VOL. 17, NO. 6 REVIEWS OF GEOPHYSICS AND SPACE PHYSICS SEPTEMBER 1979

UNSATURATED-ZONE WATER

Fred J. Molz, James M. Davidson and Ernest W. Tollner

Department of Civil Engineering, Auburn University, Auburn, Alabama 36830
Department of Soil Science, University of Florida, Gainesville, Florida 32611
Department of Agricultural Engineering, Auburn University, Auburn, Alabama 36830

Basic Research: Rigid Soils

The present theoretical base for mass transport in porous media rests mainly on empirical observations and resultant mathematical descriptions made at the macroscopic [pore size or above] level. Recently, several attempts have been made to extend the theoretical base to the molecular domain. Laroussi and De Backer [1975] derived the diffusion equation for soil moisture flow by considering the displacement of a fluid particle through an unsaturated porous medium as a Markov's stochastic process. However, Bhattacharya, Gupta and Sposito [1976a] point out that the Laroussi-De Backer interpretation of the diffusivity is invalid because their analysis does not allow for Markovian coefficients that are space and time dependent. Using the assumption that the trajectory of a water molecule is a non-homogeneous Markov process characterized by space- and time-dependent coefficients of drift and diffusion, Bhattacharya, Gupta and Sposito [1976 a,b,c,; Gupta, Sposito and Bhattacharya, 1977] developed a number of interesting results. The Buckingham-Darcy flux law was derived without relying directly on experiment, a new molecular interpretation of soil water conductivity and diffusivity was presented and a proof resulted that the diffusivity for anisotropic soil is a symmetric tensor of the second rank. Results relating to the properties of the vector matrix flux potential were discussed also.

The branch of theoretical physics that deals most fundamentally with the description of transport processes at the molecular level is non-equilibrium statistical mechanics. In a noteworthy paper, Sposito [1978a] used non-equilibrium statistical mechanical methods to derive the macroscopic differential equations of mass and momentum balance for water in a rigid, unsaturated soil. The Buckingham-Darcy flux law was derived in a second paper [Sposito, 1978b]. Such derivations offer interesting possibilities in addition to the obvious intellectual satisfaction. In particular, the hydraulic conductivity is expressed in terms of an integral over time of the correlation function for the velocities of the water molecules. Thus, if one could develop a molecular model of the velocity correlations among water molecules in a soil, the hydraulic conductivity could be calculated.

The possibility of predicting the hydraulic conductivity tensor [and other hydraulic properties] on the basis of molecular measurements and models is intriguing. During the next several years, the attempt to establish firmly the microscopic foundations of the macroscopic soil water flow equations could prove fruitful. However, results of practical value will, most likely, require quite a lot of research. Increasingly general derivations of macroscopic energy, mass and momentum conservation equations are needed, along with rigorous flux laws and expressions for transport coefficients such as the soil water diffusivity and hydraulic conductivity.

Basic Research: Swelling Soils

It was first emphasized by Philip [1971], and now generally recognized, that water movement in swelling soils is qualitatively as well as quantitatively different from that in rigid soils. Talsma [1974b] used laboratory data to illustrate the difference in the behavior of swelling and nonswelling materials. Results were also reproduced in the field where the equilibrium moisture profiles were compared in two clay soils and one loam soil with permanent shallow water tables. The clays displayed "hydric" profiles as predicted, with water moving upward against the moisture gradient. Parlange [1975a] showed that relations between sorptivity and diffusivity derived for nonswelling materials cannot be applied to swelling materials. Relations specific to swelling materials must be used.

Sposito [1975a,b,c] used a thermodynamic approach to describe vertical equilibrium moisture profiles and flows in a swelling soil. The correct differential equation for the moisture profile was found and discrepancies with previous results were shown to have been caused either by introduction of extraneous thermodynamic variables or by incorrect consideration of overburden pressure. These theoretical advances have set the stage for the development of solutions to the differential equations governing swelling soils for a wide variety of special cases of importance in hydrology, such as infiltration, evaporation, capillary rise, redistribution, and drainage. Some of this work has already begun. Sposito, Giráldez and Reginato [1976] describe the use of a material coordinate transformation which they believe will prove useful for field applications since it requires only the measurement of bulk density. Giráldez and Sposito [1978] derived practical working equations for describing steady-state, vertical moisture profiles in homogeneous swelling soils. The equations were solved on a computer, and many interesting profiles were calculated depending on whether the soil was saturated or unsaturated and whether the flows were upward or downward. In practically all cases, the overburden potential was of major importance.

The ongoing theoretical effort being applied to swelling soils must be accompanied by sound experimental work. In this regard, interesting papers were published by Wong and Yong [1975], Talsma and van der Leij [1976], and Mustafa and Hamid [1977]. Complicating factors which the theory may have to consider could include the

Paper number 9R0371.
0034-6853/79/009R-0371$06.00

effect of solutes on hydraulic properties [Dane and Klute, 1977], the possibility of hysteresis in the relationship between void ratio and moisture ratio [Towner, 1976] and the influence of macropores and pore-size distribution on the flow process [Bouma et al., 1977].

Non-Hysteretic Soil Hydraulic Properties

Theoretical advances in our understanding of transport processes in porous media are often based upon improvements in experimental procedures for measuring soil properties. Techniques to determine the hydraulic properties of natural soil systems using in situ measurements and undisturbed soil cores are needed and have continued to be developed. Alemi et al. [1976] used two centrifuge-based methods to determine the hydraulic conductivity of natural soil cores. Ahuja [1975] and Ahuja and El-Swaify [1976] describe a procedure for obtaining both the soil-water characteristic and hydraulic conductivity relationship from data measured during the wetting of a natural soil core. The above techniques agree with published data obtained using other methods. Rawls et al. [1975] present a numerical model for describing axisymmetric infiltration problems and fit the model to field data to define the hydraulic properties of field soils. Close agreement was found between the numerical model solution and independent field measurements for two sites. Baker [1977] evaluated several factors thought to influence hydraulic conductivity values obtained using the artificial crust test described by Hillel and Gardner [1970]. Diameter and height of the soil pedestal were shown to strongly affect hydraulic conductivity measurements when these parameters were small, and operator errors were small compared to other sources of error. Relative errors associated with hydraulic conductivity measurements obtained from a transient drainage field experiment were analyzed by Fluhler et al. [1976]. They found that for the wet range of the hydraulic conductivity relationship, errors could be 20-30 percent of the actual value. When hydraulic conductivity values were small, the relative errors could easily be greater than 100 percent.

The spatial variability of in situ unsaturated hydraulic conductivity measurements is considered by Carvallo et al. [1976], Baker and Bouma [1976], Baker [1978], and Keisling et al. [1977]. Significant variability in hydraulic conductivity measurements was noted both in the vertical and lateral direction for a given soil series. A simple procedure involving a Taylor-series expansion for estimating the spatial variability of such soil properties is discussed by Rao et al. [1977]. Warrick et al. [1977b] used the concept of similar media to develop techniques for describing water flow in spatially varying soils. Field data involving soil water characteristic relations and unsaturated hydraulic conductivity were collected. Comparisons made between curves fitting the data and those fitting the scaled data show that scaling reduces the squared deviations by amounts varying from 34 percent to 90 percent. The similar media concept is promising and should be pursued by other investigators using different soils.

Dirksen [1975] has developed a new method for determining the dependence of soil-water diffusivity on water content in the tensiometer range. A weighted mean diffusivity is used to linearize the one-dimensional absorption problem. To use this procedure, sorptivities must be measured in situ for a series of step-function increases in soil-water content. A procedure for measuring the unsaturated soil-water diffusivity of an anisotropic soil was developed by Sawhney et al. [1976]. The method makes use of a two-dimensional similarity solution derived for an isotropic medium.

Remote sensing of surface soil temperature appears to be a practical means of assessing soil water status in the upper 2 to 4 cm of bare soil [Idos et al., 1975; Engleman and Lin, 1976; Schmugge et al., 1977; Skidmore, 1975]. A composite relationship between the radiometric temperature and soil moisture content (correlation index of -0.96) was determined from five data sets obtained over Kansas and Texas. Other methods being evaluated for measuring soil-water content involve nuclear magnetic resonance [Matzkanin and Gardner, 1975], dielectric properties [Selig and Mansukhani, 1975], and electrical capacitance [Selig et al., 1975].

New and/or modified procedures for measuring soil-water potential more efficiently are described by Anderson and Burt [1977a,b], Savvrides et al. [1977] and Brown and Johnston [1976]. The latter authors describe a screen-covered thermocouple psychrometer for in situ measurements of soil-water potential which is less subject to microorganism contamination than previously used psychrometer systems.

Hysteretic Soil Hydraulic Properties

Results of several studies confirmed the importance of hysteresis in the hydrology of field soils. Beese and van der Ploeg [1976] studied water transport in an undisturbed soil monolith and concluded that soil suction predictions were marginally successful if one used only the sorption and desorption curves without scanning between them. Other studies verify the idea that hysteresis is too important to be neglected in the hydrology of field soils [Royer and Vachaud, 1975; Watson, Reginato and Jackson, 1975].

If hysteresis is to be included in the modeling of field soil water processes, efficient techniques must be developed for representing the hysteretic relationship between water content, potential, and possibly other variables. Parlange [1976] proposed a simple microscopic model which predicts the wetting and drying scanning curves from only one boundary of the main hysteresis loop. Such approaches which require a minimum of experimental measurement are attractive. However, further study of the Parlange [1976] model by Mualem and Morel-Seytoux [1978] indicated that his approach was unreliable since it often yielded badly distorted shapes of hysteresis curves.

Mualem and Dagan [1975] built upon previous work to develop a dependent domain model of capillary hysteresis which takes into account the phenomenon of blockage against air and water entry. The model works especially well for soils having a major portion of their hysteretic loop in the range of air entry value. Mualem [1976b] further generalized this approach to predict the hysteretic relationship between hydraulic conductivity and potential and between hydraulic conductivity and water content. Very good agreement was found between theory and experiment. Mualem [1977] summarizes some of his previous work and extends the similarity hypothesis used for the modeling of soil water characteristics. The object here is to derive simplified models of hysteresis which require a reduced amount of experimental data for calibration.

As discussed by Mualem and Morel-Seytoux [1978], studies of hysteresis have three major and sometimes incompatible objectives: 1) to improve our understanding of the physical mechanism of the observed phenomena of capillary hysteresis, 2) to improve the accuracy of the prediction of the capillary head versus water content relationship, and 3) to reduce the amount of experimental data required for calibration of the models. An appropriate weighted average of the above objectives will aid in the numerical modeling of field and laboratory systems [Cary, 1975; Lees and Watson, 1975; Gillham, Klute and Heermann, 1976; Hoa, Gaudu and Thirriot, 1977].

Single-Phase Infiltration and Redistribution

During the past four years, interest in simplified formulas for predicting infiltration has continued to be strong. This has been motivated, in part, by an increasing need to describe hydrologic processes on a watershed scale and by concern for the quality of water originated from non-point sources. A relatively simple infiltration equation was used by Swartzendruber and Hillel [1975] to develop a family of infiltration vs. time curves for a constant intensity rainfall. The curves become applicable when excess water first appears at the soil surface. Brutsaert [1977] derived a simple infiltration equation [required parameters are saturated hydraulic conductivity and sorptivity] that is quite accurate in a mathematical sense. The equation behaves properly for very small times and very large times. For these reasons, and others, the procedure is superior to that of Swartzendruber and Hillel [1975]. Reeves and Miller [1975] developed a procedure for estimating infiltration under erratic rainfall conditions. Morin and Benyamini [1977] tested a model developed by Seginer and Morin [1970] to describe soil crust formation under raindrop impact and its influence on infiltration.

Perturbation methods were employed by Babu [1976a,b,c] and Liu [1976] to analyze the horizontal and vertical infiltration of water into unsaturated soils. The solution emerges as a series of terms that can be explicitly calculated from integrals involving diffusivity functions. Diffusivity was assumed to be an exponential function of the soil-water content. Parlange and Babu [1976b] have shown that the perturbation solution is identical to the iterative results when Cisler's correction is used.

Use of the Green and Ampt [1911] model for describing infiltration has continued to be elaborated and expanded. Neuman [1976] and Mein and Farrell [1974] present theoretical justification for relating the wetting front pressure head in the infiltration model to soil characteristics. Fok [1975] has shown that the Philip two-term equation for vertical infiltration can be derived from the Green-Ampt equation. A similar comparison of these two models was made by Ahuja and Tsuji [1976]. Efficient methods for solving the Green-Ampt one-dimensional infiltration model were presented by Li et al. [1976]. A simple explicit solution resulted in a maximum error of 8 percent while an implicit solution was associated with negligible error. Necessary calculations can be performed on a desk calculator.

The Green and Ampt [1911] model was also used by Youngs and Aggelides [1976] and Chu [1977] to describe the redistribution of water following the cessation of infiltration. Good agreement between calculated and measured water table heights and drainage flux with time were obtained from field and laboratory experiments. Ghugla [1974] developed a simple mathematical, multilayer model using the diffusion equation to calculate vertical water movement in unsaturated soil. The multi-layer model is suitable for calculating the annual course of natural groundwater recharge, and was tested using data from a weighing lysimeter.

Non-Darcy flow during infiltration was detected by Poulovassilis [1977] and Gill [1976]. Experimental profiles for small times were retarded and thus became more pronounced as the soil-water content increased. For infiltration into horizontal columns, a unique relationship between water content and distance divided by the square root of time was not found. These two studies support the need for basic research on flow processes in complex soil materials.

Two-Phase Infiltration and Redistribution

Experimental and theoretical work has continued on the problem of understanding and describing the simultaneous transport of air and water in the unsaturated zone, and a general review of multiphase fluid flow through porous media was published by Wooding and Morel-Seytoux [1976]. Experimental studies [Vachaud, Gaudet and Kuraz, 1974; Linden and Dixon, 1976] further substantiated the importance of air pressure in determining the rate of infiltration in many situations. An interesting paper by Linden and Dixon [1975] showed experimentally that air pressure under border irrigation caused significant groundwater redistribution. It appears that the effect of soil air pressure on water table position should be investigated more thoroughly for small, intermediate, and large scale (watershed-size) systems.

It is now evident that any serious attempt to predict infiltration rate must begin with a determination of whether air transport effects are important. If they are, one may be able to make use of several of the advances made in recent years aimed at incorporating the effects of air and water movement during imbibition, infiltration and drainage [Brustkern and Morel-Seytoux, 1975; Morel-Seytoux, 1975; Morel-Seytoux and Kanji, 1975a,b; Morel-Seytoux, 1976; Sonu and Morel-Seytoux, 1976; Morel-Seytoux, 1977; Morel-Seytoux, 1978]. Most of the above papers developed approximate analytical solutions or formulas for calculating imbibition, infiltration, etc. Other more numerical-analysis oriented approaches were developed also [Watson and Curtis, 1975; McWhorter, 1976].

From a theoretical viewpoint, the paper by Morel-Seytoux [1975] is of particular interest because it establishes for the first time the complete symmetry between infiltration and drainage when treated as a two-phase (air-water) flow process. Earlier work at Colorado State University culminated in the paper by Morel-Seytoux [1978] which is significant from a practical viewpoint. This work provides a simple means of predicting infiltration for any complex pattern of rainfall, a physically-based tool that has eluded hydrologists for a long time. It is likely that this or related formulas will play an important future role in watershed simulation models where they will replace techniques for predicting infiltration, such as the ϕ index method, Horton's formulae and other purely empirical techniques.

Water Flow From Point and Line Sources and to Sinks

In recent years, the use of trickle irrigation systems has expanded. Jury and Earl [1977], Earl and Jury [1977] and Hachum et al. [1976] studied the influence of water application rate and irrigation frequency on movement and distribution of water within the soil profile. Water movement in the horizontal and vertical directions was described by an exponential equation, and two-dimensional wetting patterns in the soil profile were approximated by a semiellipse without a significant loss of accuracy [Hachum et al., 1976].

Analytical solutions for line water sources were developed by Warrick and Lomen [1977], Thomas et al. [1976], and Philip and Forrester [1975]. In general, these solutions assume steady-state conditions and a hydraulic conductivity exponentially related to the pressure head. The solutions provide a method for selecting lateral depth and spacing of line irrigation systems. Experimental evaluations of the analytical solutions for line sources have been conducted by Batu [1977] and Sawhney and Parlange [1974].

A paper by Hansen and Harris [1975] called attention to some of the problems inherent in the use of porous ceramic cup soil-water samplers. Variables which affected the measured concentrations of extracted nitrate and phosphate solutions included sampler intake rate, plugging, sampler depth, and sampler sizes. Theoretical papers which followed shed further light on the transient and steady-state conditions surrounding a soil-moisture sampler. Among other things a numerical solution of the radial flow equation by van der Ploeg and Beese [1977] indicated that for continuous water extraction the radius of influence of the sampler can be quite large (several feet) and therefore not representative of point quantities. Warrick and Ammozegar-Fard [1977] present analytical and numerical steady-state solutions for various flow situations. From their results, sampling volumes and regions of influence can be calculated.

Saturated-Unsaturated Flow

Many interesting problems in hydrology involve the interaction of the saturated zone and the unsaturated zone. Drawdown of a water table, recharge to groundwater and drainage of a saturated column are but a few examples. The transport processes that occur are often called saturated-unsaturated flows and have constituted an area of active quantitative research for the past decade.

Luthin, Orhun and Taylor [1975] obtained experimental data from a sector tank for transient flow toward a well. The data, which included both the saturated and unsaturated flow region, are available for testing existing and proposed numerical models. An implicit finite-difference model tested by the authors agreed well with the data. However, this study, and others, indicates that the influence of the unsaturated zone is negligible for the most common cases encountered in practice. The approximate analytical solution of Kroszynski and Dagan [1975] suggests that when unsaturated zone effects are significant, they will be felt at relatively short times, close to the pumping well, and close to the free surface. Skaggs and Tang [1976] [Tang and Skaggs, 1977] reached similar conclusions for saturated-unsaturated flow to drains, and McWhorter and Duke [1976] developed a relatively simple method for considering capillary storage and flow above the water table in drainage design. Watson and Whisler [1978] considered unsaturated-zone effects in their analysis of the decay of a perched water-table.

A more general and detailed discussion of vertical flow components in the unsaturated zone and their inclusion in the general flow equation for unconfined formations was presented by Streltsova [1976]. Hoa, Gaudu and Thirriot [1977] studied experimentally and theoretically the influence of hysteresis on transient flows in saturated-unsaturated porous media. A finite element model of two-dimensional flow in a wedge of soil with time-dependent boundary conditions did not agree well with experiment unless hysteresis was considered.

Narasimhan and Witherspoon [1977] developed an elaborate theoretical model and numerical algorithm [Narasimhan, Witherspoon and Edwards, 1978] which applies to multi-dimensional saturated-unsaturated flow in deformable porous media. The model couples a 3-D flow field with a 1-D vertical deformation field. Conservation of fluid mass is expressed using an elemental volume which contains a constant volume of solids. The theory is quite general and allows for nonelastic deformation. Permeability and compressibility coefficients can be nonlinear functions of effective stress, hysteresis is considered in the unsaturated zone, and the relation between pore pressure change and effective stress change may be a function of saturation. The model and algorithm should yield some interesting insights when applied to systems of hydrologic interest.

Since the water table normally moves in saturated-unsaturated flow situations, such phenomena can be considered as members of the broader class of problems involving moving boundaries. Nakano [1978] developed a fundamental analysis of moving boundary problems as related to the hydrodynamics of porous media. The author states that earlier studies of the conditions at a saturated-unsaturated boundary are correct as far as they go, but are not complete because no consideration was given to discontinuities in certain variables such as the change in water content with respect to time. Nakano [1978] derives the complete boundary condition and then goes on to justify theoretically the introduction of a thin but finite transition zone around the moving boundary. Such a device increases computational simplicity because detailed tracking of the boundary position is no longer required. Other numerical approaches for solving saturated-unsaturated flow problems were developed by Hornung [1977] and by Cushman and Kirkham [1978].

Coupled Transport of Water and Solutes

Efforts to describe nonsigmoidal and asymmetrical solute distributions commonly observed in disturbed and undisturbed soil systems have increased in recent years. Van Genuchten and Wierenga [1976, 1977] and Van Genuchten et al. [1977] used a conceptual mathematical model similar to that described by Coats and Smith [1964] to divide soil water into mobile and immobile liquid phases. Their approach explained asymmetrical solute distributions and early solute breakthrough in effluents from unsaturated [Gaudet et al., 1977], sandy soils. The role of soil structure in enhancing hydrodynamic dispersion was illustrated by Anderson and Bouma [1977 a,b]. These authors observed more dispersion in subangular blocky structures than prismatic structures, which they attributed to flow along structural units.

The spatial variability of water flow in natural field soils was shown to be a major cause of the larger hydrodynamic dispersion coefficient observed in natural systems. Biggar and Nielsen [1976], using data from a large field study, showed that estimates of the pore-water velocity and dispersion coefficient from measured solute displacement data were log-normally distributed. Similar results were obtained by van De Pol et al. [1977] using a steady-state field experiment. Extremes in solute displacement were measured at different soil depths within the plot. Such measurements were also reported by Quisenberry and Phillips [1976].

Selim et al. [1977] and De Smedt and Wierenga [1978] have shown that effluent data from soil columns with nonuniform water content and adsorption characteristics may be described with a mathematical model for a uniform soil. The coefficients used in the model were the arithmetic averages of the water contents, adsorption coefficients, flow velocities, and dispersion coefficients from each soil layer. Thus, the use of statistically-valid data in mathematical models for uniform soils can serve as a first approximation for describing flow processes in nonuniform soils.

The importance of hydrodynamic stability in producing asymmetrical solute distributions in the soil profile and log-normally distributed mean pore-water velocities and dispersion coefficients should be given consideration in the future. Parlange and Hill [1976], Philip [1975a,b] and White et al. [1976] have pointed out that when vertical infiltration is perturbed by sharp changes in the pressure gradient behind the wetting front, "fingers" are developed.

Several efforts were made to describe the mobility and distribution of solutes which are adsorbed on colloidal surfaces or are transformed within the soil-water phase. Enfield and Bledsoe [1975], Helyar and Munns [1975] and Mansell et al. [1977] attempted to quantify various phosphorus reactions and the transport of specific phosphorus species through soils. Phosphorus effluent concentrations were described best using an irreversible sink for chemical immobilization, or precipitation with a nonlinear reversible kinetic adsorption-desorption equation. Kirda et al. [1974] and Watts and Hanks [1978] assumed first order kinetic reactions to describe nitrogen transformation processes in a soil. The calculated total mass of individual nitrogen species and their concentration distributions with depth were in reasonable agreement with measured data. Wierenga et al. [1975], combining a transient water flow model with a chemical plate theory model, obtained good agreement between measured and predicted depth distribution profiles for SO_4^{-2}, Cl^-, Na^+ and Ca^{+2}.

Transport in Freezing Soil-Water Systems

Expanding interest in arctic and near-arctic regions is continuing to provide motivation for research on transport processes in frozen and partially frozen soils. As discussed by Amerman et al. [1975] and Guymon [1975, 1976], water transport in frozen soil is fundamentally involved with heat transport and with thermal processes such as heat of vaporization and heat of fusion which accompany phase changes. Therefore the overall process is quite complex and additional basic research is needed before an acceptable understanding of the various phenomena emerges. There is still some controversy as to the driving forces that cause water flux in a frozen soil and their relative importance. It is difficult to measure transport coefficients in frozen systems, especially in the field, and their variations are complicated by phase changes. Salt effects are also significant.

Papers of fundamental importance were published by Miller et al. [1975] and by Loch and Miller [1975]. A key contention of the Miller et al. [1975] paper is that the ice phase in frozen soil is not immobile under conditions of steady-state liquid transport. Ice grains surrounded by liquid films can migrate through noncolloidal soil by melting at the "upstream" end and freezing at the "downstream" end. This effect has potentially important implications for coupling between liquid movement in the solid and liquid phases and between water and heat transport. The paper lays the foundation for a pore model of mass and heat transport in frozen soils and introduces concepts ignored by many previous authors. Loch and Miller [1975] apply some of these concepts to the problem of frost heaving.

Groenevelt and Kay [1977] continued their non-equilibrium thermodynamic study of transport processes in frozen soils with a paper devoted to water and ice potentials. What the authors call envelope pressure potentials of the liquid water and ice in a frozen soil are defined. The envelope pressure potential of liquid water is a generalization of the concept of overburden potential in an unfrozen swelling soil. Loch and Kay [1978] studied experimentally water redistribution in partially frozen, saturated silt soils. They concluded that existing theories could not be used to predict location of an ice lens relative to a freezing front because they do not consider the important effects of overburden pressure.

Using a conventional hydrodynamic approach, Guymon and Luthin [1974] developed a one-dimensional, finite-element model of coupled heat and moisture transport for arctic soils. Their model was based on the Richards equation and the heat conduction equation. As our understanding of frozen systems improves, more rigorous and general models should be forthcoming.

The infiltration of meltwater and the upward movement of soil moisture beneath a snowpack are fundamental to the prediction of runoff during a spring thaw. Presently, research in these areas appears to be occurring primarily in the Soviet Union. Komarov and Makarova [1973] studied the effect of ice content, temperature, cementation, and freezing depth of a soil on meltwater infiltration. They conclude that permeability depends primarily on ice content and freezing depth, with very large variations in these quantities existing over a basin. Kasansky [1974] presented a statistically-based model for describing infiltration into frozen ground, and Romanov, Paulova and Kalyuzhnyy [1974] discuss meltwater infiltration into frozen podzolic and chernozem soils and the effect on the spring runoff coefficient in wooded drainage basins. Peck [1974] notes that the maximum prethaw soil moisture content is often observed immediately prior to the spring melt. The primary mechanism for this accumulation of soil moisture appears to be the upward movement of water in both the liquid and vapor phases induced by a temperature gradient.

There is no fundamental reason why a snowpack should not be considered as an extension of the unsaturated zone. Colbeck [1975, 1976] presents a theory for water flow through a layered snowpack and derives equations describing water movement in dry snow. This, and additional work pertaining to water transport in snow, is discussed in detail by Colbeck [1978]. In general, rain-on-snow events can produce anything from serious floods to no runoff, depending on many variable factors such as the transport properties of the snow itself, the temperature, and the meltwater infiltration discussed previously. Obviously, complex interactions exist among soil, snowpack, vegetation and atmosphere. This fundamentally important area which intimately involves the unsaturated zone is wide open for research at many levels.

Coupled Water, Heat, and Vapor Transport in Non-Frozen Soil

The simultaneous transport of water and heat in non-frozen soils is not as complicated as in the frozen case and has a better grounding in theory. However, there is still considerable disagreement between experiment and theoretical predictions. Kimball et al. [1976] intensively sampled a field plot at 0.5-hour intervals and tested the ability of the theory of Philip and de Vries [1957] [de Vries, 1958] to predict soil-heat fluxes. Unmodified, they found the theory predictive only over a small range of water content. The authors conclude that their data and the data of others indicate that an individual "calibration" of the theory for a particular soil is required before reliable predictions of soil-heat flux can be obtained. In an earlier work, Jackson et al. [1974] performed a rigorous field test of the Philip-de Vries theory with respect to prediction of water flux. Their data indicated that the theory predicts water fluxes reasonably well only for an intermediate water content range when the diffusivities are known precisely.

Jury and Bellatuoni [1976a,b] studied water and heat movement under surface rocks in a field soil. The rocks did not completely cover the soil but were scattered about on the surface. The authors consistently observed, and were able to predict, a net lateral movement of heat toward the soil under the rocks over a 24-hour period. Based on this observation, it was reasoned that due to the thermal gradients, water vapor would move under the rocks where it would then be insulated from evaporative loss. Ultimately, the accompanying vapor flux was detected and explained theoretically. Although the amount of moisture transferred to the rock-covered soil was not large, this interesting phenomenon might well make a significant contribution to the water balance of a drought-tolerant desert plant.

Hadas [1977a,b] performed additional experimental tests of the Philip-de Vries theory. He found that the theory accurately predicted the transfer of heat by vapor under steady-state conditions, but underestimated it under transient conditions. Hadas suggests that the discrepency is due mainly to phenomena such as movement by pressure and density gradients that are not considered in the Philip-de Vries development. Such effects are dependent on soil aggregate size.

An important study of heat and vapor movement during infiltration into dry soils by Perrier and Prakash [1977] illustrated the relationship between heat, water vapor and liquid water as a wetting front advances. Upon wetting a dry soil, a large amount of heat is evolved. Resulting evaporation supplies a vapor phase. As liquid continually moves into dry soil, the vapor phase moves as a front immediately ahead of the wetting front. In addition, a large fraction of the heat evolved moves as a heat front in advance of both the vapor and liquid fronts. A final phenomenon detected was a cooling of the soil-water mixture immediately behind the wetting front. Thus, the passing of a wetting front is accompanied by first a rise and then an abrupt fall in temperature.

As the above discussions indicate, many good experimental studies were performed during the past four years. Theoretical studies were not as abundant although Raats [1975b] presented an enlightening discussion which related to both the Philip-de Vries approach and to the non-equilibrium thermodynamic approach to water and heat transport in unfrozen soils. Future research is needed to make existing theories more applicable to field conditions. This concept was advocated by both Jackson et al. [1974], Kimball et al. [1976] and Hadas [1977a]. Additional basic research is required in order to completely understand the phenomena described by Perrier and Prakash which amounts to water, heat, and vapor transport in the presence of a chemical reaction.

An interesting paper was published by Aston and Gill [1976]. These authors developed a numerical model of coupled vapor, heat and liquid water transport in a soil with simulated fire conditions on the surface. The model was tested with experimental grass fire data and with moist soil in a tube with its surface heated by a radiant heater. The agreement between theory and experiment was reported to be good.

Water Transport in Soil Containing Roots

A large amount of water in the unsaturated zone flows from soil to roots and a surprisingly small amount from roots to soil [Molz and Peterson, 1976]. In recent years, water transport in the soil-root system has received an increasing amount of study. A number of studies dealt with one- and two-dimensional models of water transport which were based on the Richards equation containing a spatially distributed sink term to represent water extraction by roots. Feddes, Bresler and Neuman [1974] performed a field test of a one-dimensional model of vertical water transport in a soil containing roots. Over a period of seven weeks, the authors obtained good agreement between calculated and measured soil moisture profiles. In a later study [Neuman, Feddes and Bresler, 1975], the authors developed a two-dimensional finite element model of water flow in soil with water uptake by roots. One- and two-dimensional field tests of the model agree well with measured data and illustrate the flexibility of the finite element approach in treating complex field conditions. Feddes et al. [1976a] elaborate further concerning the use of a water-dependent root extraction function.

Raats [1975a, 1976] presented several analytical solutions to special cases of the flow equation with water extraction. Lomen and Warrick [1976] developed analytical solutions for the one-dimensional steady-state case with several different functions modeling water uptake. Other authors [Hillel, van Beek and Talpaz, 1975; Hillel, Talpaz and van Keulen, 1976] presented CSMP simulations of water and solute flow in soil-root systems.

In order to apply models of water transport in soils containing roots, methods must be developed for measuring the hydraulic properties of such soils and for determining rooting characteristics and water extraction patterns. In a series of papers, Arya, Farrell and Blake [1975] [Arya, Blake and Farrell, 1975a,b] considered these problems. Field and laboratory methods were used to measure the moisture characteristic, hydraulic conductivity and diffusivity of undisturbed soil cores. Then a detailed study was made in the presence of growing soybean roots. Among other things, the authors conclude that the resistance to flow in the immediate vicinity of a root (rhizosphere) is relatively small and that two-dimensional water flow and extraction patterns are associated with row crops. In another study, Rice [1975] made in situ measurements of the relations of pressure head to water content and to hydraulic conductivity in a soil containing roots. Flux and water content changes were calculated over two-hour intervals which allowed a detailed picture of the water transport-extraction process to be developed.

A rather fundamental unknown which relates to the derivation of realistic root water extraction functions is the location of the principal resistance(s) to flow in the soil-root cortex-root xylem pathway. Several studies suggest that a major resistance is presented by the root cortex. Using a recently-developed theory [Molz and Ikenberry, 1974], Molz [1975, 1976] studied radial water flow in concentric cylinders of soil and root tissue. Numerical results suggested that in many cases, there will be small water potential gradients in the soil relative to those in the root in the upper 90 percent of the water availability range. Taylor and Klepper [1975] came to a similar conclusion based on experiments performed with soil containing cotton roots. However, experiments and calculations by So, Aylmore and Quirk [1976] indicated that rhizosphere resistance was of the same order of magnitude as the root resistance in the -1 to -2 bar potential range.

In two recent papers, Herkelrath, Miller and Gardner [1977a,b] investigated the influence of soil water content and soil water potential on water uptake by the roots of winter wheat. The experiments were performed in a carefully-controlled laboratory environment, and many interesting effects were observed. The authors interpret their data as indicating that soil-root contact played a major role in determining water uptake rate.

Further research is needed to understand fully the various resistances in the soil-root pathway and the effect they have on water absorption. Little is known concerning the mechanism(s) which seems to prevent water loss from relatively moist roots to dry soil. It is also possible that coupling between water flows and solute flows could play a significant role in water uptake [Dalton, Raats, and Gardner, 1974].

Numerical Methods and Simulation

Techniques for the numerical solution of differential equations describing unsaturated-zone processes continue to be developed and refined. Many studies [Jeppson, 1974a,b; Amerman and Monke, 1977; Haverkamp, et al., 1977; Perrens and Watson, 1977; Hayhoe, 1978a; Zaradny, 1978], while quite informative, dealt primarily with refinements to existing techniques and applications or with comparisons of different methods for solving the same problem. Finite element methods [Gray and Pinder, 1976; Zyvoloski, Bruch and Sloss, 1976; Hayhoe, 1978b] were applied successfully to several transport processes. For many problems, either finite element or finite difference methods are acceptable [Hayhoe, 1978b] although the finite element method appears to have the edge in solving the diffusion-convection equation [Gray and Pinder, 1976]. Of course the advantages of finite element procedures for irregularly-shaped domains are generally recognized.

A series of papers were published dealing with solutions of the non-linear diffusion equation using perturbation, iterative and optimization techniques [Parlange, 1975b,c,d; Brutsaert, 1976; Parlange and Babu, 1976a,b; Liu, 1976; Parlange and Babu, 1977]. These methods are semi-analytical in nature and generally yield highly accurate approximate solutions with relatively little computation. Brutsaert's [1976] method appears to be superior, both with respect to accuracy (error < 0.1 percent) and ease of computation. A serious limitation for hydrologic applications is that such solution methods apply only to homogeneous media. Krishnamurthi, Sunada and Longenbauch [1978] discuss oscillation of a numerical solution to a modified Richards equation and develop criteria for non-oscillatory solutions.

Closing Comments

During the past four years notable advances were made in many areas of unsaturated zone hydrology. These included attempts to extend the theoretical basis for describing transport processes in rigid soils to the molecular scale, advances in our understanding of water transport in swelling soils, and development of conceptual models for solid and liquid phase transport in frozen soils. Existing theory was further elaborated and applied to single-phase infiltration, two-phase infiltration, flow involving sources and sinks, saturated-unsaturated flow, and flow in soil containing roots. Many worthwhile studies were devoted to coupling phenomena involving liquid water, solutes, heat and water vapor.

In much of this work, it is evident that the most universal problem facing modern unsaturated-zone hydrologists is the measurement and representation of soil hydraulic properties on a scale useful for application. This problem is made even more acute by the small- and large-scale heterogeneity of natural systems. While new instruments and methods have been devised for making in situ measurements of soil hydraulic properties, and improved techniques have been developed for representing the effects of hysteresis, nothing approaching a "breakthrough" can be claimed. It is not even known if the ultimate solution to this problem will be conceptual or technological in nature. Will increasingly sophisticated measurements and measurement devices enable us to gradually apply our conceptual models in a truly predictive manner, or will the resulting measurements be so ambiguous that they ultimately force the development of a radically different theory? This is the central question of modern unsaturated-zone hydrology, and a great deal of future effort will be devoted to obtaining an answer.

Additional References

Loch, J.P.G., and R.D. Miller, Tests of the concept of secondary frost heaving, Soil Science Society of America Proceedings, 39, 1036-1041, 1975.

Miller, R.D., J.P.G. Loch, and E. Bresler, Transport of water and heat in a frozen permeameter, Soil Science Society of America Proceedings, 39, 1029-1035, 1975.

Loch, J.P.G., and B.D. Kay, Water redistribution in partially frozen, saturated silt under several temperature gradients and overburden loads, Soil Science Society of America Journal, 42, 400-406, 1978.

References

Ahuja, L.R., Applicability of the Green-Ampt approach to water infiltration through surface crust, Soil Science, 118, 283-288, 1974a.

Ahuja, L.R., Unsaturated hydraulic conductivity from cumulative inflow data, Soil Science Society of America Proceedings, 38, 695-699, 1974b.

Ahuja, L.R., A one-step wetting procedure for determining both water characteristic and hydraulic conductivity of a soil core, Soil Science Society of America Proceedings, 39, 418-423, 1975.

Ahuja, L.R., and S.A. El-Swaify, Determining both water characteristics and hydraulic conductivity of a soil core at high water contents from a transient flow experiment, Soil Science, 121, 198-204, 1976.

Ahuja, L.R., S.A. El-Swaify and A. Rahman, Measuring hydrologic properties of soil with a double-ring infiltrometer and multiple-depth tensiometers, Soil Science Society of America Journal, 40, 494-499, 1976.

Ahuja, L.R. and G.Y. Tsuji, Use of the Green-Ampt equation with variable conductivity, Soil Science Society of America Journal, 40, 619-622, 1976.

Alemi, M.H., D.R. Nielsen, and J.W. Biggar, Determining the hydraulic conductivity of soil cores by centrifugation, Soil Science Society of America Journal, 40, 212-218, 1976.

Amerman, C.R., Soil water modeling I: a generalized simulator of steady, two-dimensional flow, Transactions of the American Society of Agricultural Engineers, 19, 466-470, 1976.

Amerman, C.R., A. Klute, R.W. Skaggs, and R.E. Smith, Soil water, Reviews of Geophysics and Space Physics, 13, 451-454, 1975.

Amerman, C.R., and E.J. Monke, Soil water modeling II: on sensitivity to finite difference grid spacing, Transactions of the American Society of Agricultural Engineers, 20, 478-484, 1977.

Anderson, J.L. and J. Bouma, Water movement through pedal soils: I. saturated flow, Soil Science Society of America Journal, 41, 413-418, 1977a.

Anderson, J.L. and J. Bouma, Water movement through pedal soils II. unsaturated flow, Soil Science Society of America Journal, 41, 419-423, 1977b.

Anderson, M.G. and T.P. Burt, Automatic monitoring of soil moisture conditions in a hillslope spur and hollow, Journal of Hydrology, 33, 27-36, 1977a.

Anderson, M.G. and T.P. Burt, A laboratory model to investigate the soil moisture conditions on a draining slope, Journal of Hydrology, 33, 383-390, 1977b.

Aron, G., A.C. Miller, Jr., and D.F. Lakatos, Infiltration formula based on SCS curve number, Journal of the Irrigation and Drainage Division, ASCE, 103, 419-427, 1977.

Arya, L.M., G.R. Blake and D.A. Farrell, A field study of soil water depletion patterns in presence of growing soybean roots: II. effect of plant growth on soil water pressure and water loss patterns, Soil

Science Society of America Proceedings, 39, 430-436, 1975a.

Arya, L.M., G.R. Blake and D.A. Farrell, A field study of soil water depletion patterns in the presence of growing soybean roots: III. rooting characteristics and root extraction of soil water, Soil Science Society of America Proceedings, 39, 437-444, 1975b.

Arya, L.M., D.A. Farrell, and G.R. Blake, A field study of soil water depletion patterns in presence of growing soybean roots: I. determination of hydraulic properties of the soil, Soil Science Society of America Proceedings, 39, 424-430, 1975.

Aston, A.R. and A.M. Gill, Coupled soil moisture, heat and water vapour transfers under simulated fire conditions, Australian Journal of Soil Research, 14, 55-66, 1976.

Babu, D.K., Infiltration analysis and perturbation methods 1. absorption with exponential diffusivity, Water Resources Research, 12, 89-93, 1976a.

Babu, D.K., Infiltration analysis and perturbation methods 2. horizontal absorption, Water Resources Research, 12, 1013-1018, 1976b.

Babu, D.K., Infiltration analysis and perturbation methods 3. vertical infiltration, Water Resources Research, 12, 1019-1024, 1976c.

Baker, F.G., Factors influencing the crust test for in situ measurement of hydraulic conductivity, Soil Science Society of America Journal, 41, 1029-1032, 1977.

Baker, F.G., Variability of hydraulic conductivity within and between nine Wisconsin soil series, Water Resources Research, 14, 103-108, 1978.

Baker, F.G. and J. Bouma, Variability of hydraulic conductivity in two subsurface horizons of two silt loam soils, Soil Science Society of America Journal, 40, 219-222, 1976.

Baker, F.G., P.L.M. Veneman, and J. Bouma, Limitations of the instantaneous profile method for field measurement of unsaturated hydraulic conductivity, Soil Science Society of America Proceedings, 38, 885-888, 1974.

Balasubramanian, V., L.R. Ahuja, Y. Kanehiro and R.E. Green, Movement of water and nitrate in an unsaturated aggregated soil during nonsteady infiltration - a simplified solution for solute flow, Soil Science, 122, 245-255, 1976.

Basak, P. and M.R. Madhav, Hydraulic conductivity in surface active soils, Australian Journal of Soil Research, 14, 121-127, 1976.

Batu, V., Steady infiltration from a ditch: theory and experiment, Soil Science Society of America Journal, 41, 677-682, 1977.

Batu, V., Steady infiltration from single and periodic strip sources, Soil Science Society of America Journal, 42, 544-549, 1978.

Beese, F. and R.R. van der Ploeg, Influence of hysteresis on moisture flow in an undisturbed soil monolith, Soil Science Society of America Journal, 40, 480-484, 1976.

Beese, F., R.R. van der Ploeg, and W. Richter, Test of a soil water model under field conditions, Soil Science Society of America Journal, 41, 979-984, 1977.

Ben-Asher, J., N. Diner, A Brandt, and D. Goldberg, Measurement of hydraulic conductivity and diffusivity for predicting the process of soil water infiltration from a trickle source, Water Resources Bulletin, 11, 1187-1196, 1975.

Bhattacharya, R., V. Gupta, and G. Sposito, Markovian stochastic basis for the transport of water through unsaturated soil, Soil Science Society of America Journal, 40, 465-467, 1976a.

Bhattacharya, R., V. Gupta and G. Sposito, On the physical interpretation of the soil water diffusivity in terms of the theory of the Markov processes, Soil Science, 121, 313-314, 1976b.

Bhattacharya, R., V. Gupta, and G. Sposito, On the stochastic foundations of the theory of water flow through unsaturated soil, Water Resources Research, 12, 503-512, 1976c.

Bianchi, W.C., Powdered metal plates for constructing unsaturated flow cells, Soil Science Society of America Proceedings, 38, 683-684, 1974.

Biggar, J.W. and D.R. Nielsen, Spatial variability of the leaching characteristics of a field soil, Water Resources Research, 12, 78-84, 1976.

Blackburn, W.H., Factors influencing infiltration and sediment production of semiarid rangelands in Nevada, Water Resources Research, 11, 929-937, 1975.

Bouma, J., and J.L. Anderson, Water and chloride movement through soil columns simulating pedal soils, Soil Science Society of America Journal, 41, 766-770, 1977.

Bouma, J., A. Jongerius, D. Boersma, A. Jager and D. Schoonderbeek, A function of different types of macropores during saturated flow through four swelling soil horizons, Soil Science Society of America Journal, 41, 945-950, 1977.

Bouwer, H., Infiltration into increasingly permeable soils, Journal of the Irrigation and Drainage Division, ASCE, 102, 127-136, 1976.

Bowers, S.A., S.J. Smith, H.D. Fisher, and G.E. Miller, Soil water measurement with an inexpensive spectrophotometer, Soil Science Society of America Proceedings, 391-393, 1975.

Brakensiek, D.L., Estimating the effective capillary pressure in the Green and Ampt infiltration equation, Water Resources Research, 13, 680-682, 1977.

Brakensiek, D.L., and C.A. Onstad, Parameter estimation of the Green and Ampt infiltration equation, Water Resources Research, 13, 1009-1012, 1977.

Bresler, E., Two-dimensional transport of solutes during nonsteady infiltration from a trickle source, Soil Science Society of America Proceedings, 39, 604-613, 1975.

Bresler, E., and D. Russo, Two-dimensional solutes transfer during nonsteady infiltration: laboratory test of mathematical model, Soil Science Society of America Proceedings, 39, 585-587, 1975.

Brown, R.W. and R.S. Johnston, Extended field use of screen-covered thermocouple psychrometers, Agronomy Journal, 68, 995-996, 1976.

Bruce, R.R., A.W. Thomas, L.A. Harper, and R.A. Leonard, Soil Science Society of America Journal, 41, 455-460, 1977.

Bruce, R.R., A.W. Thomas, and F.D. Whisler, Prediction of infiltration into layered field soils in relation to profile characteristics, Transactions of the American Society of Agricultural Engineers, 19, 693-698, 1976.

Brustkern, R.L., and H.J. Morel-Seytoux, Description of water and air movement during infiltration, Journal of Hydrology, 24, 21-35, 1975.

Brutsaert, W., More on an approximate solution for nonlinear diffusion, Water Resources Research, 10, 1251-1252, 1974.

Brutsaert, W., The concise formulation of diffusive sorption of water in a dry soil, Water Resources Research, 12, 1118-1124, 1976.

Brutsaert, W., Vertical infiltration in dry soil, Water Resources Research, 13, 363-368, 1977.

Bybordi, M., Effect of abrupt textural change on potential profiles during steady-state infiltration, Soil Science, 120, 92-95, 1975.

Cameron, D.R., and A. Klute, Convective-dispersive solute transport with a combined equilibrium and kinetic adsorption model, Water Resources Research, 13, 183-188, 1977.

Carbon, B.A., Redistribution of water following precipitation on previously dry sandy soils, Australian Journal of Soil Research, 13, 13-19, 1975.

Carvallo, H.O., D.K. Cassel, J. Hammond, and A. Bauer, Spatial variability of in situ unsaturated hydraulic conductivity of Maddock sandy loam, Soil Science, 121, 1-8, 1976.

Cary, J.W., Soil water hysteresis: temperature and pressure effects, Soil Science, 120, 308-311, 1975.

Chow, T.L., Fritted glass beam materials as tensiometers and tension plates, Soil Science Society of America Journal, 41, 19-22, 1977.

Chu, S.T., Transient drainage equations for nonhomogeneous soils, Transactions of the American Society of Agricultural Engineers, 20, 1085-1088, 1977.

Chu, S.T., Infiltration during an unsteady rain, Water Resources Research, 14, 461-466, 1978.

Clapp, R.B. and G.M. Hornberger, Empirical equations for some soil hydraulic properties, Water Resources Research, 14, 601-604, 1978.

Clothier, B.E., D.R. Scotter and J.P. Kerr, Water retention in soil underlain by a coarse-textured layer: theory and a field application, Soil Science, 123, 392-399, 1977.

Coats, K.H., and B.D. Smith, Dead-end pore volume and dispersion in porous media, Society of Petroleum Engineering Journal, 4, 73-84, 1964.

Colbeck, S.C., A theory of water flow through a layered snow pack, Water Resources Research, 11, 261-266, 1975.

Colbeck, S.C., An analysis of water flow in dry snow, Water Resources Research, 12, 523-527, 1976.

Colbeck, S.C., The physical aspects of water flow through snow, Advances in Hydroscience, 11, 165-207, 1978.

Collis-George, N., Infiltration equations for simple soil systems, Water Resources Research, 13, 395-403, 1977.

Corey, A.T., and R.H. Brooks, Drainage characteristics of soils, Soil Science Society of America Proceedings, 39, 251-255, 1975.

Cushman, J. and D. Kirkham, A two-dimensional linearized view of one-dimensional unsaturated-saturated flow, Water Resources Research, 14, 319-324, 1978.

Dalton, F.N., P.A.C. Raats and W.R. Gardner, Simultaneous uptake of water and solutes by plant roots, Agronomy Journal, 67, 334-339, 1974.

Dane, J.H., Calculation of hydraulic conductivity decreases in the presence of mixed NaCl-$CaCl_2$ solutions, Canadian Journal of Soil Science, 58, 145-152, 1978.

Dane, J.H. and A. Klute, Salt effects on the hydraulic properties of a swelling soil, Soil Science Society of America Journal, 41, 1043-1049, 1977.

Dane, J.H. and P.J. Wierenga, Effect of hysteresis on the prediction of infiltration, redistribution and drainage of water in a layered soil, Journal of Hydrology, 25, 229-242, 1975.

Davidson, J.M., D.R. Baker, and G.H. Brusewitz, Simultaneous transport of water and adsorbed solutes through soil under transient flow conditions, Transactions of the American Society of Agricultural Engineers, 18, 535-539, 1975.

De Latt, P.J.M., A pseudo steady-state solution of water movement in the unsaturated zone of the soil, Journal of Hydrology, 30, 19-27, 1976.

De Smedt, F. and P.J. Wierenga, Solute transport through soil with nonuniform water content, Soil Science Society of America Journal, 42, 7-10, 1978a.

De Smedt, F. and P.J. Wierenga, Approximate analytical solution for solute flow during infiltration and redistribution, Soil Science Society of America Journal, 42, 407-412, 1978b.

de Vries, D.A., Simultaneous transfer of heat and moisture in porous media, Transactions of the American Geophysical Union, 39, 909-916, 1958.

Dirksen, C., Field test of soil water flux meters, Transactions of the American Society of Agricultural Engineers, 17, 1038-1042, 1974.

Dirksen, C., Determination of soil water diffusivity by sorptivity measurements, Soil Science Society of America Proceedings, 39, 22-27, 1975.

Dirksen, C., and M.J. Huber, Soil water flow model with two-dimensional automatic gamma ray attenuation scanner, Water Resources Research, 14, 611-614, 1978.

Dixon, R.M., Design and use of closed-top infiltrometers, Soil Science Society of America Proceedings, 39, 755-763, 1975.

Dunham, R.J., and P.H. Nye, The influence of soil water content on the uptake of ions by roots: II. chloride uptake and concentration gradients in soil, Journal of Applied Ecology, 11, 581-595, 1974.

Eagleman, J.R., and W.C. Lin, Remote sensing of soil moisture by a 21-cm passive radiometer, Journal of Geophysical Research, 81, 3660-3666, 1976.

Earl, K.D. and W.A. Jury, Water movement in bare and cropped soil under isolated trickle emitters: II. analysis of cropped soil experiments, Soil Science Society of America Journal, 41, 856-861, 1977.

Ehlers, W., Observations on earthworm channels and infiltration on tilled and untilled loess soil, Soil Science, 119, 242-249, 1975.

Ehlers, W., Rapid determination of unsaturated hydraulic conductivity in tilled and untilled loess soil, Soil Science Society of America Journal, 40, 837-840, 1976.

Elrick, D.E., D.E. Smiles, N. Baumgartner, and P.H. Groenevelt, Coupling phenomena in saturated homo-ionic montmorillonite: I. experimental, Soil Science Society of America Journal, 40, 490-491, 1976.

Elzeftawy, A., and R.S. Mansell, Hydraulic conductivity calculations for unsaturated steady-state and transient-state flow in sand, Soil Science Society of America Proceedings, 39, 599-603, 1975.

Enfield, C.G., and B.E. Bledsoe, Fate of wastewater phosphorus in soil, Journal of the Irrigation and Drainage Division, ASCE, 101, 145-155, 1975.

England, C.B., Modeling soil water hydrology under a post oak (Quercus stellata wangenh.) - shortleaf pine (Pinus echinata mill.) stand in East Texas, Water Resources Research, 13, 683-686, 1977.

Falayi, O., and J. Bouma, Relationships between the hydraulic conductance of surface crusts and soil management in a typic hapludalf, Soil Science Society of America Proceedings, 39, 957-963, 1975.

Feddes, R.A., E. Bresler and S.P. Neuman, Field test of a modified numerical model for water uptake by root systems, Water Resources Research, 10, 1199-1206, 1974.

Feddes, R.A., S.P. Neuman, and E. Bresler, Finite element analysis of two-dimensional flow in soils considering water uptake by roots: II. field applications, Soil Science Society of America Proceedings, 39, 231-237, 1975.

Feddes, R.A., P. Kowalik, K. Kolinska-Malinka, and H. Zaradny, Simulation of field water uptake by plants using a soil water dependent root extraction function, Journal of Hydrology, 31, 13-26, 1976.

Feddes, R.A., P. Kowalik, S.P. Neuman, and E. Bresler, Finite difference and finite element simulation of field water uptake by plants, Hydrological Sciences Bulletin, 21, 81-98, 1976b.

Fluhler, H., M.S. Ardakani, and L.H. Stolzy, Error propagation in determining hydraulic conductivities from successive water content and pressure head profiles, Soil Science Society of America Journal, 40, 830-836, 1976.

Fok, Y-S., A comparison of the Green-Ampt and Philip two-term infiltration equations, Transactions of the American Society of Agricultural Engineers, 18, 1073-1075, 1975.

Fredlund, D.G. and N.R. Morgenstern, Stress state variables for unsaturated soils, Journal of the Geotechnical Engineering Division, ASCE, 103, 447-466, 1977.

Frenkel, H., A. Hadas and W.A. Jury, The effect of salt precipitation and high sodium concentrations on soil hydraulic conductivity and water retention, Water Resources Research, 14, 217-222, 1978.

Garber, M., and D. Zaslavsky, Flow in a soil layer underlined by an impermeable membrane, Soil Science, 123, 1-9, 1977.

Gaudet, J.P., H. Jegat, G. Vachaud, and P.J. Wierenga, Solute transfer, with exchange between mobile and stagnant water, through unsaturated sand, Soil Science Society of America Journal, 41, 665-671, 1977.

Ghosh, R.K. and S.P. Maity, Influence of antecedent moisture on infiltration of water into soils (in situ), Soil Science, 122, 124-125, 1976.

Ghugla, G., A multi-layer model for gravity drainage of unsaturated soil, International Association of Hydrological Sciences Publication No. 101, 608-615, 1974.

Ghuman, G.S., S.M. Verma, and S.S. Prihar, Effect of application rate, initial soil wetness, and redistribution time on salt displacement by water, Soil Science Society of America Proceedings, 39, 7-10, 1975.

Gifford, Gerald F., Applicability of some infiltration formulae to rangeland infiltrometer data, Journal of Hydrology, 28, 1-11, 1975.

Gilding, B.H. and Peletier, L.A., The Cauchy problem for an equation in the theory of infiltration, Archive for Rational Mechanics and Analysis, 61, 127-140, 1976.

Gilding, B.H., Properties of solutions of an equation in the theory of infiltration, Archive for Rational Mechanics and Analysis, 65, 203-225, 1977.

Gill, M.A., Analysis of one-dimensional non-Darcy vertical infiltration, Journal of Hydrology, 31, 1-11, 1976.

Gill, M.A., A layered infiltration model for homogeneous soils, Journal of Hydrology, 36, 121-131, 1978.

Gillham, R.W., A. Klute and D.F. Heermann, Hydraulic properties of a porous medium: measurement and empirical representation, Soil Science Society of America Journal, 40, 203-207, 1976.

Giráldez, J.V., and G. Sposito, Moisture profiles during steady vertical flows in swelling soils, Water Resources Research, 14, 314-318, 1978.

Grant, D.R., Measurement of soil moisture near the surface using a neutron moisture meter, Journal of Soil Science, 26, 124-129, 1975.

Gray, W.G. and G.F. Pinder, An analysis of the numerical solution of the transport equation, Water Resources Research, 12, 547-555, 1976.

Green, W.E. and G.A. Ampt, Studies in physics: I. the flow of air and water through soils, Journal of Agricultural Science, 4, 1-24, 1911.

Groenevelt, P.H. and B.D. Kay, Water and ice potentials in frozen soils, Water Resources Research, 13, 445-450, 1977.

Gumbs, F.A. and B.P. Warkentin, Prediction of infiltration of water into aggregated clay soil samples, Soil Science Society of America Proceedings, 39, 255-263, 1975.

Gumbs, F.A. and B.P. Warkentin, Bulk density, saturation water content and rate of wetting of soil aggregates, Soil Science Society of America Journal, 40, 28-33, 1976.

Gupta, S.C., R.H. Dowdy, and W.E. Larson, Hydraulic and thermal properties of a sandy soil as influenced by incorporation of sewage sludge, Soil Science Society of America Journal, 41, 601-605, 1977.

Gupta, S.C., D.A. Farrell, and W.E. Larson, Determining effective soil water diffusivities from one-step outflow experiments, Soil Science Society of America Proceedings, 38, 710-716, 1974.

Gupta, V.K., G. Sposito, and R.N. Bhattacharya, Toward an analytical theory of water flow through inhomogeneous porous media, Water Resources Research, 13, 208-210, 1977.

Guymon, Gary L., Soil-moisture-temperature for Alaskan lowland, Journal of the Irrigation and Drainage Division, ASCE, 101, 187-199, 1975.

Guymon, G.L., Summer moisture-temperature for arctic tundra, Journal of the Irrigation and Drainage Division, ASCE, 102, 403-411, 1976.

Guymon, G.L. and J.N. Luthin, A coupled heat and moisture transport model for arctic soils, Water Resources Research, 10, 995-1001, 1974.

Hachum, A.Y., and J.F. Alfaro, Water infiltration and runoff under rain applications, Soil Science Society of America Journal, 41, 960-966, 1977.

Hachum, A.Y., J.F. Alfaro, and L.S. Willardson, Water movement in soil from trickle source, Journal of the Irrigation and Drainage Division, ASCE, 102, 179-192, 1976.

Hadas, A., Drying of layered soil columns under nonisothermal conditions, Soil Science, 119, 143-148, 1975.

Hadas, A., Evaluation of theoretically predicted thermal conductivities of soils under field and laboratory conditions, Soil Science Society of America Journal, 41, 460-466, 1977a.

Hadas, A., Heat transfer in dry aggregated soil: I. heat conduction, Soil Science Society of America Journal, 41, 1055-1059, 1977b.

Hansen, E.A. and A.R. Harris, Validity of soil-water samples collected with porous ceramic cups, Soil Science Society of America Journal, 39, 528-536, 1975.

Harr, R.D., Water flux in soil and subsoil on a steep forested slope, Journal of Hydrology, 33, 37-58, 1977.

Harris, A.R., and E.A. Hansen, A new ceramic cup soil-water sampler, Soil Science Society of America Proceedings, 39, 157-158, 1975.

Haverkamp, R., M. Vauclin, J. Touma, P.J. Wierenga, and G. Vachaud, A comparison of numerical simulation models for one-dimensional infiltration, Soil Science Society of America Journal, 41, 285-294, 1977.

Hayhoe, H.N., Numerical study of quasi-analytic and finite difference solutions of the soil-water transfer equation, Soil Science, 125, 68-74, 1978a.

Hayhoe, H.N., Study of the relative efficiency of finite difference and Galerkin techniques for modeling soil-water transfer, Water Resources Research, 14, 97-102, 1978b.

Helyar, K.R., and D.N. Munns, Phosphate fluxes in the soil-plant system: a complete simulation, Hilgardia, 43, 103-130, 1975.

Herkelrath, W.N., E.E. Miller and W.R. Gardner, Water uptake by plants: I. divided root experiments, Soil Science Society of America Journal, 41, 1033-1037, 1977a.

Herkelrath, W.N., E.E. Miller and W.R. Gardner, Water uptake by plants: II. the root contact model, Soil Science Society of America Journal, 41, 1037-1043, 1977b.

Hildebrand, M.A., and D.M. Himmelblau, Transport of nitrate ion in unsteady, unsaturated flow in porous media, American Institute of Chemical Engineers Journal, 23, 326-335, 1977.

Hillel, D., On the role of soil moisture hysteresis in the suppression of evaporation from bare soil under diurnally cyclic evaporativity, Soil Science, 122, 309-314, 1976.

Hillel, D.I. and W.R. Gardner, Measurement of unsaturated conductivity and diffusivity by infiltration through an impeding layer, Soil Science, 109, 149-153, 1970.

Hillel, D., and H. Talpaz, Simulation of soil water dynamics in layered soils, Soil Science, 123, 54-62, 1977.

Hillel, D., and C.H.M. van Bavel, Simulation of profile water storage as related to soil hydraulic properties, Soil Science Society of America Journal, 40, 807-815, 1976.

Hillel, D.I., C.H.M. van Bavel, and H. Talpaz, Dynamic simulation of water storage in fallow soil as affected by mulch of hydrophobic aggregates, Soil Science Society of America Proceedings, 39, 826-833, 1975.

Hillel, D., C.G.E.M. van Beek, and H. Talpaz, A microscopic-scale model of soil water uptake and salt movement to plant roots, Soil Science, 120, 385-399, 1975.

Hillel, D., H. Talpaz and H. van Keulen, A macroscopic-scale model of water uptake by a nonuniform root system and of water and salt movement in the soil profile, Soil Science, 121, 242-255, 1976.

Hoa, N.T., R. Gaudu, and C. Thirriot, Influence of the hysteresis effect on transient flows in saturated-unsaturated porous media, Water Resources Research, 13, 992-996, 1977.

Hornung, U., A numerical method for the simulation of unsteady groundwater flow in both saturated and unsaturated soils, Soil Science, 124, 140-144, 1977.

Hsieh, J.J.C. and C.G. Enfield, Steady-state method of measuring unsaturated hydraulic conductivity, Communications in Soil Science and Plant Analysis, 5, 123-129, 1974.

Hundal, S.S., G.O. Schwab, and G.S. Taylor, Drainage system effects on physical properties of a lakebed clay soil, Soil Science Society of America Journal, 40, 300-305, 1976.

Idso, S.B., R.D. Jackson, R.J. Reginato, B.A. Kimball, and F.S. Nakayama, The dependence of bare soil albedo on soil water content, Journal of Applied Meteorology, 14, 109-113, 1975.

Idso, S.B., T.J. Schmugge, R.D. Jackson, and R.J. Reginato, The utility of surface temperature measurements for the remote sensing of surface soil water status, Journal of Geophysical Research, 80, 3044-3049, 1975.

Jackson, R.D., R.J. Reginato, B.A. Kimball and F.S. Nakayama, Diurnal soil-water evaporation: comparison of measured and calculated soil-water fluxes, Soil Science Society of America Proceedings, 38, 861-866, 1974.

Jackson, R.D., B.A. Kimball, R.J. Reginato, S.B. Idso and F.S. Nakayama, Heat and water transfer in a natural soil environment, in Heat and Mass Transfer in the Biosphere, Vol. I: Transfer Processes in the Plant Environment, edited by D.A. de Vries, pp. 67-76, Scripta Book Publishing Co., Washington, D.C., 1975.

James, L.G., and C.L. Larson, Modeling infiltration and redistribution of soil water during intermittent application, Transactions of the American Society of Agricultural Engineers, 19, 482-488, 1976.

Jayawardane, N.S., A method for computing and comparing upward flow of water in soils from a water table using the flux/unsaturated conductivity ratio, Australian Journal of Soil Research, 15, 17-25, 1977.

Jeppson, R.W., Axisymmetric infiltration in soils, I. numerical techniques for solution, Journal of Hydrology, 23, 111-130, 1974a.

Jeppson, R.W., Axisymmetric infiltration in soils, II. summary of infiltration characteristics related to problem specifications, Journal of Hydrology, 23, 191-202, 1974b.

Jeppson, R.W., W.J. Rawls, W.R. Hamon and D.L. Schreiber, Use of axisymmetric infiltration model and field data to determine hydraulic properties of soils, Water Resources Research, 11, 127-138, 1975.

Jury, W.A., and B. Bellantuoni, Heat and water movement under surface rocks in a field soil: I. thermal effects, Soil Science Society of America Journal, 40, 505-509, 1976a.

Jury, W.A., and B. Bellantouni, Heat and water movement under surface rocks in a field soil: II. moisture effects, Soil Science Society of America Journal, 40, 509-513, 1976b.

Jury, W.A. and K.D. Earl, Water movement in bare and cropped soil under isolated trickle emitters: I. analysis of bare soil experiments, Soil Science Society of America Journal, 41, 852-856, 1977.

Jury, W.A., H. Fluhler, and L.H. Stolzy, Influence of soil properties, leaching fraction, and plant water uptake on solute concentration distribution, Water Resources Research, 13, 645-650, 1977.

Jury, W.A., H. Frenkel and L.H. Stolzy, Transient changes in the soil-water system from irrigation with saline water: I. theory, Soil Science Society of America Journal, 42, 579-585, 1978.

Jury, W.A., H. Frenkel, D. Devitt and L.H. Stolzy, Transient changes in the soil-water system from irrigation with saline water: II. analysis of experimental data, Soil Science Society of America Journal, 42, 585-590, 1978.

Kasansky, A.B., A statistical filtration model for the inseepage of melt water into frozen ground, International Association of Hydrological Sciences Publication No. 100, 241-245, 1974.

Keisling, T.C., J.M. Davidson, D.L. Weeks, and R.D. Morrison, Precision with which selected soil physical parameters can be estimated, Soil Science, 124, 241-248, 1977.

Kimball, B.A., R.D. Jackson, R.J. Reginato, F.S. Nakayama and S.B. Idso, Comparison of field-measured and calculated soil-heat fluxes, Soil Science Society of America Journal, 48, 18-25, 1976.

King, T.G., and J.R. Lamberg, Simulation of deep seepage to a water table, Transactions of the America Society of Agricultural Engineers, 19, 50-60, 1976.

Kirda, C., J.L. Starr, C. Misra, J.W. Biggar, and D.R. Nielsen, Nitrification and denitrification during miscible displacement in unsaturated soil, Soil Science Society of America Proceedings, 38, 772-776, 1974.

Komarov, V.D., and T.T. Makarova, Effect of the ice content, temperature, cementation, and freezing depth of the soil on melt-water infiltration in a basin, Soviet Hydrology, Selected Papers No. 3, 243-249, 1973.

Krishnamurthi, N., D.K. Sunada and R.A. Longenbaugh, Mathematical modeling of natural groundwater recharge, Water Resources Research, 13, 720-724, 1977.

Krishnamurthi, N., D.K. Sunada, and R.A. Longenbaugh, On oscillation of numerical solution of a modified Richards' equation, Water Resources Research, 14, 52-54, 1978.

Kroszynski, U., Flow in a vertical porous column drained at its bottom at constant flux, Journal of Hydrology, 24, 135-153, 1975.

Kroszynski, U.I. and G. Dagan, Well pumping in unconfined aquifers: the influence of the unsaturated zone, Water Resources Research, 11, 479-490, 1975.

Laroussi, C. and L. De Backer, Physical interpretation of the diffusion equation parameters according to Markov's stochastic processes theory, Soil Science, 120, 169-173, 1975.

Laroussi, C., G. Vandervoorde, and L. De Backer, Experimental investigation of the diffusivity coefficient, Soil Science, 120, 249-255, 1975.

Lawrence, G.P., Measurement of pore sizes in fine-textured soils: a review of existing techniques, Journal of Soil Science, 28, 527-540, 1977.

Lees, S.J., and K.K. Watson, The use of a dependent domain model of hysteresis in numerical soil water studies, Water Resources Research, 11, 943-948, 1975.

Lehman, O.R., Percolation rates with surface layers of gravel or clay flocs on soil fed clear and turbid waters, Water Resources Research, 14, 539-541, 1978.

Levin, I., and F.C. Van Rooyen, Soil water flow and distribution in horizontal and vertical directions as influenced by intermittent water application, Soil Science, 124, 355-365, 1977.

Levin, M.J. and D.R. Jackson, A comparison of in situ extractors for sampling soil water, Soil Science Society of America Journal, 41, 535-536, 1977.

Li, R., M.A. Stevens, and D.B. Simons, Solutions to green-ampt infiltration equation, Journal of the Irrigation and Drainage Division, ASCE, 102, 239-248, 1976.

Ligon, J.T., T.V. Wilson, J.F. Allen, and U.P. Singh, Tracing vertical translocation of soil moisture, Journal of the Hydraulics Division, ASCE, 103, 1147-1158, 1977.

Lin, S.H., Nonlinear adsorption in porous media with variable porosity, Journal of Hydrology, 35, 235-243, 1977.

Linden, D.R. and R.M. Dixon, Water table position as affected by soil air pressure, Water Resources Research, 11, 139-143, 1975.

Linden, D.R., and R.M. Dixon, Soil air pressure effects on route and rate of infiltration, Soil Science Society of America Journal, 40, 963-965, 1976.

Liu, P.L.F., A perturbation solution for a non-linear diffusion equation, Water Resources Research, 12, 1235-1240, 1976.

Lomen, D.O. and A.W. Warrick, Solution of the one-dimensional linear moisture flow equation with implicit water extraction functions, Soil Science Society of America Journal, 40, 342-344, 1976.

Luthin, J.N., and G.L. Guymon, Soil moisture-vegetation-temperature relationships in central Alaska, Journal of Hydrology, 23, 233-246, 1974.

Luthin, J.N., A. Orhun, and G.S. Taylor, Coupled saturated-unsaturated transient flow in porous media: experimental and numeric model, Water Resources Research, 11, 973-978, 1975.

Lzeftawy, A.E., and R.S. Mansell, Hydraulic conductivity calculations for unsaturated steady-state and transient-state flow in sand, Soil Science Society of America Proceedings, 39, 599-603, 1975.

Maeda, T., and B.P. Warkentin, Void changes in allophane soils determining water retention and transmission, Soil Science Society of America Proceedings, 39, 398-403, 1975.

Mahony, J.J., Tensiometer measurements in anisotropically loaded swelling soils, Soil Science, 120, 421-427, 1975.

Manley, R.E., The soil moisture component of mathematical catchment simulation models, Journal of Hydrology, 35, 341-356, 1977.

Mansell, R.S., H.M. Selim, P. Kanchanasut, J.M. Davidson and J.G.A. Fiskel, Experimental and simulated transport of phosphorus through sandy soils, Water Resources Research, 13, 189-194, 1977.

Matzdorf, K.D., D.K. Cassel, B.K. Worchester, and D.D. Malo, In situ hydraulic conductivity at four hillslope locations in a closed drainage system, Soil Science of America Proceedings, 39, 508-512, 1975.

Matzkanin, G.A. and C.G. Gardner, Nuclear magnetic resonance sensors for moisture measurement in roadways, Transportation Research Record 532, 77-86, 1975.

McCown, R.L., G.G. Murtha, and G.D. Smith, Assessment of available water storage capacity of soils with restricted subsoil permeability, Water Resources Research, 12, 1255-1259, 1976.

McLaren, A.D., Comments on nitrate reduction in unsaturated soil, Soil Science Society of America Journal, 40, 698-699, 1976.

McWhorter, D.B., Vertical flow of air and water with a flux boundary condition, Transactions of the American Society of Agricultural Engineers, 19, 259-265, 1976.

McWhorter, D.B. and H.R. Duke, Transient drainage with nonlinearity and capillarity, Journal of the Irrigation and Drainage Division, ASCE, 102, 193-204, 1976.

Meek, B.D., and L.B. Grass, Redox potential in irrigated desert soils as an indicator of aeration status, Soil Science Society of America Proceedings, 39, 870-875, 1975.

Mehuys, G.R., L.H. Stolzy, J. Letey, and L.V. Weeks, Effect of stones on the hydraulic conductivity of relatively dry desert soils, Soil Science Society of America Proceedings, 39, 37-42, 1975.

Mein, R.G., and D.A. Farrell, Determination of wetting front suction in the Green-Ampt equation, Soil Science Society of America Proceedings, 38, 872-876, 1974.

Miller, D.E., Effect of daily irrigation on water content and suction profiles in soils of three textures, Soil Science Society of America Proceedings, 39, 512-515, 1975.

Miller, R.D. and E. Bresler, A quick method for estimating soil water diffusivity functions, Soil Science Society of America Journal, 41, 1020-1022, 1977.

Mohan, A., Heat transfer in soil-water-ice systems, Journal of the Geotechnical Engineering Division, ASCE, 101, 97-113, 1975.

Molz, F.J. and E. Ikenberry, Water transport through plant cells and cell walls: theoretical development, Soil Science Society of America Proceedings, 38, 699-704, 1974.

Molz, F.J., Potential distributions in the soil-root system, Agronomy Journal, 67, 726-729, 1975.

Molz, F.J., Water transport in the soil-root system: transient analysis, Water Resources Research, 12, 805-808, 1976.

Molz, F.J., and C.M. Peterson, Water transport from roots to soil, Agronomy Journal, 68, 901-904, 1976.

Morel-Seytoux, H.J., Drainage rates from a vertical column, Hydrological Sciences Bulletin, 20, 249-255, June 1975.

Morel-Seytoux, H.J., Derivation of equations for rainfall infiltration, Journal of Hydrology, 31, 203-219, 1976.

Morel-Seytoux, H.J., Derivation of equations for variable rainfall infiltration, Water Resources Research, 14, 561-568, 1978.

Morel-Seytoux, H.J., and J. Khanji, Equation of infiltration with compression and counterflow effects, Hydrological Sciences Bulletin, 20, 505-517, 1975a.

Morel-Seytoux, H.J., and J. Khanji, Prediction of imbibition in a horizontal column, Soil Science Society of America Proceedings, 39, 613-617, 1975b.

Morel-Seytoux, H.J., T.A. Pick, and T. Jonch-Clausen, Computation of infiltration for unsteady uninterrupted high rainfall, Journal of Hydrology, 35, 221-234, 1977.

Morin, J. and Y. Benyamini, Rainfall infiltration into bare soils, Water Resources Research, 13, 813-817, 1977.

Mualem, Y., A new model for predicting the hydraulic conductivity of unsaturated porous media, Water Resources Research, 12, 513-522, 1976a.

Mualem, Y., Hysteretical models for prediction of the hydraulic conductivity of unsaturated porous media, Water Resources Research, 12, 1248-1254, 1976b.

Mualem, Y., Extension of the similarity hypothesis used for modeling the soil water characteristics, Water Resources Research, 13, 773-780, 1977.

Mualem, Y., Hydraulic conductivity of unsaturated porous media: generalized microscopic approach, Water Resources Research, 14, 325-334, 1978.

Mualem, Y. and G. Dagan, A dependent domain model of capillary hysteresis, Water Resources Research, 11, 452-460, 1975.

Mualem, Y. and G. Dagan, Hydraulic conductivity of soils: unified approach to the statistical models, Soil Science Society of America Journal, 42, 392-396, 1978.

Mualem, Y. and H.J. Morel-Seytoux, Analysis of a capillary hysteresis model based on a one-variable distribution function, Water Resources Research, 14, 605-610, 1978.

Mustafa, M.A., and K.S. Hamid, Comparisons of two models for predicting the relative hydraulic conductivity of salt-affected swelling soils, Soil Science, 123, 149-154, 1977.

Nakano, M., Pore volume distribution and curve of water content versus suction of porous body: 1. two boundary drying curves, Soil Science, 122, 5-14, 1976a.

Nakano, M., Pore volume distribution and curve of water content versus suction of porous body: 2. the boundary wetting curve, Soil Science, 22, 100-106, 1976b.

Nakano, M., Soil water movement during the first stage of drying of a moist, sandy soil under a very low drying rate, Soil Science, 124, 67-72, 1977.

Nakano, Y., Theory and numerical analysis of moving boundary problems in the hydrodynamics of porous media, Water Resources Research, 14, 125-134, 1978.

Narasimhan, T.N., and P.A. Witherspoon, Numerical model for saturated-unsaturated flow in deformable porous media, 1. theory, Water Resources Research, 13, 657-664, 1977.

Narasimhan, T.N., P.A. Witherspoon, and A.L. Edwards, Numerical model for saturated-unsaturated flow in deformable porous media 2. the algorithm, Water Resources Research, 14, 255-261, 1978.

Neuman, S.P., Wetting front pressure head in the infiltration model of Green and Ampt, Water Resources Research, 12, 564-566, 1976.

Neuman, S.P., R.A. Feddes, and E. Bresler, Finite element analysis of two-dimensional flow in soils considering water uptake by roots: I. theory, Soil Science Society of America Proceedings, 39, 224-230, 1975.

Nnyamah, J.U. and T.A. Black, Rates and patterns of water uptake in a Douglas-fir forest, Soil Science Society of America Journal, 41, 972-979, 1977.

Palkovics, W.E., and G.W. Petersen, Contribution of lateral soil water movement above a fragipan to streamflow, Soil Science Society of America Journal, 41, 394-400, 1977.

Panikar, J.T., and G. Nanjappa, Time of ponding--comparison of results of the Parlange solution with the Smith and Mein-Larson models, Journal of Hydrology, 31, 175-179, 1976.

Panikar, J.T., and G. Nanjappa, Suction head at wet front in unsaturated-flow problems --a new definition, Journal of Hydrology, 33, 1-14, 1977.

Parlange, J-Y., A note on the moisture diffusivity of saturated swelling systems from desorption experiments, Soil Science, 120, 156-158, 1975a.

Parlange, J-Y., Convergence and validity of time expansion solutions: a comparison to exact and approximate solutions, Soil Science Society of America Proceedings, 39, 3-6, 1975b.

Parlange, J-Y., On solving the flow equation in unsaturated soils by optimization: horizontal infiltration, Soil Science Society of America Proceedings, 39, 415-418, 1975c.

Parlange, J-Y., Theory of water movement in soils: 11. conclusion and discussion of some recent developments, Soil Science, 119, 158-161, 1975d.

Parlange, J-Y., Capillary hysteresis and the relationship between drying and wetting curves, Water Resources Research, 12, 224-228, 1976.

Parlange, J-Y., and D.E. Aylor, Response of an unsaturated soil to forest transpiration, Water Resources Research, 11, 319-323, 1975.

Parlange, J-Y., and D.K. Babu, A comparison of techniques for solving the diffusion equation with an exponential diffusivity, Water Resources Research, 12, 1317-1318, 1976a.

Parlange, J-Y., and D.K. Babu, On solving the infiltration equation—a comparison of perturbation and iterative techniques, Water Resources Research, 12, 1315-1316, 1976b.

Parlange, J-Y., and D.K. Babu, On solving nonlinear diffusion equation: a comparison of perturbation, iterative, and optimal techniques for an arbitrary diffusivity, Water Resources Research, 12, 213-214, 1977.

Parlange, J-Y., and D.E. Hill, Theoretical analysis of wetting front instability in soils, Soil Science, 122, 236-239, 1976.

Passioura, J.B., Determining soil water diffusivities from one-step outflow experiments, Australian Journal of Soil Research, 15, 1-8, 1977.

Peck, E.L., Effect of snow cover on upward movement of soil moisture, Journal of the Irrigation and Drainage Division, ASCE, 100, 405-412, 1974.

Peck, A.J., R.J. Luxmoore, and J.L. Stolzy, Effects of spatial variability of soil hydraulic properties in water budget modeling, Water Resources Research, 13, 348-354, 1977.

Perrens, S.J., and K.K. Watson, Numerical analysis of two-dimensional infiltration and redistribution, Water Resources Research, 13, 781-790, 1977.

Perrier, E.R. and O. Prakash, Heat and vapor movement during infiltration into dry soils, Soil Science, 124, 73-76, 1977.

Philip, J.R., Hydrology of swelling soils, in Salinity and Water Use, edited by T. Talsma and J.R. Philip, pp. 95-107, MacMillan, London, 1971.

Philip, J.R., Stability analysis of infiltration, Soil Science Society of America Proceedings, 39, 1042-1049, 1975a.

Philip, J.R., The growth of disturbances in unstable infiltration flows, Soil Science Society of America Proceedings, 39, 1049-1053, 1975b.

Philip, J.R. and D.A. de Vries, Moisture movement in porous materials under temperature gradients, Transactions of the American Geophysical Union, 38, 222-232, 1957.

Philip, J.R. and R.I. Forrester, Steady infiltration form buried, surface, and perched point and line sources in heterogeneous soils: II. flow details and discussion, Soil Science Society of America Proceedings, 39, 408-414, 1975.

Philips, R.E., T. NaNagara, R.E. Zartman, and J.E. Leggett, Diffusion and mass flow of nitrate-nitrogen to plant roots, Agronomy Journal, 68, 63-66, 1976.

Poulovassilis, A., Flow characteristics during infiltration into a horizontal sand column, Water Resources Research, 13, 369-374, 1977.

Poulovassilis, A., and W.M. El-Ghamry, Hysteretic steady state soil water profiles, Water Resources Research, 13, 549-557, 1977.

Poulovassilis, A. and E. Tzimas, The hysteresis in the relationship between hydraulic conductivity and soil water content, Soil Science, 120, 327-331, 1975.

Pratt, P.F., J.E. Warneke, and P.A. Nash, Sampling the unsaturated zone in irrigated field plots, Soil Science Society of America Journal, 40, 277-279, 1976.

Pressland, A.J., Soil moisture redistribution as affected by throughfall and stemflow in an arid zone shrub community, Australian Journal of Botany, 24, 641-649, 1976.

Quisenberry, V.L., and R.E. Phillips, Percolation of surface-applied water in the field, Soil Science Society of America Journal, 40, 484-489, 1976.

Raats, P.A.C., Distribution of salts in the root zone, Journal of Hydrology, 27, 237-248, 1975a.

Raats, P.A.C., Transformations of fluxes and forces describing the simultaneous transport of water and heat in unsaturated porous media, Water Resources Research, 11, 938-942, 1975b.

Raats, P.A.C., Analytical solutions of a simplified flow equation, Transactions of the American Society of Agricultural Engineers, 19, 683-689, 1976.

Raats, P.A.C., Laterally confined, steady flows of water from sources and to sinks in unsaturated soils, Soil Science Society of America Journal, 41, 294-304, 1977.

Rao, P.S.C., P.V. Rao, and J.M. Davidson, Estimation of the spatial variability of the soil water flux, Soil Science Society of America Journal, 41, 1208-1209, 1977.

Rao, P.S.C., R.E. Green, L.R. Ahuja, and J.M. Davidson, Evaluation of a capillary bundle model for describing solute dispersion in aggregated soils, Soil Science Society of America Journal, 40, 815-820, 1976.

Raudkivi, A.J. and N. Van U'u, Soil moisture movement by temperature gradient, Journal of the Geotechnical Engineering Division, ASCE, 102, 1225-1244, 1976.

Rawls, W.J., W.R. Hmon, and D.L. Schreiber, Use of axisymmetric infiltration model and field data to determine hydraulic properties of soils, Water Resources Research, 11, 127-139, 1975.

Reeves, M. and E.E. Miller, Estimating infiltration for erratic rainfall, Water Resources Research, 11, 102-110, 1975.

Reginato, R.J., Sampling soil-water distribution in the surface centimeter of a field soil, Soil Science, 120, 292-294, 1975.

Reginato, R.J., S.B. Idso, J.F. Vedder, R.D. Jackson, and M.B. Blanchard, Soil water content and evaporation determined by thermal parameters obtained from ground-based and remote measurements, Journal of Geophysical Research, 81, 1617-1620, 1976.

Reichardt, K., P.L. Libardi, and D.R. Nielsen, Unsaturated hydraulic conductivity determination by a scaling technique, Soil Science, 120, 165-168, 1975.

Reid, I., Seasonal variability of rainwater redistribution by field soils, Journal of Hydrology, 25, 71-80, 1975.

Rein, R.G., Jr., V.V. Hathi, and C.M. Sliepcevich, Creep of sand-ice system, Journal of the Geotechnical Engineering Division, ASCE, 101, 115-128, 1975.

Rice, R.C., Diurnal and seasonal soil water uptake and flux within a bermudagrass root zone, Soil Science Society of America Proceedings, 39, 394-398, 1975.

Rogers, J.S., Small tensiometers for field and laboratory studies, Soil Science Society of America Proceedings, 38, 690-691, 1974.

Romanov, V.V., K.K. Pavlova, and I.L. Kalyuzhnyy, Meltwater losses through infiltration into podzolic soils and chernozems, Soviet Hydrology, Selected Papers, No. 1, 32-42, 1974.

Rose, D.A., Hydrodynamic dispersion in porous materials, Soil Science, 123, 227-283, 1977.

Royer, J.M. and G. Vachaud, Field determination of hysteresis in soil-water characteristics, Soil Science Society of America Proceedings, 39, 221-223, 1975.

Savvides, L., R.S. Ayers, and M. Ashkar, A modified mercury tensiometer, Soil Science Society of America Journal, 41, 660-661, 1977.

Sawhney, B.L., and J-Y. Parlange, Two-dimensional water infiltration from a trench in unsaturated soils, Soil Science Society of America Proceedings, 38, 867-871, 1974.

Sawhney, B.L., and J-Y. Parlange, Radial movement of saturated zone under constant flux: theory and application to the determination of soil-water diffusivity, Soil Science Society of America Journal, 40, 635-639, 1976.

Sawhney, B.L., J-Y. Parlange, and N.C. Turner, Determination of soil-water diffusivity for anisotropic stratified soils, Soil Science Society of America Journal, 40, 7-9, 1976.

Saxena, G.K., R.S. Mansell, and C.C. Hortenstine, Drainage of vertical columns of Lakeland sand, Soil Science, 120, 1-12, 1975.

Schmugge, T., B. Glanchard, A. Anderson, and J. Wang, Soil moisture sensing with aircraft observations of the diurnal range of surface temperature, Water Resources Bulletin, 14, 169-178, 1978.

Schmugge, T.J., J.M. Menelley, A. Rango, and R. Neff, Satellite microwave observations of soil moisture variations, Water Resources Bulletin, 13, 265-281, 1977.

School, D.G., Hydraulic properties in a chaparral stand, Soil Science Society of America Journal, 40, 14-18, 1976.

Scotter, D.R., Salt and water movement in relatively dry soil, Australian Journal of Soil Research, 12, 27-35, 1974.

Scotter, D.R., Liquid and vapour phase transport in soils, Australian Journal of Soil Research, 14, 33-41, 1976.

Seginer, I., and J. Morin, A model of surface crusting and infiltration of bare soils, Water Resources Research, 6, 629-633, 1970.

Selig, E.T. and S. Mansukhani, Relationship of soil moisture to the dielectric property, Journal of the Geotechnical Engineering Division, ASCE, 101, 755-770, 1975.

Selig, E.T., D.C. Wobschall, S. Manusukhani, and A. Motiwala, Capacitance sensor for soil moisture measurement, Transportation Research Record 532, 64-76, 1975.

Selim, H.M. and R.S. Mansell, Analytical solution of the equation for transport of reactive solutes through soils, Water Resources Research, 12, 528-532, 1976.

Selim, H.M., J.M. Davidson, and P.S.C. Rao, Transport of reactive solutes through multilayered soils, Soil Science Society of America Journal, 41, 3-10, 1977.

Selim, H.M., R.S. Mansell, and A. Elzeftawy, Distributions of 2,4-D and water in soil during infiltration and redistribution, Soil Science, 121, 176-183, 1976.

Severson, R.C. and D.F. Grigal, Soil solution concentrations: effect of extraction time using porous ceramic cups under constant tension, Water Resources Bulletin, 12, 1161-1170, 1976.

Shirazi, G.A. and M. Isobe, Calibration of neutron probe in some selected Hawaiian soils, Soil Science, 122, 165-170, 1976.

Simmers, I., Effect of soil heat flux on the water balance of a small catchment, Hydrological Sciences Bulletin, 22, 433-445, 1977.

Singh, B.P., and S. Chandra, Evaluation of the optimal thickness of soil between source and detector in the gamma-ray transmission method, Journal of Hydrology, 32, 189-191, 1977.

Skaggs, R.W. and Y-K. Tang, Saturated and unsaturated flow to parallel drains, Journal of the Irrigation and Drainage Division, ASCE, 102, 221-238, 1976.

Skidmore, E.L., J.D. Dickerson, and H. Schimmelpfennig, Evaluating surface-soil water content by measuring reflectance, Soil Science Society of America Proceedings, 39, 238-242, 1975.

Slack, D.C., C.T. Haan and L.G. Wells, Modeling soil water movement into plant roots, Transactions of the American Society of Agricultural Engineers, 20, 919-927, 1977.

Sloneker, L.L., T.C. Olson, and W.C. Moldenhauer, Soil-water pressure during intermittent simulated rain application measured with a new rapid-response tensiometric technique, Soil Science Society of America Proceedings, 38, 985-987, 1974.

Smiles, D.E. and J.R. Philip, Solute transport during absorption of water by soil: laboratory studies and their practical implications, Soil Science Society of America Journal, 42, 537-544, 1978.

Smith, R.E., Approximations for vertical infiltration rate patterns, Transactions of the America Society of Agricultural Engineers, 19, 505-509, 1976.

Smith, R.E. and J-Y. Parlange, A parameter-efficient hydrologic infiltration model, Water Resources Research, 14, 533-538, 1978.

So, H.B., L.A.G. Aylmore, and J.P. Quirk, The resistance of intact maize roots to water flow, Soil Science Society of America Journal, 40, 222-225, 1976.

Sonu, J. and H.J. Morel-Seytoux, Water and air movement in bounded deep homogeneous soil, Journal of Hydrology, 29, 23-42, 1976.

Sposito, G., A thermodynamic integral equation for the equilibrium moisture profile in swelling soil, Water Resources Research, 11, 499-500, 1975a.

Sposito, G., On the differential equation for the equilibrium moisture profile in swelling soil, Soil Science Society of America Proceedings, 39, 1053-1056, 1975b.

Sposito, G., Steady vertical flows in swelling soils, Water Resources Research, 11, 461-464, 1975c.

Sposito, G., The statistical mechanical theory of water transport through unsaturated soil 1. the conservation laws, Water Resources Research, 14, 474-478, 1978a.

Sposito, G., The statistical mechanical theory of water transport through unsaturated soil 2. deviation of the Buckingham-Darcy flux law, Water Resources Research, 14, 479-484, 1978b.

Sposito, G., J.V. Giráldez and R.J. Reginato, The theoretical interpretation of field observations of soil swelling through a material coordinate transformation, Soil Science Society of America Journal, 40, 208-211, 1976.

Stone, D.A., Effects of fine-particle amendments on the soil moisture characteristics of a gravelly sandy loam and on crop yields, Journal of Agricultural Science, 81, 303-310, 1973.

Streltsova, T.D., Unsaturated zone and vertical-flow components in draining unconfined formations, Journal of Hydrology, 31, 119-124, 1976.

Stroosnijder, L., and G.H. Bolt, Nomographic interpretation of water absorption data in terms of a two-parametric diffusivity-water content function, Soil Science Society of America Proceedings, 38, 876-880, 1974.

Swartzendruber, D., and D. Hillel, Infiltration and runoff for small field plots under constant intensity rainfall, Water Resources Research, 11, 445-451, 1975.

Talsma, T., The effect of initial moisture content and infiltration quantity of redistribution of soil water, Australian Journal of Soil Research, 12, 16-26, 1974a.

Talsma, T., Moisture profiles in swelling soils, Australian Journal of Soil Research, 12, 71-75, 1974b.

Talsma, T., and A. van der Leij, Infiltration and water movement in an in situ swelling soil during prolonged ponding, Australian Journal of Soil Research, 14, 337-349, 1976.

Tang, Y.K. and R.W. Skaggs, Experimental evaluation of theoretical solutions for subsurface drainage and irrigation, Water Resources Research, 13, 957-965, 1977.

Taylor, H.M. and B. Klepper, Water uptake by cotton root systems: an examination of the single root model, Soil Science, 120, 57-67, 1975.

Thomas, A.W., H.R. Duke, D.W. Zachmann, and E.G. Kruse, Comparisons of calculated and measured capillary potentials from line sources, Soil Science Society of America Journal, 40, 10-14, 1976.

Towner, G.D., The application of the overburden potential theory to swelling soils, Water Resources Research, 12, 1313-1314, 1976.

Tsuji, G.Y., R.T. Watanabe, and W.S. Sakai, Influence of soil microstructure on water characteristics of selected Hawaiian soils, Soil Science Society of America Proceedings, 39, 28-33, 1975.

Turner, N.C. and J-Y. Parlange, Two-dimensional similarity solution: theory and application to the determination of soil-water diffusivity, Soil Science Society of America Proceedings, 39, 387-390, 1975.

Vachaud, G., J.P. Gaudet, and V. Kuraz, Air and water flow during ponded infiltration in a vertical bounded column of soil, Journal of Hydrology, 22, 89-108, 1974.

van Bavel, C.H.M., R. Lascano and D.R. Wilson, Water relations of fritted clay, Soil Science Society of America Journal, 42, 657-659, 1978.

van De Pol, R.M., P.J. Wierenga, and D.R. Nielsen, Solute movement in a field soil, Soil Science Society of America Journal, 41, 10-13, 1977.

van der Ploeg, R.R., Simulation of moisture transfer in soils: one-dimensional infiltration, Soil Science, 118, 349-357, 1974.

van der Ploeg, R.R., and F. Beese, Model calculations for the extraction of soil water by ceramic cups and plates, Soil Science Society of America Journal, 41, 466-470, 1977.

van der Ploeg, R.R., and P. Benecke, Unsteady, unsaturated, N-dimensional moisture flow in soil: a computer simulation program, Soil Science Society of America Proceedings, 38, 881-885, 1974.

van Genuchten, M.T., and P.J. Wierenga, Mass transfer studies in sorbing porous media I. analytical solutions, Soil Science Society of America Journal, 40, 473-480, 1976.

van Genuchten, M.T., and P.J. Wierenga, Mass transfer studies in sorbing porous media: II. experimental evaluation with tritium (${}^3H_2O$), Soil Science Society of America Journal, 41, 272-278, 1977.

van Genuchten, M.T., P.J. Wierenga, and G.A. O'Connor, Mass transfer studies in sorbing porous media: III. experimental evaluation with 2,4,5-T, Soil Science Society of America Journal, 41, 278-285, 1977.

Vauclin, M., R. Haverkamp, J. Touma, G. Vachaud, and J-Y. Parlange, A comparison of exact and numerical solutions of the diffusion equation near singularities, Soil Science, 124, 181-185, 1977.

Vinogradov, B.V., Remote determination of soil moisture by aerospace methods, Soviet Hydrology Selected Papers, No. 4, 340-361, 1973.

Wagenet, R.J., and J.L. Starr, A method for the simultaneous control of the water regime and gaseous atmosphere in soil columns, Soil Science Society of America Journal, 41, 658-659, 1977.

Warrick, A.W., Analytical solutions to the one-dimensional linearized moisture flow equation for arbitrary input, Soil Science, 120, 79-84, 1975.

Warrick, A.W. and A. Amoozegar-Fard, Soil water regimes near porous cup water samplers, Water Resources Research, 13, 203-207, 1977.

Warrick, A.W., and D.O. Lomen, Time-dependent linearized infiltration: III. strip and disc sources, Soil Science Society of America Journal, 40, 639-643, 1976.

Warrick, A.W., and D.O. Lomen, Flow from a line source above a shallow water table, Soil Science Society of America Journal, 41, 849-852, 1977.

Warrick, A.W., G.J. Mullen, and D.R. Nielsen, Predictions of the soil water flux based upon field-measured soil-water properties, Soil Science Society of America Journal, 41, 14-19, 1977a.

Warrick, A.W., G.J. Mullen and D.R. Nielsen, Scaling field-measured soil hydraulic properties using a similar media concept, Water Resources Research, 13, 355-362, 1977b.

Watson, K.K. and A.A. Curtis, Numerical analysis of vertical water movement in a bounded profile, Australian Journal of Soil Research, 13, 1-11, 1975.

Watson, K.K. and S.J. Lees, Simulation of the rainfall-runoff process using a hysteretic infiltration-redistribution model, Australian Journal of Soil Research, 13, 133-140, 1975.

Watson, K.K. and F.D. Whisler, Comparison of drainage equations for the gravity drainage of stratified profiles, Soil Science Society of America, 40, 631-635, 1976.

Watson, K.K. and F.D. Whisler, The use of dynamic soil water characteristics in a numerical desorption model, Soil Science, 125, 83-91, 1978.

Watson, K.K., R.J. Reginato, and R.D. Jackson, Soil water hysteresis in a field soil, Soil Science Society of America Proceedings, 39, 242-246, 1975.

Watson, K.K., F.D. Whisler and A.A. Curtis, Numerical analysis of one-dimensional decay of a perched watertable, Journal of Hydrology, 36, 109-119, 1978.

Watts, D.G., and R.J. Hanks, A soil-water-nitrogen model for irrigated corn on sandy soils, Soil Science Society of America Journal, 42, 492-499, 1978.

Webb, S.N., and K.K. Watson, Gravity drainage of a sand profile under a time-dependent surface flux, Australian Journal of Soil Research, 15, 9-16, 1977.

Wells, L.G., R.W. Skaggs, Upward movement in field cores, Transactions of the American Society of Agricultural Engineers, 19, 275-283, 1976.

Whisler, F.D., Calculating the unsaturated hydraulic conductivity and diffusivity, Soil Science Society of America Journal, 40, 150-151, 1976.

White, I., P.M. Colombera, and J.R. Philip, Experimental study of wetting front instability induced by sudden change of pressure gradient, Soil Science Society of America Journal, 40, 824-829, 1976.

White, I., P.M. Colombera, and J.R. Philip, Experimental studies of wetting front instability induced by gradual change of pressure gradient and by heterogeneous porous media, Soil Science Society of America Journal, 41, 483-489, 1977.

Wierenga, P.J., Solute distribution profiles computed with steady-state and transient water movement models, Soil Science Society of America Journal, 41, 1050-1055, 1977.

Wierenga, P.J., M.J. Shaffer, S.P. Gomez, and G.A. O'Connor, Predicting ionic distributions in large soil columns, Soil Science Society of America Proceedings, 39, 1080-1084, 1975.

Wind, G.P., and W. Van Doorne, A numerical model for the simulation of unsaturated vertical flow of moisture in soils, Journal of Hydrology, 24, 1-20, 1975.

Wong, H.Y. and R.N. Yong, Unsaturated flow mechanisms in low-swelling clays, Soil Science, 120, 339-348, 1975.

Wooding, R.A., and H.J. Morel-Seytoux, Multiphase fluid flow through porous media, Annual Review of Fluid Mechanics, 8, 233-274, 1976.

Youngs, E.G. and S. Aggelides, Drainage to a water table analysed by the Green-Ampt approach, Journal of Hydrology, 31, 67-79, 1976.

Youngs, E.G. and A. Poulovassilis, The different forms of moisture profile development during the redistribution of soil water after infiltration, Water Resources Research, 12, 1007-1012, 1976.

Yule, D.F. and W.R. Gardner, Longitudinal and transverse dispersion coefficients in unsaturated plainfield sand, Water Resources Research, 14, 582-588, 1978.

Zaslavsky, D., and M. Garber, Infiltration through soil with a slightly permeable buried membrane, Soil Science, 122, 321-330, 1976.

Zaradny, H., Boundary conditions in modeling water flow in unsaturated soils, Soil Science, 125, 75-82, 1978.

Zotimov, N.V., Experimental determination of soil moisture on irrigated lands from radioactive soil emission, Soviet Hydrology, Selected Papers, No. 6, 491-499, 1973.

Zur, B., and D. Savaldi, Infiltration under a pulsed water application: 1. the nature of the flow system, Soil Science, 124, 127-134, 1977.

Zyvoloski, G., J.C. Bruch, Jr., and J.M. Sloss, Solution of equation for two-dimensional infiltration problems, Soil Science, 122, 65-70, 1976.