INDIRECT METHODS FOR ESTIMATING THE HYDRAULIC PROPERTIES OF UNSATURATED SOILS

Riverside, California, October 11-13, 1989

edited by

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This publication is the result of an international workshop on "Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils," held at the Riverside Sheraton Hotel and Convention Center in Riverside, California, October 11-13, 1989. The workshop was designed to evaluate the current state-of-the-art in estimating the unsaturated hydraulic properties from more easily measured soil data, such as soil texture, bulk density, organic matter content, or soil water retention data. The hydraulic properties are probably the most important parameters affecting the rate of water flow and chemical transport in soil. While direct measurement of the hydraulic properties is increasingly viewed impractical or uneconomical for most applications, indirect methods have evolved to the point where they seem to provide reliable answers for many problems.

About 120 scientists and engineers from some 15 countries were invited to participate and to discuss their previous or current research at the workshop. The participants included soil physicists, soil chemists, chemical engineers, hydrologists, and agricultural and petroleum engineers. Their expertise ranged from the highly theoretical to very applied and practice-oriented. The multi-disciplinary group had a unique chance to interact with each other, to appreciate the problems and opportunities in porous media modeling and characterization, and to discover commonalities and differences between the different disciplinary research efforts. These proceedings contain the papers presented at this workshop. While the workshop was held in the fall of 1989, the authors had an opportunity to update and modify their papers until June 1992. Hence, the contents of these proceedings should reflect the state of research, and its applications, until approximately the middle of 1992.

The workshop had the fortune of being sponsored by a large number of governmental, professional, and private organizations (see next page). Their commitment to the workshop certainly indicates the importance of the topic. Success of the workshop would have been impossible without the input from a large number of colleagues and friends in Riverside and elsewhere. I like to thank all those who served on the Planning and Technical Advisory Committees. In Riverside, the help by Donna Cooney and Carol Hansen of the Department of Soil and Environmental Sciences of the University of California, Riverside, proved to be indispensable and was much appreciated. Gladys Greer and Peggy Carroll provided similar support from the U. S. Salinity Laboratory. Many thanks also to the people of the Physics group of the Salinity Laboratory for continuous help before during and after the workshop. These individuals include Walter Russell, Jack Jobes, Chris Smith, Todd Skaggs, Gulab Singh, Pete Shouse, Feiko Leij, Alan Mitchell, and Tim Ellsworth. Finally, many thanks to all participants for making the workshop such a successful event.

Martinus Th. van Genuchten
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ON ESTIMATING THE HYDRAULIC PROPERTIES OF UNSATURATED SOILS

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This introductory paper gives a brief overview of current methods for estimating the hydraulic properties of unsaturated soils. Numerous methods are now available for the direct measurement of the hydraulic properties, i.e., the water retention and the hydraulic conductivity functions. Most of these methods are extremely time-consuming and expensive, especially for in situ field-measurement of the hydraulic conductivity. Alternatively, a large number of indirect methods have been derived to estimate the hydraulic properties from more easily measured soil properties, including the use of water retention data to estimate the unsaturated soil hydraulic conductivity curve, and the use of soil texture and other data routinely available from soil surveys to estimate the water retention curve. Advantages and disadvantages of the different methods are discussed, and specific areas in need of further research are outlined.

INTRODUCTION

There is increasing evidence that the quality of the earth's soil and water resources is being adversely affected by the release of a variety of agricultural and industrial pollutants into the environment. In efforts to better monitor and manage the migration of chemicals in the subsurface, scientists and engineers over the past several decades have developed increasingly complex computer models describing how water and chemicals move into and through the unsaturated zone. Computer models have become indispensable tools in research for quantifying and integrating the most pertinent physical, chemical, and biological processes operative in the unsaturated (vadose) zone of soils and fractured rocks. Planning, action, and extension agencies are also increasingly relying on the use of models for predicting the long-term impacts of alternative soil and water management practices on crop yield and groundwater quality, and for remedial action purposes. This trend of using models as tools in research and management will probably continue as computer costs keep decreasing and the needs for more detailed predictions further increase.

The reliable application of computer models to field-scale flow and transport problems implies a commensurate effort in quantifying a large number of model parameters, especially the unsaturated hydraulic properties. As our ability to numerically simulate complicated flow and transport systems increases, the accuracy of future simulations may well depend on the accuracy with which we can estimate our model parameters. Thus, there is a growing need for more efficient and accurate methods to estimate the relevant model parameters. Methods for determining the unsaturated hydraulic conductivity, K, in particular, are viewed as inadequate by theoreticians and practitioners alike. Unfortunately, the hydraulic conductivity is probably the most important parameter affecting water and solute movement in the vadose zone.

Water flow in porous media is typically described with the unsaturated flow or Richards equation:
where \( h \) is the soil water pressure head, \( \theta \) is the volumetric water content, \( K \) is the hydraulic conductivity, \( t \) is time, and \( z \) is soil depth. A large number of laboratory and field methods have been developed over the years for measuring \( K \) as a function of \( h \) or \( \theta \). They are based on solving the inverse problem, i.e., an analytical or numerical solution of the hydraulic model describing the flow process is optimized with respect to such flow attributes as water content and pressure head [Russo et al., 1991]. These methods, nearly without exception, are costly and difficult to implement. Enormous investments of time and money have been made, and continue to be made, by soil scientists, hydrologists, and others, to measure the hydraulic properties of field soils using methods that have only marginally improved over the past several decades. Accurate and effective measurement of the hydraulic properties is confounded by the extreme spatial variability of the hydraulic conductivity in the subsurface. The hydraulic conductivity frequently also shows significant variations in time because of cultivation of agriculture activities, shrink-swell phenomena of fine-textured soil, the effects of particle dispersion and soil crusting, and changes in the composition of the soil solution.

In sharp contrast to direct methods for measuring the hydraulic properties, relatively little attention is being paid to the development of indirect methods which predict the hydraulic properties from more easily measured data, including water retention data, and pore- or particle-size distributions. This is unfortunate since indirect methods generally are more convenient and far less costly to implement. Moreover, indirect methods often give hydraulic conductivity estimates which may well be accurate enough, or are close to being accurate enough, for many applications. We note, however, that the formulation and evaluation of indirect methods hinges on experimental data which usually are obtained with direct procedures. Thus, the utility of indirect approaches does not obviate the need for continued research toward improved direct methods.

In this introductory paper we shall briefly review both the direct and indirect methods for estimating the unsaturated hydraulic properties. Among the indirect approaches are predictions of the hydraulic conductivity from water retention data, and methods which correlate the hydraulic functions with soil texture and other data routinely available from soil survey databases. The review is carried out within the context of papers published in these proceedings.

ESTIMATING THE HYDRAULIC PROPERTIES BY SOLVING THE INVERSE PROBLEM

Direct Solution Methods

Recent reviews of direct methods for measuring the hydraulic conductivity, \( K \), and the soil water diffusivity, \( D = K (dh/d\theta) \), of unsaturated soils are given by Klute and Dirksen [1986] and Green et al. [1986] for laboratory and field conditions, respectively. Most laboratory methods are steady-state procedures based on direct approximations of Darcy's equation. Popular transient methods include the Bruce and Klute [1956] method, and variations thereof such as the hot-air method developed by Arya et al. [1975], where the diffusivity is estimated from horizontal water content distributions, and
the sorptivity method of Dirksen [1975]. Popular field methods include the instantaneous profile method of Rose et al. [1965] and Watson [1966], various unit-gradient type approaches [Nielsen et al., 1973; Sisson and van Genuchten, 1991], sorptivity methods following ponded infiltration [Clothier and White, 1981; Chong and Green, 1983], and the crust method introduced by Bouma et al. [1971], the latter based on steady water flow. Many variations of these methods have also been implemented [e.g., Jones and Wagena, 1984; van Genuchten et al., 1985; Green et al., 1986].

The above direct methods for measuring the hydraulic conductivity function, \( K(h) \) or \( K(\theta) \), or the soil water diffusivity, \( D(\theta) \), involve numerical approximations or simplifications of (1). For this purpose, (1) is usually reduced to a linear first-order partial differential equation for which unique solutions are available. The parameters \( K \) or \( D \) are considered to be the dependent variables which can be expressed in terms of directly observable parameters (usually pressure heads and water contents). This approach is classified as the direct method [Neuman, 1973] or the equation error criterion [Yeh, 1986], the latter referring to observation and interpolation errors. While relatively simple in concept, these direct inversion methods have a number of limitations that restrict their use in practice. For example, most methods are very time-consuming to execute, especially those based on field-drainage experiments involving medium- and fine-textured soils, because of the need to adhere to relatively restrictive initial and boundary conditions (e.g., free drainage of an initially saturated soil profile).

The need to impose simple boundary conditions is often impractical, particularly for field experiments where accurate implementation of boundary conditions on a large scale may be very difficult. Methods requiring repeated steady-state flow situations, or other equilibrium conditions are also tedious, while linearization and other approximations or interpolations to allow (semi-)analytic inversions of the flow equation may also introduce errors. Finally, information about uncertainty in the estimated hydraulic parameters is not readily derived from direct measurements.

**Indirect Solution Methods**

A more flexible approach for solving the inverse problem is by using parameter estimation methods. Such methods have the potential of simultaneously estimating the retention and hydraulic conductivity functions from transient flow data [Zachman et al., 1981; Dane and Hruska, 1983; Horning, 1983; Kool et al., 1987; Russo et al., 1991]. In this approach the (forward) flow problem may be formulated for any particular set of initial and boundary conditions, and solved with appropriate analytical or numerical methods. One way to implement parameter estimation methods is to assume certain constitutive functions for the hydraulic properties, and then to estimate the coefficients in those functions by using an optimization algorithm which minimizes a given objective function (usually the sum of the squared deviations between observed and calculated water contents, pressure heads, water flow rates, and/or other attributes characterizing unsaturated flow). Frequently used functions for the hydraulic properties are equations proposed by Brooks and Corey [1964], van Genuchten [1980], Campbell [1974], and Russel [1988]. These functions are based on statistical pore-size distributions models, mostly those by Burhans [1953] and Mualem [1976a], which relate the unsaturated hydraulic conductivity function in some theoretical fashion with the water retention curve.

The solution of the inverse problem in this manner is said to be done according to the indirect method [Neuman, 1973], not to be confused with indirect methods to determine hydraulic properties that bypass a solution of the flow problem altogether, or the output error criterion [Yeh, 1986]. Recent applications [e.g., Kool et al., 1987; Kool...
and Parker, 1988; Russo et al., 1991; Hills et al., 1988; Sisson and van Genuchten, 1991; Hudson et al., 1991] indicate several advantages of parameter estimation methods as compared to the more classical direct measurement techniques: (i) there is no need to mathematically invert (and hence approximate) the governing flow equation, (ii) the method yields hydraulic properties over the full range of water contents, (iii) the method yields information about parameter uncorrelatedness and model accuracy, and (iv) parameter estimation methods permit experimental conditions to be selected on the basis of convenience and expediency, rather than by an overriding need to simplify the mathematics. Thus, the method is easily extended to infiltration [Russo et al., 1991], hysteretic water flow [Kool and Parker, 1987], to layered soils [Shouse et al., 1992], to arbitrary initial conditions or time-varying soil surface boundary conditions, and situations involving simultaneous water and solute movement [Mishra and Parker, 1989].

While parameter estimation methods pose several advantages, a number of problems related to computational efficiency, convergence, and parameter uniqueness, remain to be solved [Kool et al., 1987; Russo et al., 1991; van Dam et al., 1992], especially when many hydraulic parameters must be estimated simultaneously. Furthermore, a substantial experimental effort may still be required to obtain sufficient data to warrant this type of estimation method.

ESTIMATING THE HYDRAULIC CONDUCTIVITY FROM WATER RETENTION DATA

As discussed above, the measurement of the hydraulic properties by solving the inverse problem is time-consuming, expensive, and often subject to simplifying assumptions. One alternative to direct measurement is to use theoretical methods which predict the hydraulic conductivity from more easily measured field or laboratory water retention data. Theoretical methods are usually based on statistical pore-size distribution models [Corey, 1992], which assume water flow through cylindrical soil pores, and incorporate the equations of Darcy and Poiseuille. An excellent review of these methods is given by Mualem [1992]. His review indicates an abundance of methods for predicting the unsaturated hydraulic conductivity from measured water retention data. Of these, Kuuz [1992] identified three broad groups of models, i.e., those related to the theories by Childs and Collis-George [1950], Burdine [1953] and Mualem [1976a]. The Burdine and Mualem group of models are of the general form

\[ K(S_e) = K_e S_e \int h^{-1}(x) dx \left[ \int h^{1}(x) dx \right] \]  (2)

and

\[ K(S_e) = K_e S_e \left[ \frac{\int h^{-1}(x) dx}{\int h^{1}(x) dx} \right] \]  (3)

where

\[ h(x) = \frac{1}{2} \left( \frac{k_x}{k_y} \right)^{1/2} x \]
respectively, where \( K_r \) is the saturated hydraulic conductivity, \( t \) is a pore-connectivity or tortuosity parameter, \( S_r = (\theta - \theta_f)/(\theta - \theta_d) \) is effective saturation, and \( \theta_f \) and \( \theta_d \) are the residual and saturated water contents. Equation (2) has been used extensively in the petroleum engineering literature; with \( t = 0 \) the model of Gates and Tempelhar-Lietz [1950] is obtained while Burdine [1953] used \( t = 2 \). Burdine's model was applied by Brooks and Corey [1964] to derive their classical function for the unsaturated hydraulic conductivity. Equation (2) can also be interpreted [Muallem, 1976a] to be the analytical approximation of numerical models developed by Childs and Collis-George [1950] and Marshall [1958] who assumed \( t = 0 \), Kurse et al. [1968] and Jackson [1972] who suggested \( t = 1 \), and Millington and Quirk [1961] who used \( t = 4/3 \).

Equation (3) was derived by Muallem [1976a] from previous pore-size distribution models by including the effects of pore connectivity. Using \( K(h) \) or \( K(f) \) and \( f(h) \) from 45 soils, Muallem concluded that the empirical coefficient \( f \) in his model should be about 0.5. Because Muallem's database [Muallem, 1976b] consisted of mostly repacked laboratory soils, the value of 0.5 for \( f \) can only be a rough approximation. Our experience indicates that \( f \) may vary greatly without affecting the agreement between observed and predicted conductivity values [Yates et al., 1992].

This brief summary shows that many predictive models can be formulated, with differences between the models occurring in especially the exponent \( f \) [cf. Muallem and Dagan, 1978]. Some of the differences in \( f \) appear to be caused by the fact that the different expressions were calibrated with data from different types of soils (usually a small number). Also, as outlined below, a variety of closed-form expressions for the water retention have been used in conjunction with the conductivity models. Hence, it is imperative that a more comprehensive study involving the most promising predictive models be conducted using a hydraulic database which covers a broad range of disturbed and undisturbed soils. The importance of model calibration should not be underestimated. Pore-size distribution models give, by their very nature, an extremely simplified picture of actual soils, especially of disturbed, structured or macroscopic field soils. The same is of course true for unsaturated fractured rocks [Peters and Klaavater, 1988; Wang, 1991]. Soils and fractured rocks simply do not consist of bundles of smooth, interacting or noninteracting parallel cylindrical pores, and hence any approximation with a pore-size distribution model is somewhat suspect. A more pragmatic approach would be to treat the inherently over-simplified models in a semi-empirical manner by making sure that they (i) accurately reflect the phenomenological properties of observed unsaturated hydraulic conductivity curves, and (ii) are "validated" by comparisons with a large number of laboratory and field conductivity data.

Application of predictive pore-size distribution models requires independent estimates of the water retention curve. Measured input retention data for the predictive models can be given either as point values, or in terms of closed-form equations using parameters which are fitted to observed data. Inventories of analytical water retention functions are given by van Genuchten and Nielsen [1985] and Vreekerken [1992]. Unfortunately, most available retention functions can not be easily incorporated into the above pore-size distribution models to yield relatively simple closed-form analytical expressions for the hydraulic conductivity. Exceptions are the equations of Brooks and Corey [1964], Vaiser [1968], Campbell [1974], van Genuchten [1980], and Russo [1981]. While useful, these functions should again be viewed as approximations of the actual retention in the field. Alternatively, one could also use more complicated expressions, such as the multi-porosity functions of Durner [1992], or use cubic spline approximations. These alternatives potentially provide more accurate representations of observed
retention data, but require numerical integrations if included in predictive conductivity equations. Unfortunately, field data sets seldom provide enough resolution and detail to justify the implementation of these alternative expressions.

The use of analytical functions in flow and transport studies has several advantages. For example, they permit a more efficient comparison of the hydraulic properties of different soils and soil horizons [e.g., Rawls, 1992; Carsel, 1992]. They are also more easily used in scaling procedures [Hopmans, 1992], and provide a means for interpolation or extrapolation to parts of the retention curve for which little or no information is available. Furthermore, they can be interpreted in terms of physically-based processes and parameters [Nielson and Lucaner, 1992]. Analytical functions also allow more efficient data handling in unsaturated flow models. Similar advantages of scaling and data-handling are of course important when setting up Geographical Information Systems involving the soil hydraulic properties [Bouma and Bregt, 1989].

Because of their simplicity and ease of use, predictive models for \( K(h) \) or \( K(\theta) \) have become very popular in numerical studies of unsaturated flow using Richards' equation. Results to date suggest that predictive models work reasonably well for many coarse- and medium-textured soils, but that predictions for fine-textured and most structured soils remain unreliable. As indicated by several studies documented in these proceedings, the full potential of predictive methods has not yet been fully explored. Some of the shortcomings are due to inadequate or incomplete calibration of the predictive models with field data. For example, more research into the relation between the factor \( t \) and soil textural or structural properties is needed [cf. Schuh and Cline, 1990]. Because of the field-scale spatial variability problem, it appears that predictive models, including those based on soil textural properties (to be discussed next), eventually will become the only viable means for characterizing the unsaturated hydraulic properties of large land areas, while direct measurement may only be justified for site-specific problems.

ESTIMATING THE HYDRAULIC PROPERTIES FROM SOIL TEXTURE AND RELATED DATA

Many attempts have been made to statistically correlate the soil hydraulic properties to soil texture and other soils data, including bulk density, organic matter content, and/or cation exchange capacity, clay mineralogy and soil structure. Examples in those proceedings are given by Campbell and Shiozawa [1992], Rawls et al. [1992], Baumer [1992], Carsel [1992], and Rajkai and Vdrahlav [1992]. Two alternative approaches are followed: (i) parameters in specific hydraulic models are correlated directly with soil texture and related data, and (ii) water contents at selected pressure heads are estimated from the surrogate soils data and subsequently used in a curve fitting exercise to estimate the complete retention function. As indicated by Thomasson and Carter [1992] and others, there seems to be a consensus that the second approach is preferable.

Regression equations have been reasonably successful in giving approximate orders of magnitude of the hydraulic properties. Thus far, most studies have remained rather empirical by ignoring past and recent work on pore-size and particle-size distribution theories. This again shows the need for a systematic and comprehensive study that integrates all available theoretical and experimental information about water retention data, the unsaturated hydraulic conductivity, particle-size distributions, organic matter, clay mineralogy, and soil structure. Williams et al. [1983] investigated the influence of
the soil texture, soil structure, organic matter content, and clay mineralogy on the water retention curve with the help of numerical classification and diagnostic methods.

Of considerable importance are the studies by Arya and Paris [1981] and Arya and Dierolf [1992] who presented a model for predicting the water retention curve from the particle-size distribution, bulk density and particle density. The model first translates the particle-size distribution into an equivalent pore-size distribution model, which in turn is related to a distribution of water contents and associated pressure heads (the latter being inversely proportional to the pore radius). The Arya-Paris model was modified by Havrka and Parange [1986] to predict the retention curve from soil texture and structure, employing the concept of shape similarity between the retention curve and the cumulative particle-size distribution. Theoretical results compared very well with measured data for ten sandy soils but the approach appears to be less accurate for medium and fine-textured soils. Still, the importance of these studies is that continuous (cumulative) particle-size distributions are being used, rather than only three particle-size classes (sand, silt, clay) typical of previous approaches. Miska et al. [1989] further modified the Arya and Paris model to estimate the retention function from particle-size distributions, and used first-order error analysis to evaluate parameter uncertainty. Other extensions, modifications, and applications are given by Wu and Voseiscal [1992], and Gupta and Ewing [1992].

Pertinent to the above approach are several recent studies which indicate additional promise in relating the cumulative particle-size distribution to the water retention curve. One of these uses fractal theory and scaled similarities to show that the empirical constant in the Arya-Paris model is equivalent to the fractal dimension of a tortuous fractal pore [Tyler and Wheatcraft, 1988, 1992]. The information was used successfully to predict water retention data from measured particle-size distributions for several coarse- and medium-textured soils. Rieu and Sposito [1991] used a fractal model for the pore- and aggregate-size distribution of structured soils and formulated expressions for the hydraulic properties of a fragmented porous medium and theoretically predicted the water retention and conductivity curves from bulk density and particle- and aggregate size data. However, such detailed information is generally not available for most soils.

A porous medium can also be represented as a network model of pore spaces. Fluid displacement in such a model can be computed on the basis of well-defined physical principles. Water retention is obtained from the global saturation, i.e., averaged over the total pore space of the computational lattice, for a given pressure [Celis and Fermund, 1992]. Dullien et al. [1992] extended this approach by calculating both retention and conductivity from the pore body and pore throat distributions. The use of such a network model alleviates some of the problems associated with the determination of hydraulic properties on "real" soils. The challenge is to formulate a model that is hydraulically equivalent to the soil.

We emphasize that the choice of a suitable method for estimating the unsaturated hydraulic properties must depend upon the required accuracy of those properties. The accuracy should be commensurate with the type of application and/or type of question being asked. As an example, Wüsten et al. [1991] and Wüsten and Bouma [1992] compared the accuracy of predicted and measured hydraulic functions in terms of functional criteria thought to be typical of many applications (i.e., travel time from the soil surface to the water table, or water storage in the soil root zone). These and other studies [e.g., de Jong, 1982] suggest that water retention parameters of soil textural groups are useful for simulating large areas of soils, but may not be accurate enough to closely approximate the soil water characteristics of specific sites.
Finally, we note that an important purpose of simulation models is to forecast future events such as crop yields or pollutant loadings to groundwater. However, simulation models can also be useful for comparing alternative management practices, the main objective then being to rank the performance of selected schemes relative to each other. Exact predictions in such cases are secondary to finding out which schemes or treatments produce the highest yields, or which are the most effective in limiting groundwater pollution. Accuracy of the unsaturated hydraulic properties for such applications is less critical than for applications requiring absolute predictions.

OPPORTUNITIES FOR RESEARCH

Papers presented at the workshop and documented in these proceedings indicate that tremendous progress has been made in the theoretical and empirical description of the unsaturated soil hydraulic properties. Additional progress may come in several areas of research. Below is a list of some of our views regarding the opportunities for additional research and development.

1. As demonstrated at the workshop and by these proceedings, quantification of the hydraulic properties of porous media is a concern shared by soil scientists, hydrologists, chemical engineers, agricultural engineers, and petroleum engineers. Various disciplines have contributed in unique ways to the current state-of-the-art. It is imperative that this cooperation be continued or even enhanced.

2. Continued emphasis is needed on the development and improvement of basic theories relating the hydraulic functions to fundamental properties and flow processes of porous media, including statistical pore- and particle-size distribution models, and network or percolation models. Such theories have resulted in equations that provide reasonable initial estimates of the hydraulic properties, including the hydraulic conductivity, for at least some applications. Payoffs of this type of theoretical research have been significant, and should remain significant in the near future.

3. Fundamental problems remain in the description of the water retention and hydraulic conductivity functions near saturation. While many (quasi-)empirical relationships exist, the actual water retention curve is, in general, too complicated to permit a description with a relatively simple mathematical function using a limited number of parameters. Complications near saturation arise because of air entrapment, and water flow through soil macropores or rock fractures. These phenomena lead to apparent discontinuities in the hydraulic properties near saturation that are not easily captured with existing equations. A more broader issue is the validity of the Richards equation for conditions involving macropore and preferential flow.

4. Fundamental problems also exist in the description of the water retention and hydraulic conductivity functions in the dry end at very low (negative) pressure heads. The existence of a residual water content, or its physical interpretation, remains unclear when simulating water flow in very dry soils. Toledo et al. [1992] uses fractal geometry and thin-film physics to provide a substantive explanation of the power-law behavior of hydraulic properties at low water contents. A related issue is the validity of the Richards equation for conditions involving significant vapor flow in soils [Fayer and Gee, 1992]. This topic is significant when simulating water flow in arid and semi-arid regions.

5. More attention must be paid to the required accuracy of the hydraulic properties in terms of their application to specific flow and transport problems.
6. Development of reliable theoretical models for one and multi-phase fluid flow, and for the hydraulic parameters included in those models, requires an accurate and versatile database of soil hydraulic properties. While many data sets exist, including those in Australia, Belgium, Hungary, the Netherlands, Sweden, Switzerland, the UK, and the U.S., few of these contain sufficient hydraulic conductivity data, let alone a measure of uncertainty in the hydraulic conductivity. Similarly as graphical approaches have been established for computer models to enhance their use by potential users [van der Heijden et al., 1985], an international database should be established to provide an outlet for measured soil hydraulic and related data. It is important that such a database also considers the methods of measurement, and the method of data-analysis used for estimating the hydraulic properties (notably conductivity) from the original field-data.

7. Soil hydraulic property measurements should be standardized as much as possible. A study may be needed to delineate possible differences expected from the use of different methods of measurement and analysis, especially regarding the hydraulic conductivity, soil water content, and soil texture. Current instrumental methods must be continually updated to the extent possible. This includes fundamental experimental techniques (CAT, TDR, CT, etc), as well as improved measurement equipment such as the apparatus described by Nitsche et al. [1992].

8. Hydraulic properties are known to be affected by clay mineralogy and the concentration and ionic composition of the soil solution. The influence of these parameters on the hydraulic properties, particularly the hydraulic conductivity, should be further qualified and quantified.

CONCLUDING REMARKS

This paper shows that a variety of direct and indirect methods are available for estimating the hydraulic properties of unsaturated soils. Direct measurement methods, including those based on recently developed parameter estimation procedures, are needed for most site-specific problems. Indirect theoretical or statistical methods estimate the hydraulic properties from more easily measurable soil properties, including water retention data, soil texture, bulk density, clay mineralogy, and/or soil structure. These extremely cost-effective indirect methods have proven to be useful for a number of applications, mostly for problems involving large areas of lands on semi-detailed scales of 1:50,000 or smaller. Their accuracy for site-specific applications on detailed scales of 1:10,000 or larger still needs improvement. Innovative and comprehensive studies are needed to integrate all theoretical and experimental information relevant to the prediction of the unsaturated hydraulic properties from more easily measured soils data. Such an effort implies the development of a large international database of available water retention data, independently measured unsaturated hydraulic conductivity data, as well as soil texture and other data already available from soil surveys.

REFERENCES


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