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MILESTONES IN SOIL PHYSICS

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This special issue of *Soil Science* celebrates the enormous accomplishments made during the past century or more in the field of soil science, including some of the key articles published in *Soil Science* during its 90 years of existence. In this article, we focus on the contributions in soil physics, exemplified by the articles of Willard Gardner (1919) and John Philip (1957c), both of which are reprinted in this issue. Much of the overview is limited to the physics of water flow in unsaturated soils as described with the Richards equation, including its mathematical solutions. (Soil Science 2006;171:S21–S28)

THE 1919 *Soil Science* article by Willard Gardner was an important step forward in the studies of water flow in unsaturated soils, leading to the discovery of the Richards equation. About 70 years ago, Lorenzo A. Richards formulated a general, macroscopic theory for the flow of water in unsaturated soils (Richards, 1928, 1931). The wide applicability of that theory and its numerous extensions form the core of the discipline of soil physics. Richards' theory combines the simplest possible balances of mass and of forces. Assuming the density, ρ, of soil water to be constant, the balance of mass can be expressed as a volumetric balance equation:

$$\frac{\partial\theta}{\partial t} = -\frac{\partial\theta v}{\partial z}, \tag{1}$$

where t denotes time; z, the vertical coordinate taken positive downward; θ, the volumetric water content (Gardner used ρ for this variable), and v, the velocity of water such that θv equals the volumetric flux. Under quite reasonable assumptions for the balance of forces, Darcy's law, also appropriately referred to as the Darcy-Buckingham equation (Narasimhan, 2005), is expressed as

$$q = -K\frac{\partial h}{\partial z} + K, \tag{2}$$

where K is the hydraulic conductivity and h is the capillary pressure head defined as

$$h = \frac{p_l - p_g}{\rho g} = -\frac{p_c}{\rho g}, \tag{3}$$

where p_l and p_g are the pressures of the liquid and gaseous phases, respectively; p_c, the capillary pressure; and g, the gravitational constant. The pressure head and the hydraulic conductivity are nonlinear functions of the volumetric water content, θ. Moreover, the relationship $h(\theta)$ is hysteretic.

With the theory named after him, Richards consolidated the efforts of his predecessors, notably Charles S. Slichter, Lyman J. Briggs, Edgar Buckingham, Willard Gardner, and W. B. Haines (for details, see Philip, 1974; Gardner, 1976, 1986; and Raats, 2001). Slichter (1899; see also Wang, 1987) used the mass balance and Darcy's law to describe the flow of water in saturated soils. He also calculated the hydraulic conductivity for a packing of spheres based on a model of tubes with variable triangular cross section, finding a quadratic dependency of the hydraulic conductivity on the particle size in the process. Briggs (1897; see also Landa and Nimmo, 2003) used the Young-Laplace equation to describe the jump in pressure across liquid-gas interfaces in unsaturated soils, thus discovering in essence the inverse dependence

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of the capillary pressure head on the particle size. Buckingham (1907; see also Nimmo and Landa, 2005; Narasimhan, 2005) furthermore described hydrostatic vertical equilibrium conditions in soils, formulated in words the principle of mass balance, and extended Darcy's law to unsaturated soils.

In the article reprinted here, Gardner (1919) was the first to actually write the one-dimensional form of the macroscopic mass balance equation. For horizontal flow, he formulated, by analogy with Stokes law for the motion of a particle falling through a viscous liquid, a linear relationship between the macroscopic velocity and the *gradient of the curvature pressure* (i.e., he postulated Darcy's law). Gardner used a microscopic model for a water wedge between touching spheres to relate the curvature pressure to the water content, and used the resulting pore-scale model to derive the macroscale water retention characteristic. His equations also implied a dependency of the hydraulic conductivity on the water content.

Willard Gardner provided much inspiration and leadership in the early and mid 1900s on the hydrodynamics of unsaturated soils, causing Sterling Taylor (1965) and others to refer to Gardner as the "father of modern soil physics." As a further example, Gardner and Widtsoe (1921) motivated Darcy's law for water flow in unsaturated soils as follows:

> "We may therefore say that for the chosen element [of liquid] there exists a force acting vertically downward proportional to the mass, a pressure on each of the six sides, and a frictional drag due to the relative slipping of the element, which may be zero for any or all of the six sides, depending upon the relative velocity at each side."

With such a motivation, the theory also fits well within the framework of modern continuum theories of mixtures, provided that one recognizes from the outset the existence of separate solid, liquid, and gaseous phases, and treats these phases as superimposed continua (for reviews, see Raats, 1984, 2001).

Incidentally, Willard Gardner also played an important role in early drainage theory. After obtaining bachelor of science, master of science, and doctor of philosophy degrees in physics at Columbia University, Don Kirkham came to the Department of Physics at the Utah Agricultural Experiment Station to teach physics and mathematics. An analysis by Willard Gardner and his colleagues in the late 1920s and early 1930s of tile drainage of land overlying an artesian basin prompted Don Kirkham to perform sand tank experiments and to make a more complete mathematical analysis, resulting in three articles in the *Transactions of the American Geophysical Union* in 1939, 1940, and 1945, thus marking the start of a highly successful 60-year career in soil physics.

Returning to the unsaturated zone, Haines (1930; see also Keen, 1931) applied the Young-Laplace equation to ideal soils (i.e., packings of monodisperse spheres) to calculate water retention, including the hysteresis effect, and cohesion. The foundation of the Richards equation based on the principles of surface tension and viscous flow was treated later very comprehensively by Miller and Miller (1956). The motivation presented by Miller and Miller (1956) and the more recent formal derivation by Withaker (1986) based on the method of volume averaging nicely complement each other.

PHYSICAL CHARACTERIZATION OF SOILS

Within the context of the Richards equation, the relationships among the volumetric water content θ, pressure head h, and hydraulic conductivity K define the hydraulic properties of a soil. Much effort over the years has gone into the measurement, mathematical description, and prediction of these relationships (for examples, see Dane and Topp, 2002). After the publication of his theory in 1931, Richards' main interest was the development of sound methods for determining water retention and hydraulic conductivity characteristics and for *in situ* monitoring of the soil water and salinity status. In the period from 1941 to 1964, he published a dozen methodological articles in *Soil Science*. For anyone working with tensiometers, Richards (1949) is still very much worth reading. In the same year, Gardner and Kirkham (1949) introduced neutron scattering as a means to determine the soil water content. In the next three decades, the neutron probe was the main device for measuring the time course of water content profiles. Starting in the 1980s, neutron scattering has been supplemented by a range of electromagnetic methods (Evett and Parkin, 2005), including time domain reflectometry (for examples, see Robinson et al., 2003), ground penetrating radar, and capacitance methods.

Miller and Miller (1956) related the water retention and hydraulic conductivity characteristics of geometrically similar soils, each characterized by a length scale. They established that the Young-Laplace equation implies that the capillary pressure is inversely proportional to the length scale for geometrically similar soils at the same volumetric water content, whereas the linearized Navier-Stokes equation implies that the hydraulic conductivity is proportional to the square of the length scale. In the late 1950s and the 1960s, the Miller-Miller scaling theory was verified in a series of clever experiments by Ed Miller, Arnold Klute, and several coworkers. Later, an extension of this scaling theory served as a basis for the analysis of hydraulic characteristics of spatially variable field soils (for examples, see Reichardt et al., 1975).

Much use has been made of mathematical functions that match measured soil physical characteristics in a reasonable way. Some early literature was reviewed by Gardner (1974), whereas more recent developments were presented at two international symposia (van Genuchten et al., 1992, 1999). Various classes of soils have been defined by specific mathematical functions representing their physical properties. Two groups of classes of soils can be distinguished. One of these groups yields flow equations that can be solved analytically, in most cases because of linearization after one or more transformations. Examples of classes of soils belonging to this group and associated analytical solutions of flow problems are presented below.

Another group of classes of soils, favored in numerical studies, is based on statistical pore-size distribution models that have a relatively solid basis in Poiseuillean flow through networks of capillaries (for examples, see Childs and Collis-George, 1950; Mualem, 1976). In this group of relationships among θ, h, and K, the hydraulic conductivity is calculated from the water retention function using certain assumptions concerning the geometry of the pore system. The procedure in essence links physico-mathematical models at the Darcy and Navier-Stokes scales. Examples of relationships of this type are given by Brooks and Corey (1964) and van Genuchten (1980).

SOLUTIONS OF FLOW PROBLEMS

Analytical Solutions for Specific Classes of Soils

For the class of linear soils, the Richards equation reduces to the linear convection-diffusion equation. Neglecting the gravitational term, this equation further reduces to the linear diffusion equation that was used by Childs (1936) in a study of water flow through heavy clay soils, by Kirkham and Feng (1949) in an analysis of experiments on horizontal absorption, and by Gardner (1956) in the outflow method for measuring the diffusivity.

In pioneering articles, Philip (1957b) and Gardner (1960) also used the linear diffusion equation to calculate the water depletion pattern around individual plant roots. Philip used his calculations to demonstrate that the previously held concept of an invariable wilting point of a soil is not tenable. Gardner used the linear model as a point of departure to formulate a simple model in which the depletion resulting from uptake by a single root is treated as a series of steady flows in a cylindrical shell of soil surrounding the root, with the soil-root interface at the inner edge and the water coming from the outer edge. This simple model has served ever since as a point of departure for more sophisticated mesoscopic and macroscopic models for water uptake (for a review, see Raats, 2006).

In later work, the full linear convection-diffusion equation has served as a contrast and limit of different forms of the Richards equation for various classes of nonlinear soils (see Philip, 1969 for an early review). The class of Green and Ampt or delta function soils, for which the water content is discontinuous at wetting fronts, represents the opposite limiting behavior. In fact, Philip (1954) showed that the early solutions of Green and Ampt (1911) are solutions of a limiting form of the later Richards equation.

Other classes of soils for which analytical solutions (for numerous references, see Raats, 2001, 2002) can be obtained are (i) the class of Gardner (1958) soils for which steady flows are described with a linear equation in terms of the matric flux potential, irrespective of the spatial dimensionality of the flow problem; (ii) the class of Brooks and Corey (1964) power function soils for which similarity solutions of the Richards equation can be found; and (iii) the class of versatile nonlinear soils for which the Richards equation can be transformed into the Burgers equation, which, in turn, can be transformed to a linear diffusion equation. The basis for the last class, in essence, goes back to the doctor of philosophy thesis of John Knight (1973).

Hybrid Analytical-Numerical Solutions

It is remarkable that a large number of one-dimensional solutions of the Richards equation are of the form

$$z = z(\theta, t), \;\; z = z(h, t), \tag{4}$$

where z is the depth. The simplest of such solutions are those for steady upward and downward flow as shown in the *Soil Science* articles by Youngs (1957) and Gardner (1958), and in a review by Raats and Gardner (1974).

In the article reprinted here, Philip (1957c) derived a series solution in the form of Eq.(4) for vertical infiltration in powers of $t^{1/2}$. The first transient solution in the form of Eq.(4) was already published by Ludwig E. Boltzmann in 1894 and first applied to horizontal absorption by Klute (1952). Philip's article was the first of a series of 7 articles on the theory of infiltration in Volumes 83 to 85 of *Soil Science*. The second article of the series dealt with the long-term traveling wave solution, which, again, is in the form of Eq.(4). The next four articles treated such topics as moisture profiles and their relation to experiments, the sorptivity and algebraic infiltration equations, the influence of the initial moisture content, and the effect of a water depth on the soil. The series of articles introduced new mathematical methods and gave clear physical interpretations, including their use for optimally designing or analyzing experiments. Around the same time, Philip wrote four more *Soil Science* articles on the early stages of adsorption and infiltration, on energy dissipation during adsorption and infiltration, and on absolute thermodynamic functions in soil-water studies. In a well-known Citation Classic, Philip (1969) reviewed these various articles and related work. These and much later contributions by John R. Philip are, in turn, reviewed by Raats et al. (2002) and Smiles (2005).

John Philip's series of articles on the theory of infiltration was soon widely noticed. From 1960 to 1961, Gerry Bolt already discussed the theory in his soil physics course for master of science students at Wageningen University. Don Kirkham also paid much attention to it in his lectures, eventually resulting in 60 textbook pages that provided numerous details of the derivations (Kirkham and Powers, 1972). But the most important early contact of John Philip in the northern hemisphere was likely E. C. Childs of the Agricultural Research Council Unit of Soil Physics of the University of Cambridge (for contributions by Childs, see Youngs et al., 1974).

In the 40-year period from 1936 to 1975, the Cambridge group published an impressive and varied series of 41 articles in *Soil Science*, representing a quarter of the group's output. Among these are, in the period from 1943 to 1951, a series of 6 articles by E. C. Childs on the water table, equipotentials, and streamlines in drained lands. In 1956, as a visitor with the Cambridge group, John Philip inspired a program of testing his solutions of the Richards equation experimentally, and of seeking extensions of the theory of infiltration. The first *Soil Science* article by Youngs (1957) sought to verify experimentally the solution of the infiltration problem in the article by Philip now reprinted. In his next two *Soil Science* articles, Youngs (1958a,b) presents data on redistribution, an important problem not dealt with in the series of articles by Philip. His data later inspired many other studies of redistribution, particularly of the role of hysteresis in that process. In the period from 1962 to 1975, A. Poulovassilis of the Cambridge group published in *Soil Science* seven articles on hysteresis, exploring initially the concept of independent domains (Poulovassilis, 1962); later, Poulovassilis also explored the concept of dependent domains (Poulovassilis and Childs, 1972). Going beyond the theory of Richards, the two-fluid phase character of unsaturated soils became apparent by three *Soil Science* articles on water content profile development and air compression during absorption and infiltration (Youngs and Peck, 1964; Peck, 1965a,b). The 1974 issue of *Soil Science* dedicated to the life and work of E. C. Childs shows that some 30 years ago, soil physics could already cope with a wide range of practical problems in the agronomic, hydrologic, and environmental areas.

In the period from 1971 to 1975, Jean-Yves Parlange published in *Soil Science* a series of 11 articles. The first two articles of the series (Parlange, 1971a,b) addressed the same physical problems as those addressed by Klute (1952) and by the series of seven articles by Philip, whereas the other nine articles treated such topics as two- and three-dimensional absorption, two- and three-dimensional steady infiltration, unsteady infiltration from spherical cavities, multidimensional cavities under pressure, one-dimensional infiltration with constant flux at the surface, the dynamics of capillary rise, and cavities with constant flux. Typically, Parlange's solutions were iterative approaches, using an integral moment balance as constraint. Parlange's method was noticed soon by others. For example, Knight and Philip (1973) criticized its convergence, whereas Cisler (1974) proposed improvements for the iterative approach. As an alternative, Philip (1973) and Philip and Knight (1974) developed a flux concentration method in which the integral mass balance, not the integral moment balance, was used as a constraint. With numerous colleagues around the world, particularly in the United States, Australia, and France, Jean-Yves Parlange has been pursuing solutions of Richards equation ever since, resulting in a further 35 contributions in *Soil Science* by 1995 and many more in other journals.

Numerical Solutions

In the early work of Klute (1952) and Philip (1955, 1957a,c) it was already clear that most flow problems in the unsaturated zone require, at least in part, numerical analysis. In a comprehensive review by Breaster et al. (1971), most early numerical studies discussed concerned one-dimensional flow, including complications arising from hysteresis, ponding, and moving water tables. Rubin (1968) was the first to numerically analyze a two-dimensional flow problem using an alternating direction implicit method. About a dozen studies of two-dimensional problems followed in the next three years, all using various finite difference methods. The first comprehensive three-dimensional model was published by Freeze (1971).

The progress with especially multidimensional models was initially hampered not only by the low speed of available computers but also by the invoked numerical methods. In addition, finite difference methods were awkward for handling curved boundaries and coping with anisotropic media for which the principal axes do not coincide with the coordinate axes. These limitations have been largely overcome with the introduction of Galerkin finite element (for examples, see Neuman, 1973), control volume finite element (Therrien and Sudicky, 1996), and integrated finite difference techniques (Narasimhan and Witherspoon, 1976), more accurate mass-conservative numerical solution schemes for the Richards equation (Celia et al., 1990), and more powerful iterative matrix equation solvers for multidimensional problems (for a review and numerous references, see van Genuchten and Sudicky, 1999).

FUTURE OPPORTUNITIES

Thanks to Willard Gardner and John R. Philip and their colleagues during the past century, soil physics has slowly matured into a well-established scientific discipline. This overview of past contributions has, by necessity, been limited mostly to flow in unsaturated soils, as described with the Richards equation, and has been very arbitrary because many others not cited here have equally contributed over the years.

Echoing Alvin Weinberg, John Philip (1991) pointed out 15 years ago that many important societal problems are transscientific: even if a problem can be stated in the language of science, scientific analysis may not provide a full answer but, at best, provide some intellectual discipline. Smiles et al. (2000) suggested that such intellectual discipline may well come from simulation models. We believe that this is most likely if the availability of simulation results is accompanied by a more thorough understanding of the underlying physical, chemical, and biological processes.

Faster computers and more advanced methods for solving the Richards equation are now making it possible to efficiently solve transient variably saturated flow problems in multidimensional heterogeneous subsurface systems that may include parts of the saturated zone and overland flow as needed (for examples, see Panday and Huyakorn, 2004). This capability to tackle increasingly complicated problems has shifted research to such post-Richards problems as swelling and shrinkage phenomena (for examples, see reviews by Smiles, 2000 and Raats, 2002), pore-scale flow processes, local-scale nonequilibrium flow (e.g., dynamic memory effects as described by Hassanizadeh and Gray, 1990, 1993), flow in structured soils or unsaturated fractured rock (for examples, see review by Simunek et al., 2003), unstable flow (Van Duijn et al., 2004) and preferential flow in general (for examples, see review by Hendrickx and Flury, 2001), flow in the capillary fringe, root water uptake, multiphase flow, nonisothermal flow, and uncertainty. Many contributions on nonisothermal flow actually expanded upon a mechanistic theory by Philip and de Vries (1957) for the simultaneous movement of heat and moisture, although alternative formulations within the framework of the thermodynamics of irreversible processes are also possible.

Additional developments have been in the area of solute transport, exemplified by the initial work of Don Nielsen and Jim Biggar in the early 1960s (for examples, see Nielsen and Biggar, 1962) and continuing up the present. This article cannot do justice to the many contributions in this area of research, which now encompasses such topics as nonequilibrium transport, transport in fractured rock, colloid and colloid-facilitated transport, and multicomponent reactive transport. We simply refer to a recent review by Simunek and van Genuchten (2006) that includes many references. The shear number of topics now being tackled shows that soil physics has also increasingly become a partner of other disciplines in efforts to integrate all relevant physical, chemical, and biological processes operative in the unsaturated zone, with research ranging from the pore scale to the field and larger scales. *Soil Science* has served the scientific community well for 90 years. We trust that this journal will remain an important outlet of both disciplinary and interdisciplinary research touching upon soil physics and its related disciplines.

REFERENCES

Breaster, C., G. Dagan, S. Neuman, and D. Zaslavsky. 1971. A survey of the equations and solutions of unsaturated flow in porous media. First Annual Report (Part 1), Project No. A10-SWC-77, Grant No. FG-Is-287 made by USDA under PL480. Technion Israel Institute of Technology and Research and Development Foundation Ltd, Hydrodynamics and Hydraulic Eng. Lab.

Briggs, L. J. 1897. The mechanics of soil moisture. *In:* USDA Division of Soils, Bull. 10. Washington, DC: Government Printing Office, pp. 24.

Brooks, R. H., and A. T. Corey. 1964. Hydraulic properties of porous media. *In:* Hydrology Paper 3. Fort Collins, CO: Colorado State University, pp. 27.

Buckingham, E. 1907. Studies on the movement of soil moisture. *In:* USDA Bureau of Soils, Bull. 38. Washington, DC: Government Printing Office, pp. 61.

Celia, M. A., E. T. Bououtas, and R. L. Zarba. 1990. A general mass-conservative numerical solution for the unsaturated flow equation. Water Resour. Res. 26:1483–1496.

Childs, E. C. 1936. The transport of water through heavy clay soils: I. J. Agric. Sci. 26:114–127.

Childs, E. C., and N. Collis-George. 1950. The permeability of porous materials. Proc. Roy. Soc., London, Ser. A 201:392–405.

Cisler, J. 1974. Note on the Parlange method for the numerical solution of horizontal infiltration of water in soil. Soil Sci. 117:70–73.

Dane, J. J., and G. C. Topp (eds.). 2002. Methods of Soil Analysis, Part 4. Physical Methods. Soil Science Society of America, Madison, WI.

Evett, S. R., and G. W. Parkin. 2005. Advances in soil watercontent sensing: the continuing maturation of technology and theory. Vadose Zone J. 4:986–991.

Freeze, R. A. 1971. Three-dimensional, transient, saturated-unsaturated flow in a groundwater basin. Water Resour. Res. 7:347–366.

Gardner, W. 1919. The movement of moisture in soil by capillarity. Soil Sci. 7:313–317.

Gardner, W., and J. A. Widtsoe. 1921. The movement of soil moisture. Soil Sci. 11:215–232.

Gardner, W. H. 1976. Historical highlights in American soil physics. Soil Sci. Soc. Am. J. 41:221–229.

Gardner, W. H. 1986. Early soil physics into the mid-20th century. *In:* Stewart B. A. (ed.). Adv. Soil Sci, 4, 1–101.

Gardner W. R. 1956. Calculation of capillary conductivity from pressure plate outflow data. Soil Sci. Soc. Am. Proc. 20:317–320.

Gardner, W. R. 1958. Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Sci. 85:228–232.

Gardner, W. R. 1960. Dynamic aspects of water availability to plants. Soil Sci. 89:63–73.

Gardner, W. R. 1974. The permeability problem. Soil Sci. 117:243–249.

Gardner, W. R., and D. Kirkham. 1952. Determination of soil moisture by neutron scattering. Soil Sci. 73:391–401.

Green, W. H., and G. A. Ampt. 1911. Studies in soil physics. Part I. The flow of air and water through soils. J. Agric. Sci. 4:1–24.

Haines, W. B. 1930. Studies in the physical properties of soil. V. The hysteresis effect in capillary properties and the modes of moisture distribution associated therewith. J. Agric. Res. 20:97–116.

Hassanizadeh, S. M., and W. G. Gray 1990. Mechanics and thermodynamics of multiphase flow in porous media including interphase boundaries. Adv. Water Resour. 13:169–186.

Hassanizadeh, S. M., and W. G. Gray. 1993. Thermodynamic basis of capillary pressure in porous media. Water Resour. Res. 29:3389–3405.

Hendrickx, J. M. H., and M. Flury. 2001. Uniform and preferential flow, mechanisms in the vadose zone. *In:* Conceptual Models of Flow and Transport in the Fractured Vadose Zone. National Research Council, National Academy Press, Washington, DC, pp. 149–187.

Keen, B. A. 1931. The Physical Properties of the Soil. London, UK: Longmans.

Kirkham, D., and C. L. Feng. 1949. Some tests of the diffusion theory, and laws of capillary flow, in soils. Soil Sci. 67:29–40.

Kirkham, D., and W. L Powers. 1972. Advanced Soil Physics. New York, NY: Wiley-Interscience. xvii + pp. 534.

Klute, A. 1952. A numerical method for solving the flow equation for water in unsaturated materials. Soil Sci. 73:105–116.

Knight, J. H. 1973. Solutions of the nonlinear diffusion equation: existence, uniqueness, and estimation [PhD thesis]. Australian National University, Canberra, ATC, Australia.

Knight, J. H., and J. R. Philip. 1973. On solving the unsaturated flow equation. 2. Critique of Parlange's method. Soil Sci. 116:407–416.

Landa, E. R., and J. R. Nimmo. 2003. The life and scientific contributions of Lymann J. Briggs. Soil Sci. Soc. Am. J. 67:681–693.

Miller, E. E., and R. D. Miller. 1956. Physical theory of capillary flow phenomena. J. Appl. Phys. 27:324–332.

Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12(3):513–522.

Narasimhan, T. N. 2005. Buckingham, 1907: an appreciation. Vadose Zone J. 4:434–441.

Narasimhan, T. N., and P. A. Witherspoon. 1976. An integrated finite difference method for analyzing fluid flow inporous media. Water Resour. Res. 12(1):57–64.

Neuman, S. P. 1973. Saturated-unsaturated seepage by finite elements. J. Hydraul. Div. ASCE 99:2233–2250.

Nielsen, D. R., and J. W. Biggar. 1962. Miscible displacement, III. Theoretical considerations. Soil Sci. Soc. Am. Proc. 26:216–221.

Nimmo J. R., and E. R. Landa. 2005. The soil physics contributions of Edgar Buckingham. Soil Sci. Soc. Am. J. 69:328–342.

Panday, S., and P. S. Huyakorn. 2004. A fully coupled physically-based spatially-distributed model for evaluating surface/subsurface. Adv. Water Resour. 27:361–382.

Parlange, J. Y. 1971a. Theory of water movement in soils: 1. One-dimensional absorption. Soil Sci. 111:134–137.

Parlange, J. Y. 1971b. Theory of water movement in soils: 2. One-dimensional infiltration. Soil Sci. 111:170–174.

Peck, A. J. 1965a. Moisture profile development and air compression during water uptake by bounded porous bodies: 2. Horizontal columns. Soil Sci. 99:327–334.

Peck, A. J. 1965b. Moisture profile development and air compression during water uptake by bounded porous bodies: 3. Vertical columns. Soil Sci. 100:44–51.

Philip, J. R. 1954. An infiltration equation with physical significance. Soil Sci. 77:153–157.

Philip, J. R. 1955. Numerical solution of equations of the diffusion type with diffusivity concentration dependent. Trans. Faraday Soc. 51:885–892.

Philip, J. R. 1957a. Numerical solution of equations of the diffusion type with diffusivity concentration dependent: 2. Aust. J. Phys. 10:29–42.

Philip, J. R. 1957b. The physical principles of soil water movement during the irrigation cycle. Proc. 3rd Congr. Int. Comm. Irrig. Drain. San Francisco. 8.125–8.153.

Philip, J. R. 1957c. The theory of infiltration: 1. The infiltration equation and its solution. Soil Sci. 83:345–357.

Philip, J. R. 1969. Theory of infiltration. Adv. Hydrosci. 5:215–296.

Philip, J. R. 1973. On solving the unsaturated flow equation. 1. The flux-concentration relation. Soil Sci. 116:328–335.

Philip, J. R. 1974. Fifty years progress in soil physics. Geoderma 12:265–280.

Philip, J. R. 1991. Soils, natural science, and models. Soil Sci. 151:91–98.

Philip, J. R., and D. A. de Vries. 1957. Moisture movement in porous materials under temperature gradients. Trans. Am. Geophys. Union 38:222–232.

Philip, J. R., and J. H. Knight. 1974. On solving the unsaturated flow equation. 3. New quasi-analytical technique. Soil Sci. 117:1–13.

Poulovassilis, A. 1962. Hysteresis of pore water, an application of the concept of independent domains. Soil Sci. 93:405–412.

Poulovassilis, A., and E. C. Childs. 1972. The hysteresis of pore water: the non-independence of domains. Soil Sci. 112:301–312.

Raats, P. A. C. 1984. Applications of the theory of mixtures in soil science. Truesdell C. (ed.). Appendix 5D. *In:* Rational thermodynamics, with an appendix by C. C. Wang, 2nd ed. Springer Verlag, New York, NY, pp. 326–343.

Raats, P. A. C. 2001. Developments in soil-water physics since the mid 1960s. Geoderma 100: 355–387.

Raats, P. A. C. 2002. Flow of water in rigid and non-rigid, saturated and unsaturated soils. *In:* The Modeling and Mechanics of Granular and Porous Materials. G. Capriz, V. N. Ghionna, and P. Giovine (eds.). Birkhäuser, Boston, MA, pp. 181–211.

Raats, P. A. C., D. E. Smiles, and A. W. Warrick. 2002. Contributions to environmental mechanics: introduction. *In:* Geophysical Monograph 129, Environmental Mechanics: Water, Mass and Energy Transfer in the Biosphere. P. A. C. Raats, D. E. Smiles, and A. W. Warrick (eds.). American Geophysical Union, Washington, DC, pp. 1–28.

Raats, P. A. C. 2006. Uptake of water from soils by plant roots. Transport in porous media. In press.

Raats, P. A. C., and W. R. Gardner. 1974. Movement of water in the unsaturated zone near a water table. *In:* Drainage for Agriculture. Agronomy Monograph 17. van Schilfgaarde J. (ed.). American Society of Agronomy, Madison, WI, pp. 311–357.

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

Richards, L. A. 1928. The usefulness of capillary potential to soil moisture and plant investigators. J. Agric. Res. 37:719–742.

Richards, L. A. 1931. Capillary conduction of liquids through porous mediums. Physics 1:318–333.
Richards, L. A. 1949. Methods of measuring soil moisture tension. Soil Sci. 68:95–112.
Robinson, D. A., S. B. Jones, J. M. Wraith, D. Or, and S. P. Friedman. 2003. A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry. Vadose Zone J. 2:444–475.
Rubin, J. 1968. Theoretical analysis of two-dimensional,transient flow of water in unsaturated and partly unsaturated soils. Soil Sci. Soc. Am. Proc. 32:607–615.
Simunek, J., N. J. Jarvis, M. Th. van Genuchten, and A. Gärdenäs. 2003. Review and comparison of models for describing non-equilibrium and preferential flow and transport in the vadose zone. J. Hydrol. 272(1–4):14–35.
Simunek, J., and M. Th. van Genuchten. 2006. Contaminant transport in the unsaturated zone: theory and modeling. *In:* The Handbook of Groundwater Engineering, Chapter 22, Second Edition. J. W. Delleur (ed.). CRC Press, Boca Raton, FL, pp. 22.1–22.46.
Slichter, C. S. 1899. Theoretical investigation of the motion of ground water. U.S. Geol. Survey, 19th Annu. Rep. Part 2. pp. 295–384.
Smiles, D. E. 2000. Hydrology of swelling soils: a review. Aust. J. Soil Res. 38:501–521.
Smiles, D. E. 2005. John Robert Philip 1927–1999. Hist. Rec. Aust. Sci. 16:221–246.
Smiles, D. E., I. White, and C. J. Smith. 2000. Soil science education and society. Soil Sci. 165:87–97.
Taylor, S. A. 1965. Willard Gardner 1883–1964. Soil Sci. 100:79–82.
Therrien, R., and E. A. Sudicky. 1996. Three-dimensional analysis of variably-saturated flow and solute transport in discretely-fractured porous media. J. Contam. Hydrol. 23:1–44.
Van Duijn, C. J., G. J. M. Pieters, and P. A. C. Raats. 2004. Steady flows in unsaturated soils are stable. Transp. Porous Media 57:215–244.
van Genuchten, M. Th. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44: 892–898.
van Genuchten, M. Th., and E. A. Sudicky. 1999. Recent advances in vadose zone flow and transport modeling. *In:* Vadose Zone Hydrology: Cutting Across Disciplines. Parlange M. B., and Hopmans J. W. (eds.). Oxford University Press, New York, NY, pp. 155–193.
van Genuchten, M. Th., F. J. Leij, and L. J. Lund (eds.). 1992. Proc. Int. Workshop, Indirect Methods of Estimating the Hydraulic Properties of Unsaturated Soils. Univ. of California, Riverside, CA, pp. 718.
van Genuchten, M. Th., F. J. Leij, and L. Wu (eds.). 1999. Proc. Int. Workshop, Characterization and Measurement of the Hydraulic Properties of Unsaturated Porous Media. Parts 1 and 2. University of California, Riverside, CA, pp. 1602.
Wang, H. F. 1987. Charles Sumner Slichter—an engineer in mathematician's clothing. *In:* The History of Hydrology. Landa E. R., Ince S. (eds.). 3:103–112.
Withaker, S. 1986. Flow in porous media II: The governing equations for immiscible, two-phase flow. Transp. Porous Media. 1:105–125.
Youngs, E. G. 1957. Moisture profiles during vertical infiltration. Soil Sci. 84:283–290.
Youngs, E. G. 1958a. Redistribution of moisture in porous materials after infiltration: 1. Soil Sci. 86:117–125.
Youngs, E. G. 1958b. Redistribution of moisture in porous materials after infiltration: 2. Soil Sci. 86: 202–207.
Youngs, E. G., and A. J. Peck. 1964. Moisture profile development and air compression during water uptake by bounded porous bodies: 1. Theoretical introduction. Soil Sci. 98:290–294.
Youngs, E. G., G. D. Towner, and A. Poulovassilis. 1974. Ernest Carr Childs. In memoriam. Soil Sci. 117:241–242.