83: Models for Indirect Estimation of Soil Hydraulic Properties

MARCEL G SCHAAP

University of California Department of Environmental Sciences

Q1 *This •article describes methods for the indirect estimation of soil hydraulic properties, such as soil water retention and hydraulic conductivity characteristics. Indirect methods can be classified into semiphysical methods that are based on mechanical assumptions regarding particle and pore arrangements, and statistical methods that are known as pedotransfer functions. Both classes are described and evaluated on their merits, and some characteristic examples are given. A list of applicable software is described at the end of the article and an extensive reference list provides sufficient material for further background information.*

INTRODUCTION

Qualitative knowledge about soil hydraulic properties such as water retention and hydraulic conductivity has historically been an important factor for assessing the suitability of land for agriculture, settlement, or trafficability. In modern agricultural and engineering practices, varying degrees of quantitative detail about soil hydraulic properties are needed for determining the soil water holding capacity, infiltration, percolation, and runoff rates, or for quantifying the transport of pollutants in soil. Although automation and computer technology have certainly advanced the ease with which hydraulic properties can be measured (cf. Dane and Topp, 2002, *see* **Chapter 81, Measuring Soil Hydraulic Properties, Volume 1** by Dürner), their determination has by no means become easy. Many measurement methods are still labor-intensive and expensive. In addition, soil hydraulic properties are often subject to considerable spatial and sometimes temporal variability, making measurements less representative. Measurements of hydraulic properties for regional, continental, or global scales are virtually impossible.

The expense and difficulty of performing soil hydraulic measurements in laboratory or field are often used as arguments for developing indirect methods for estimating soil hydraulic properties using widely available surrogate data. The general method is to define physical relations or find statistical correlations between predictors such as soil texture and the soil hydraulic properties. After the modeling exercise, the model can be tested on independent data, or be applied for common use. In the past decades, literally hundreds of such studies have been performed. This review considers two main classes of indirect methods, semiphysical and empirical approaches, and briefly discusses common modeling concepts. Reviews with slightly different perspectives concerning indirect models can be found in Rawls *et al.* (1991) and Wösten *et al.* (2001). Most model development is data-driven and requires soil databases in which both predictors and measured hydraulic properties are present. This review will therefore also discuss some pertinent databases and software packages.

SEMIPHYSICAL MODELS

Semiphysical methods recognize the shape similarity between the cumulative particle-size distribution and the water retention characteristic. Although none of the models can predict hydraulic properties from first principles, they do offer valuable conceptual insights into the physical relations between the texture distribution and the pore-size distribution. A drawback of these methods is that they often require very detailed particle-size distributions, making them almost as difficult to apply as direct measurements. Three model types can be discerned in the literature.

Encyclopedia of Hydrological Sciences. Edited by M. Anderson.

The Arya–Paris Model

The Arya and Paris (1981) model uses information from k particle-size classes to estimate k pairs of water contents and pressure heads. Each class is thought of to consist of n_k spherical particles of mean radius R_k. The pore volume of this class is associated with a cylindrical pore of radius r_k. The Arya–Paris model assumes that the bulk density is the same for each particle class. The pore volume, V_k, for each particle-size class is then

$$V_\mathrm{k} = \left(\frac{W_\mathrm{k}}{\rho_\mathrm{s}}\right)e \tag{1}$$

where W_k is the total mass in particle class k and ρ_s is the particle density. The water content follows by summing the V_k of all particle-size classes $1 \ldots \mathrm{k}$, starting with the class with the smallest R_k. The void ratio, e, is given by

$$e = \frac{(\rho_\mathrm{s} - \rho_\mathrm{b})}{\rho_\mathrm{b}} \tag{2}$$

The radius of the pore belonging to class k is given by (Arya and Paris, 1981):

$$r_\mathrm{k} = \frac{R_\mathrm{k}\sqrt{2en_\mathrm{k}^{(1-\alpha_\mathrm{ap})}}}{3} \tag{3}$$

where n_k is the number of spherical particles of radius R_k required to fill the mass in the particle-size class. The corresponding pressure head is subsequently calculated with the capillary law. The empirical parameter α_ap accounts for non-spherical soil particles and should be equal or greater than 1. Arya and Paris (1981) initially determined that α_ap ranged between 1.31 and 1.43 for five texturally different soils, but later it was found that α_ap varied between 1.02 and 2.97 (Arya *et al.*, 1982; Schuh *et al.*, 1988; Mishra *et al.*, 1989). Arya *et al.* (1999a) modified the original Arya–Paris concept by allowing α_ap to vary according to particle size and extended the model to unsaturated conductivity (Arya *et al.*, 1999b). To our knowledge, this model extension has not yet been tested on independent data.

Fractal Approaches

Several studies used fractal concepts to develop indirect methods. Fractal patterns reveal themselves by exhibiting power-law scaling relations between the observed quantity and the measurement scale, R. Employing a somewhat similar logic as the Arya–Paris model, fractal behavior may be found on a particle number basis (e.g. Tyler and Wheatcraft, 1989) as

$$N \sim R^{-D_\mathrm{N}} \tag{4}$$

where N is the number of particles greater than a measurement scale R, and D_N is the fractal dimension (ranging between 0 and 3). A fractal particle-size distribution thus exhibits a straight line in a simple log N versus log R plot. Tyler and Wheatcraft (1989) argued that the parameter α_ap in the Arya and Paris (1981) equation should be equal to $D_\mathrm{N}-1$. Tyler and Wheatcraft (1992), however, indicated that "soils that show fractal scaling are a rather small subset of the soils commonly encountered in the field". Indeed, using more than 1100 soil data sets, Tietje and Tapkenhinrichs (1993) demonstrated that the fractal approach of Tyler and Wheatcraft (1989) was not more accurate than the original Arya and Paris (1981) concept with $\alpha_\mathrm{ap} = 1.38$. Other fractal-based approaches were proposed by Rieu and Sposito (1991a, b) and Bird *et al.* (2000) who included soil structure into the fractal concept.

The Haverkamp and Parlange Model

Haverkamp and Parlange (1986) built a semiphysical model around the simple assumption that the pore radius r is linearly related to the particle radius R

$$r = \gamma R \tag{5}$$

where γ is a factor of proportionality, requiring that pores of different sizes have the same shape. Combined with the capillary law that links pore size to capillary pressure, it follows that a retention characteristic can be derived from a cumulative particle-size distribution. Haverkamp and Parlange (1986) developed a somewhat complex model that included hysteresis phenomena to estimate Brooks and Corey (1964) retention parameters by curve fitting the van Genuchten (1980) equation to the cumulative particle-size distribution. This approach was later simplified and tested by Schaap and Bouten (1996), who showed that the model can successfully be applied to sandy soils. Bouraoui *et al.* (1999) showed that a modified and simplified Haverkamp and Parlange concept could be applied to a large part of the textural triangle. However, beyond these references, the Haverkamp and Parlange model has attracted little following in the literature.

EMPIRICAL MODELS

Empirical methods, often called *pedotransfer functions* (PTFs, Bouma and van Lanen, 1987), generally focus on practical applicability and often use more or less simple statistical models to estimate hydraulic properties. Contrary to most physically based models, empirical methods often require limited – but easily accessible – input data such as sand, silt, or clay percentages and porosity, although more elaborate combinations of input data are also possible (cf. Rawls *et al.*, 1991; Wösten *et al.*, 2001). There are many different PTFs, and it is impractical to describe all these in detail. We will limit ourselves to describing some modeling concepts while giving some examples of characteristic PTFs. The concepts distinguished in this review are, class-based methods, point-based, and parametric approaches.

Class PTFs

Class PTFs provide hydraulic properties for particular soil classes. The advantage of class PTFs is their simplicity (essentially, they consist of lookup tables) and modest requirements regarding input data. Only class information is necessary, thus enabling estimates of hydraulic properties from qualitative field data. Class PTFs for the 12 USDA textural classes were reported by Clapp and Hornberger (1978), Rawls *et al.* (1982), Carsel and Parrish (1988), Rawls and Brakensiek (1985), and Schaap and Leij (1998), among others. Wösten *et al.* (1999) provided average van Genuchten (1980) retention- and unsaturated conductivity parameters for 12 soil classes based on the FAO textural classification but also made a further distinction for subsoils, topsoils, and organic soils. The resulting class average parameters were used in conjunction with a GIS system to estimate the available water content on a scale of 1 : 1 000 000 for most of the European Union. Other large-scale applications can be found in Kern (1995) and Imam *et al.* (1999). A drawback of class PTFs is that discrete changes of hydraulic properties occur between two adjacent classes (e.g. loam to sandy loam, or topsoil to subsoil). Such changes may not always be realistic, especially for small-scale applications. Instead, point-based or parametric PTFs provide continuously varying estimates that may be more useful in such cases.

Point PTFs

Point PTFs use simple linear expressions to estimate individual water retention or conductivity points (i.e. water content-pressure or conductivity-pressure points) from texture and other soils data. Point PTFs are arguably the most precise of PTFs because they estimate the hydraulic points directly, without relying on parameterized forms of the hydraulic characteristics such as done by parametric PTFs (cf. Schaap and Bouten, 1996; Minasny *et al.*, 1999 for some comparisons). A drawback of point PTFs is that they are limited in making estimates at specific pressure heads. However, if necessary, parameterized results can be obtained by fitting appropriate retention equations to the point estimates (e.g. Saxton *et al.*, 1986). In most cases, separate regression equations are used for each pressure. Tietje and Tapkenhinrichs (1993) noted that this causes some point PTFs to exhibit unrealistically increasing water contents with stronger suctions. Examples of point PTFs can be found in Rawls *et al.* (1982), Rawls *et al.* (1983), Ahuja *et al.* (1985), Rajkai and Varallyay (1992), Thomasson and Carter (1992), Bristow *et al.* (1999), Minasny *et al.* (1999), and Renger *et al.* (1999).

Parametric PTFs

Parametric PTFs estimate parameters of retention or conductivity equations, such as the Brooks and Corey (1984), van Genuchten (1980), and the Mualem (1976) equations. Contrary to class PTFs, these models estimate hydraulic parameters that vary continuously with input data. Contrary to point PTFs, parametric PTFs can provide hydraulic properties at arbitrary capillary pressures. It is impossible to describe all of these approaches; we will therefore give only a few well-known examples.

Brakensiek *et al.* (1984), Rawls and Brakensiek (1985), and Rawls *et al.* (1992) presented parametric PTFs that estimated Brooks and Corey (1964) parameters and saturated hydraulic conductivity from porosity, ϕ, and sand and clay percentages (S and C, respectively). In these PTFs, the saturated water content is set equal to the porosity while the other Brooks-Corey parameters and the saturated hydraulic conductivity are related to S, C, and ϕ, using the polynomial

$$\begin{aligned} p = {} & a_1 + a_2 S + a_3 C + a_4 \phi + a_5 S^2 + a_6 C^2 + a_7 \phi^2 \\ & + a_8 S\phi + a_9 C\phi + a_{10} S^2 C + a_{11} S^2 \phi + a_{12} C^2 \phi \\ & + a_{13} S C^2 + a_{14} C \phi^2 + a_{15} S^2 \phi^2 + a_{16} C^2 \phi^2 \end{aligned} \qquad (6)$$

where p is a Brooks–Corey parameter or the saturated hydraulic conductivity and a_i are model coefficients.

Vereecken *et al.*, (1989, 1990) provided expressions for water retention and unsaturated hydraulic conductivity for 182 Belgian soil horizons. The water retention was described with a modified van Genuchten equation and the unsaturated hydraulic conductivity was described with the Gardner (1958) equation. Vereecken *et al.* (1989, 1990) provided a number of ways to estimate the seven hydraulic parameters in these equations. One of the approaches was fitting the parameters $a_1 \ldots a_6$ in the equation

$$\begin{aligned} f(p) = {} & a_1 + a_2 f(C) + a_3 f(Si) + a_4 f(S) \\ & + a_5 f(OM) + a_6 f(\rho_\mathrm{b}) \end{aligned} \qquad (7)$$

where p is the hydraulic parameter being estimated, S: Sand, C: clay, Si: silt, ρ_b: bulk density, OM: organic matter, and $f()$ indicates that a transformation (e.g. logarithms, exponents, etc.) may be applied to the parameter in ellipses.

Artificial neural networks form a special class of PTFs and were introduced by Pachepsky *et al.* (1996), Schaap and Bouten (1996), and Tamari *et al.* (1996). Neural networks are sometimes described as "universal function approximators" that can "learn" to approximate any continuous (nonlinear) function to any desired degree of accuracy (cf. Haykin, 1994). An advantage of neural networks as compared to regression PTFs is that they require no *a priori* model concept (e.g. linear or exponential functions). This property makes ANNs well suited to build empirical PTFs. However, the method also results in black-box models in which the exact relations between predictors and hydraulic properties are difficult to determine.

Mixed results have been obtained with neural network PTFs. Schaap and Bouten (1996) and Schaap *et al.* (1998) showed that neural networks made estimates with significantly smaller errors than more traditional approaches. Pachepsky *et al.* (1996) found that neural networks perform better than multiple linear regressions when used as point PTFs, but that the two methods produced comparable results when used as parametric PTFs. Tamari *et al.* (1996) reported that neural networks were not better than multiple linear regressions if the uncertainty in the data was large. Minasny *et al.* (1999) found that nonlinear regression reached a similar performance as a neural network approach.

DATABASES AND SOFTWARE

Several public databases have been compiled that suit the development and testing of models for the indirect estimation of hydraulic properties. The oldest database is probably UNSODA (Nemes *et al.*, 2001 and available at: **`www.ussl.ars.usda.gov/models/unsoda.htm`**). This world wide database contains data about laboratory and field hydraulic and other relevant soil characteristics for 790 soils. The HYPRES database contains similar soils data as UNSODA, but for European soils. HYPRES was described in Wösten *et al.* (1999) and is available at **`www.macaulay.ac.uk/hypres/index.html`**.

Several software packages for estimating soil hydraulic properties are available on the internet. Soil Water Characteristics from Texture (SWCT) is based on Saxton *et al.* (1986) and estimates wilting point, field capacity, and available water content. SWCT is part of the Soil Plant Atmosphere Water (SPAW) Field and Pond Hydrology package and is targeted at farmers and resource managers interested in water and nutrient budgeting in soil and ponds, and is available at **`http://www.bsyse.wsu.edu/saxton/spaw/`**.

SOILPAR is a program developed by M. Donatelli and M. Acutis at the Research Institute for Industrial Crops (ISCI), Bolongna, Italy. The program implements 10-point PTFs and four parametric PTFs for water retention and hydraulic conductivity, and can be downloaded at **`http://www.sipeaa.it/ASP/ASP2/SOILPAR.asp`**. The program provides a wide range of plotting and data analysis functions.

Rosetta is a Windows-based program that implements artificial neural network PTFs published by Schaap *et al.* (1998), Schaap and Leij (1998), and Schaap and Leij (2001), and is available from **`http://www.ussl.ars.usda.gov/models/rosetta/rosetta.HTM`**. The program implements five parametric PTFs for the estimation of water retention saturated and unsaturated hydraulic conductivity. Rosetta uses a hierarchical approach to maximize the accuracy of the PTF estimates given a particular data availability.

Minasny and McBratney (2002) developed the Neuropack software package (**`http://www.usyd.edu.au/su/agric/acpa/neuropack/neuropack.htm`**). Unlike the other software packages that implement existing PTFS, Neuropack is primarily intended to develop neural network-based PTFs. Optimization results can be saved and or be tested using independent soils data.

CONCLUSION

Indirect methods are valuable assets in many soils applications because they allow estimation of soil hydraulic properties where none exist or where direct measurements would be prohibitive. The many different models that exist are mostly geared toward particular soils or datasets (Schaap and Leij, 1998). A number of common PTFs were tested for general applicability in Tietje and Tapkenhinrichs (1993), Kern (1995), Tietje and Hennings (1996), Schaap *et al.* (1998), Minasny *et al.* (1999), and Wösten *et al.* (2001). However, these studies showed that no clearly superior PTF exists that works well in all applications. When possible, it is therefore advisable to test several PTFs for accuracy before blindly trusting the results.

Some important issues exist that are worth considering within the context of indirect estimations. Most indirect methods are based on hydraulic data from laboratory measurements, yet are usually applied to field situations. Laboratory and field measurements do not necessarily yield similar results, so it is possible that estimates of indirect methods are biased. Another issue is that most indirect methods were developed using data from specific parts of the world, particularly for soils from temperate climates. With the exception of a few studies (e.g. Epebinu and Nwadialo, 1993; Tomasella and Hodnett, 1997; Bristow *et al.*, 1999), hydraulic data and corresponding indirect methods about tropical soils are a virtual *terra incognita*. Obtaining comprehensive soil and hydraulic data for regions beyond those now represented in regional and international databases will probably help improve the general applicability of indirect methods and aid the management of local natural and agricultural resources.

Acknowledgment

M.G. Schaap was supported, in part, by the SAHRA science and technology center under a grant from NSF (EAR-9876800).

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