Soil Moisture

L. L. Boersma, D. Kirkham, D. Norum, R. Ziemer, J. C. Guitjens, J. Davidson, and J. N. Luthin

Infiltration continues to occupy the attention of soil physicists and engineers. A theoretical and experimental analysis of the effect of surface sealing on infiltration by *Edwards and Larson [1969]* showed that raindrops reduced the infiltration rate by as much as 50% for a two-hour period of infiltration. The effect of raindrops on the surface infiltration rate of soils has been investigated by *Seginer and Morin [1970]* who used an infiltration model based on the Horton equation. The effect of antecedent moisture on infiltration rate was shown by *Powell and Beasley [1967]* to be dependent on crop cover, degree of aggregation, and bulk density. The effect of snow cover and type of frost on the soil infiltration rate has been studied by *Haupt [1967]* on small plots in the Sierra Nevada Mountains in California. The steady infiltration from a shallow, circular, inundated area on the horizontal surface of a semi-infinite porous medium is treated by a method of linearization by *Wooding [1968]*.

The infiltration law of Green and Ampt is used to analyze the infiltration into heterogeneous profiles by *Childs and Bybordi [1969]* .

The one-dimensional infiltration redistribution, and evaporation and drainage of water from a soil was investigated by using a numerical method by *Hanks et al. [1969] . The* computed results compared favorably with measured results. Extensions of existing quasi analytical methods for solving the nonlinear Fokker-Planck equation by describing water movement in two- and three-dimensional transient and steady systems are discussed by *Philip [1968a, 1968b]* .

L. L. Boersma is with the Department of Soils, .Oregon State University, Corvallis, Oregon 97331. D. Kirkham is with the Department of Agronomy, Iowa State University, Ames, Iowa 50010. D. Norum is with the Department of Agricultural Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada. R. Ziemer is with the Forest Experiment Station, Arcata, California 95521. J. C. Guitjens is with the Department of Soil and Water Science, University of Nevada, Reno, Nevada 89507. J. Davidson is with the Department of Agronomy, Oklahoma State University, Stillwater, Oklahoma 74074. J. N. Luthin is with the Department of Water Science and Engineering, University of California, Davis, California.

A simplified picture of the infiltration of water into sands is presented by *Smith [1967]* who uses conventional concepts of capillary forces and gravity. The soil water profiles after the cessation of infiltration, both with and without evaporation from the soil surface, have been investigated in the field by *Davidson et al. [1969]* and compared with theory. Similar work is reported by *Gardner et al. [1970] , Staple [1969] , Rubin [1967] , Rose [1968a, 1968b, 1969c] , Remson [1967] , and Ibrahim and Brutsaert [1967] .*

The applicability of Darcy's law to unsaturated flow continues to receive attention in an experiment performed by *Thames and Evans [1968] . They* found a linear relationship between flux and gradient only during the early stages of infiltration. Nonlinearity appeared at low gradients over a wide range of water contents. *Bondarenko [1968]* found that capillary flow velocity at low pressure gradients is not proportional to the gradient and that for hydrogen bonded liquids Darcy's law is not generally valid. Additional work is reported by *Swartzendruber [1968] , Olson and Swartzendruber [1968] , Stark [1968], Wright [1968], and Miller et al. [1969]*.

A comprehensive review of the methods used to solve the dispersion equations for miscible fluids in two and three dimensions is given by *Shamir and Harleman [1967a, 1967b] . An* improved numerical method is presented, and the procedures have been checked against several simple models.

The problem of the dispersion at the interface of two miscible fluids that are different in density and viscosity has been studied by *Li and Yeh [1968]* and *Bachmat and Elrich [1970]*. Solutions are presented for the dispersion at the interface of liquids in two-dimensional flow.

The effect of an irregular, oscillating air flow in soils induced by turbulence in the atmosphere on the transport of water vapor and oxygen in soils is the subject of an analysis by *Scotter and Raats [1968]* . Conditions of dynamic similarity for the simultaneous motions of pairs of miscible constituents in porous mediums were presented by *Raats and Scotter [1968]* . Miscible displacement experiments performed on unsaturated glass beads gave break-through curves that compared to similar curves for saturated flow, shifted to the left [Krupp *and Elrick, 1968]*. The shift is attributed to the slow release of stagnant water held in the larger pores. The movement of water in response to thermal gradients has been investigated by *Cassel et al. [1969], Hoekstra [1969], Kulik [1968], Rose [1968a,* *1968b, 1968c]., Sartz [1969] , and Weeks et al, [1968].*

The bulk transfer of water due to temperature gradients has been studied by *Benz et al. [1968]* in the field under conditions of a high water table, saline soil, and artesian pressure. Benz et al. found that a lowering of the water table during the winter months was due to the upward migration of water towards the colder soil surface. The modification of soil temperature due to the temperature of the infiltration water has been studied by *Wierenga et al. [1970]* .

Evaporation from the soil has received attention. Numerical methods are generally used to solve the appropriate equation by *Whisler et al. [1968a, 1968b]* and *Bresler and Hanks [1969]*. Experimental data are presented by *Black et al. [1969] , Hellar [1968] , Fritton et al. [1967] , Hanks et al. [1967] , Bresler and Kemper [1970] , Gardner and Gardner [1969] , and Fritton et al. [1970]*.

The extensive literature on drainage theory has been extended by *Warrick and Kirkham [1969]* and *Powers et al. [1967]* to include the seepage of ponded water into full ditch drains. The effect of the capillary fringe on practical drainage design was examined in the field by means of an electrical resistance network by *Lembke [1969] . He* concluded that the additional flow rate due to the capillary fringe is probably of no significance in the design of drainage systems. An exhaustive analysis has been made of the Dupuit-Forchheimer theory and its consequences by *Kirkham [1967] . The* limits of usefulness of drainage .equations based on Dupuit-Forchheimer theory are presented. A finite difference method for the solution of steady state free surface problems has been presented by *Jeppson [1968a, 1968b] . The* method consists of getting a solution in the ø,ψ plane with the coordinate directions *x* and *y* considered as dependent variables. Solutions are presented for several problems in which capillary effects are ignored (see also *Jeppson and Nelson [1970]).* The steady downward flow to a water table, which includes a partially saturated zone, is analyzed by *Arbajbhirama and Kridakoran [1968]* by using the Scott-Corey equation describing the change in capillary pressure during steady downward flow of a wetting liquid. Solutions of the Boussinesq equation were compared to a viscous flow model for transient drainage of sloping land by *Chauhan et al. [1968]* .

The measurement of the hydraulic conductivity of unsaturated soils continues to be a subject for investigation and development. Transient flow data obtained during horizontal infiltration were used by *Vachaud [1967] to* calculate the unsaturated hydraulic conductivity of two soils.

The measurement of entrapped gas in relation to unsaturated flow has been investigated by *Debacker [1967] . He* used a pressure cell as an air pycrometer to measure the volume of the free gas phase during unsaturated flow conditions. *Peck [1969]* has studied the entrapment and stability of air bubbles in soil.

A theory explaining the effect of entrapped air on the transient drainage of soil was developed and tested on a one-dimensional model *[Norum and Luthin, 1968]*. It was shown that barometric variations have little effect on the entrapped air when the draining column is open at both ends; however, when the column is closed at the bottom, an increase in atmospheric pressure lowers the water table, and a decrease in atmospheric pressure causes a water table rise. Additional evidence on the effect of barometric fluctuations on water table levels was furnished by *van Hylckama [1968]* who showed a diurnal water table fluctuation that was correlated with barometric fluctuations. Finite difference methods have been employed to determine the surface of seepage and the free water surface around a well in a pumped unconfined aquifer by *Taylor and Luthin [1969] . Finite* difference methods have been used to study unsaturated ground-water flow by *Green et al. [1970]* and *Hornberger and Remson [1970] . Steady* state seepage in an inclined soil slab was studied by *Whisler [1969] using* an electric analog, and transient flow was,studied by *Rubin [1968]*.

By representing the hydraulic conductivity as an exponential function of moisture potential, *Philip 1968b]* has solved the nonlinear equation for steady flow from buried point sources and spherical cavities.

Philip's solution of the concentration dependent diffusion equation has been adapted to horizontal infiltration into partly saturated porous materials by an approximation of the functions relating moisture content suction and moisture content capillary conductivity *[Brutsaert, 1968b, 1968c]*. In addition, *Jeppson [1968b]* presents some' solutions to steady state, free surface seepage from axisymmetric ponds to a drain layer at a finite depth. These solutions are obtained by finite difference methods. Additional work on the diffusion equation has been done by *Brutsaert and Weisman [1970]* . The radial flow of soil moisture to a cylindric sink has been examined by *Drake et al. [1969]* .

The flow toward a single plant root based upon potential theory is developed by Molz *et al. [1968]* . Their model is based upon an infinite soil mass that is initially at a uniform moisture content. The relationship between moisture content and diffusivity for the soil studied is represented by an exponential function.

Field measurements using flow cells for measuring the conductivity, acidity, and rate of water flow are described by *Cole [1968] . The* streaming potential has been used by *Abaza and Clyde [1969]* for measuring the rate of flow through porous media. The use of the neutron probe for measuring the water content of several soils in southern Italy led *Cotecchia et al. [1968]* to conclude that the measurement of water content by thermal neutron counts does not provide a sufficient guarantee of accuracy. A comprehensive survey of world-wide research and practice with nuclear meters is reported by *Smith and Womack [1968] . The* use of laboratory permeameters and the relative flow along the boundary as contrasted to the inner matrix were examined by *Worcester et al. [1968]*. They found a higher hydraulic conductivity in the outer zone for fine materials but a lower conductivity in the outer zone for coarse materials. The asymmetrical distribution of temperature around a point source in a porous media has been used by *Byrne et al. [1967] to* measure the water flux. Flow velocities of 10^{-4} cm sec^{-1} were readily measured. In addition to the point source instrument, *Byrne et al. [1968]* developed a line source instrument for measuring the flow of water in soil.

The thermocouple psychrometer uses the relationship between water potential and the ratio of actual and saturated vapor pressures, and papers on the use of the thermocouple psychrometer include those by *Rawlins and Dalton [1967]* , *Oster et al. [1969]* , and *Hoffman et al. [1969]* . *A* moisture flow meter was developed by *Cary [1968, 1970]* . *Additional* work on measuring devices was done by *Watson and Jackson [1967]* , *Weeks and Richards [1967]* , *Wendt et al. [1967]* , *Watson [1967b]* , *Cassel et al. [1968]* , *Selim et al. [1970]* ,and *Topp et al. [1967]* . *Klock et al. [1969]* used a mercury injection method to determine pore size distribution. Osmotic tensiometers were investigated by *Peck and Rabbidge [1969]* , and radioactive tracers were investigated by *Mokady and Zaslovsky [1967]* .

Probability statistics were used by *Brutsaert [1968a]* in the formation of a porous media model. The methods developed by Childs and Collis-George, and Marshall were then used to calculate the soil hydraulic conductivity. Experimental evidence gathered by *Greenberg et al. [1968]* shows a temperature dependence of the intrinsic permeability. They attribute this dependence to microstructural rearrangement in the matrix geometry of mediums having a rough or irregular surface texture. Similar experiments with smooth surfaced vitrified quartz showed no temperature effect. For orthotropic media (three mutually perpendicular planes of structural symmetry), it has been shown by *Szabo [1968]* that the Mohr circle representation of the transformation of the permeability components can be defined. Additional work on the quantitative relationship between hydraulic conductivity and the exchangeable sodium was done by *Yaron and Thomas [1968]* who present an empirical relationship based on experimental evidence.

In a series of papers, *Low et al. [1968a, 1968b]* develop thermodynamic methods for calculating from the water adsorption isotherms the change in unfrozen water content of a partially frozen soil with change in temperature at a constant pressure or with change in pressure at constant temperature.

Hysteresis is taken into account in numerical analyses of soil moisture movement by *Whisler and Watson [.1969], Remson et al. [1967],* and *Ibrahim and Brutsaert [1968]* .

The powerful numerical method of finite elements is used by many investigators [Volker, *1969; McCorquodale, 1970; Guymon, 1970; Javandel and Witherspoon, 1968]* to solve a variety of soil moisture movement problems.

Smith et al. [1967] , *Ligon [1969],* and *Ryhiner and Pankow [1969]* describe gamma radiation equipment that can be used in the field for the detection of changes in soil moisture. The main advantage of the gamma radiation equipment over the neutron method is that moisture changes in relatively small layers (1/2-inch thickness) can be detected.

Soil physicists are obviously taking more interest in soil moisture movement in swelling and shrinking soils as several papers *[Collis-George and Lal, 1970; Philip and Smiles, 1969; Smiles and Rosenthal, 1968; Philip, 1969a, 1969b]* have been published on this subject.

Probably the most comprehensive review of the physics of soil moisture movement is given in the *Proceedings of the Wageningen Symposium [International Association of Scientific Hydrology, 1968]*. Over 100 papers with authors from more than 40 countries cover the various facets of soil moisture including determination of soil moisture and soil moisture potential, determination of soil moisture properties, infiltration, mathematics of unsaturated flow, evaporation, soil moisture extraction by plants, water transport due to temperature gradients, and recharge of ground water.

Other excellent review articles include those of *Childs [1967]* on soil moisture theory, *Stallman [1967]* on flow in the zone of aeration, *van Schilfgaarde [1970]* on flow to drains, *Bear [1970]* on immiscible displacement, and *Groenevelt and Bolt [1969]* on nonequilibrium thermodynamics. Books devoted to the physics of soil moisture are those by *Childs [1969]* and *Bear et al. [1968]*.

The review given here is not complete and additional articles are given to indicate the areas in which research is being conducted.

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