar use on the Hanford Site, parts of which currently are involved in *Resource Conservation and Recovery Act of 1976* [21]and *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* [22] investigations. For example, application of the matching approach at the Hanford Site eliminates much of the uncertainty identified with its application at Yucca Mountain, such as that associated with differing deposition processes. Hanford Site information needs that could benefit from the matching approach include estimates of infiltration and modeling the fate and transport of previously disposed waste. Estimates of vadose-zone hydraulic-parameter values at waste sites located on the Hanford Site are particularly sparse because of the exposure risk associated with laboratory testing of radiologically contaminated sediment samples.

REFERENCES

1 Cornelis, W.M.; Ronsyn, J.; Van Meirvenne, M.; and Hartmann, R. 2001. “Evaluation of Pedotransfer Functions for Predicting the Soil Moisture Retention Curve.” *Soil Science Society of America Journal, 65*, 638-648. Madison, Wisconsin: Soil Science Society of America. TIC: 258085.

2 Nemes, A.; Rawls, W.J.; and Pachepsky, Y.A. 2006. "Use of the Nonparametric Nearest Neighbor Approach to Estimate Soil Hydraulic Properties." *Soil Physics*, 327-336. Madison, Wisconsin: Soil Science Society of America. TIC: 258543.

3 Rawls, W.J. and Brakensiek, D.L. 1985. “Prediction of Soil Water Properties for Hydrologic Modeling.” *Watershed Management in the Eighties, Proceedings of the Watershed Management Symposium Held in Conjunction with the ASCE Convention, Denver, Colorado, April 30-May 1, 1985.* Jones, E.B. and Ward, T.J., eds. Pages 293-299. New York, New York: American Society of Civil Engineers. TIC: 258369.

4 Carsel, R.F. and Parrish, R.S. 1988. “Developing Joint Probability Distributions of Soil Water Retention Characteristics.” *Water Resources Research, 24*, (5), 755-769. Washington, D.C.: American Geophysical Union. TIC: 247697.

5 Schaap, M.G.; Leij, F.J.; and van Genuchten, M. Th. 2001. "ROSETTA: A Computer Program for Estimating Soil Hydraulic Parameters with Hierarchical Pedotransfer Functions." *Journal of Hydrology, 251,* (3-4), 163-176. New York, New York: Elsevier. TIC: 258401.

6 USGS (United States Geological Survey) 2003. "Eastern Region Recharge Studies." Denver, Colorado: United States Geological Survey. Accessed April 5, 2006. ACC: MOL.20060718.0014.
URL: http://wwwrcamnl.wr.usgs.gov/uzf/err.html.

7 Khaleel, R. and Freeman, E.J. 1995. *Variability and Scaling of Hydraulic Properties for 200 Area Soils, Hanford Site.* WHC-EP-0883, Rev. 0. Richland, Washington: Westinghouse Hanford Company. ACC: MOL.20051115.0327.

8 van Genuchten, M.T.; Leij, F.J.; and Yates, S.R. 1991. *The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils.* EPA Report 600/2-91/065. Riverside, California: U.S. Salinity Laboratory, U.S. Department of Agriculture. TIC: 236938.

9 Truex, M.J.; Murray, C.J.; Cole, C.R.; Cameron, R.J.; Johnson, M.D.; Skeen, R.S.; and Johnson, C.D. 2001b. *Performance Assessment Monitoring Plan for the Hanford Site Low-Level Burial Grounds.* DOE/RL-2000-72. Richland, Washington: Pacific Northwest National Laboratory. ACC: MOL.20060803.0155.

10 SNL (Sandia National Laboratories) 2006. *Data Analysis for Infiltration Modeling: Extracted Weather Station Data Used to Represent Present-Day and Potential Future Climate Conditions in the Vicinity of Yucca Mountain.* ANL-MGR-MD-000015 REV 00. Las Vegas, Nevada: Sandia National Laboratories. ACC: DOC.20070109.0002.

11 Truex, M.J.; Murray, C.J.; Cole, C.R.; Cameron, R.J.; Johnson, M.D.; Skeen, R.S.; and Johnson, C.D. 2001a. *Assessment of Carbon Tetrachloride Groundwater Transport in Support of the Hanford Carbon Tetrachloride Innovative Technology Demonstration Program.* PNNL-13560. Richland, WA: Pacific Northwest National Laboratory. ACC: MOL.2006027.0064.

12 USDA 2006. *Primary Characterization Data (Nye, Nevada).* Lincoln, Nebraska: United States Department of Agriculture, Natural Resources Conservation Science. ACC: MOL.20060724.0158.

13 USDA 1999. *Soil Taxonomy, A Basic System of Soil Classification for Making and Interpreting Soil Surveys.* 2nd Edition. Number 436. Washington, D.C.: U.S. Government Printing Office. ACC: MOL.20060105.0107.

14 BSC 2006. *Data Analysis for Infiltration Modeling: Development of Soil Units and Associated Hydraulic Parameter Values*. ANL-NBS-HS-000055 REV 01. Las Vegas, Nevada: Bechtel SAIC Company.

15 Young, M.H., McDonald, E.V., Caldwell, T.G., Benner, S.G., and Meadows, D.G. 2004. "Hydraulic Properties of a Desert Soil Chronosequence in the Mojave Desert, USA." *Vadose Zone Journal, 3*, 956-963. Madison, Wisconsin: Soil Science Society of America. TIC: 258503.

16 Duniway, M.C., Herrick, J.E., Monger, H.C., and Brinegar, H. 2004. "The High Water Holding Capacity of Petrocalcic Horizons." Proceedings, SSSA Annual Meeting. Las Cruces, NM: USDA. Accessed 02/09/2006. ACC: MOL.20060809.0100. URL: http://web.nmsu.edu/~mduniway/SSSA2004.pdf .

17 Resource Concepts 1989. *Soil Survey of Yucca Mountain Study Area, Nye County, Nevada*. NWPO EV 003-89. Carson City, Nevada: Resource Concepts. TIC: 206227.

18 Schaap, M.G.; Leij, F.J.; and van Genuchten, M.Th. 1998. "Neutral Network Analysis for Hierarchical Prediction of Soil Hydraulic Properties." *Soil Science Society of America Journal, 62,* (4), 847-855. Madison, Wisconsin: Soil Science Society of America. TIC: 258402

19 Meyer, P.D.; Rockhold, M.L.; and Gee, G.W. 1997. *Uncertainty Analyses of Infiltration and Subsurface Flow and Transport for SDMP Sites*. NUREG/CR-6565. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.20060111.0286.

20 Cronican, A.E. and Gribb, M.M. 2004. "Hydraulic Conductivity Prediction for Sandy Soils." *Ground Water, 42*, (3), 459-464. Westerville, Ohio: National Ground Water Association. TIC: 258368.

21 *Resource Conservation and Recovery Act of 1976*, 42 USC 6901, et seq.

22 *Comprehensive Environmental Response, Compensation, and Liability Act of 1980*, 42 USC 9601, et seq.