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Soil Water

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Recent advances in developing methods to solve the equations governing combined saturated-unsaturated flow in two and three dimensions [*Freeze*, 1971; *Stephenson and Freeze*, 1974] have focused attention on the need to determine effective field values of the hydraulic properties of the soil. Because of natural variation from point to point, hydraulic properties for field-size units are difficult to characterize. A detailed field study was conducted by *Nielsen et al.* [1973] to determine the field variability of the hydraulic properties of the soil and to test various field methods of measuring these properties. They concluded that even seemingly uniform land areas manifest large variations in hydraulic conductivity. For a given point, methods for measuring the soil hydraulic properties will give values that are more accurate than those required to characterize an entire field because of the heterogeneity of the soil. Thus the ability to make predictions over a large area from soil properties determined at one location can range from good to unsatisfactory, depending on the prediction parameter of interest. Because of field variation in the hydraulic properties of the soil, simplified methods for calculating soil water flux and water contents during redistribution were found to be satisfactory when they were compared with more detailed numerical methods and with field measurements. Furthermore, when field variability is considered, simplified methods for measuring hydraulic conductivity or soil water diffusivity are sufficiently accurate for characterizing field conditions. The results of this study will have continued application in evaluating the worth of both simple and complex models for predicting water movement in the field.

Research is continuing toward developing, testing, and refining methods for calculating the hydraulic conductivity function from the soil water characteristic. *Jackson* [1972] compared prediction methods of *Marshall* [1958] and of *Millington and Quirk* [1959] for four soils. He found that when a matching factor at saturation was used, hydraulic conductivity could be calculated to within the limits of error of measurement. Comparison with field measurements for one soil showed that field hydraulic conductivity functions could be calculated reasonably by these methods, a conclusion also drawn by *Nielsen et al.* [1973] in the study discussed above. *Roulier et al.* [1972] were somewhat less successful in using these methods to calculate the hydraulic conductivities of field soils but found that the agreement between measured and calculated values was satisfactory when the matching factor was determined near the midpoint of the suction range of interest. *Bruce* [1972] found prediction methods worked reasonably well for coarse-grained soils but were less satisfactory for fine-textured soils with a wide pore-size range. *Campbell* [1974] used the same basic approach as Millington and Quirk but obtained a closed form expression for the conductivity function by assuming an empirical equation for the soil water characteristic. His methods worked well for five soils tested when a matching factor was used at saturation. *Sinclair et al.* [1974] predicted hydraulic conductivities with a Burdine-type equation and compared them with measured values for seven soils. *Skaggs et al.* [1973] presented an approximate method for determining the hydraulic conductivity function from the soil water characteristic and a measured infiltration rate-time relationship.

Thermal and osmotic effects on soil water movement are being analyzed with the methods of irreversible thermodynamics [*Kay and Groenevelt*, 1974; *Groenevelt and Kay*, 1974; *Joshua and de Jong*, 1973; *Banin and Low*,

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1971] or by more mechanistic approaches [*Kemper et al.*, 1972; *Harlan*, 1973].

Considerable progress has been made by Groenevelt and his co-workers in exploiting the irreversible thermodynamic approach. In their analysis they have distinguished between the microscopic continuum and macroscopic continuum points of view of a porous medium. Many who have attempted to apply the concepts of irreversible thermodynamics have not carefully recognized this distinction and have been led to incorrect formulations and interpretations of the transport equations. The review by *Groenevelt and Bolt* [1969] and two recent papers [*Kay and Groenevelt*, 1974; *Groenevelt and Kay*, 1974] report perhaps the best attempt that has been made to date in developing transport equations via irreversible thermodynamic concepts. In the latter two papers the interaction of water and heat transport in frozen and unfrozen soils is considered. Coupling between the two transports is related to the heat of vaporization, the heat of fusion, and the partial specific heat of wetting of the soil water. (It appears that the term 'coupling' is used to refer to two kinds of phenomena: (1) the contribution to the flux of water due to a thermal or solute gradient (and vice versa) and (2) the effect of the thermal or solute regime upon the transport coefficients for water movement. In this discussion, only the first kind of phenomena is considered.) An experimental study of the coefficients for coupled flow of heat and moisture was reported by *Jury and Miller* [1974]. Results were analyzed within the framework of the irreversible thermodynamic approach and also with the concepts of the theory of *Philip and de Vries* [1957]. The coupling coefficient for water flow due to a temperature gradient was found to be much larger than that predicted by the surface tension–based model of Philip and de Vries.

Krupp et al. [1972] combined the miscible displacement equation and Gouy double-layer theory to develop a model for salt flow through a soil column during miscible displacement. *Bresler* [1973*a*, *b*] developed a numerical simulation based on linking the diffusion-convection equation with a Darcy-type water flow equation for isothermal, unsaturated porous media flow. The model accounts for physicochemical interactions between solutes and the soil matrix by considering coupling effects and the mechanisms of convection, ionic diffusion, mechanical dispersion, and anion exclusion. *Bresler and Laufer* [1974] tested the Bresler model in the laboratory and numerically. Numerical tests indicated that osmotic gradients and anion exclusion effects are of minor importance in the upper parts of soils subjected to infiltration, redistribution, and evaporation.

Building on the work of *McLaren* [1969*a*, *b*, 1970, 1971] and *McLaren and Skujins* [1963], *Starr et al.* [1974] and *Misra et al.* [1974*a*, *b*, *c*] developed transport equations of the movement of various nitrogen species during leaching in unsaturated soils. The models simulate simultaneous nitrification and denitrification and stiochemetrically relate the transport and retention of nitrogen species in the gaseous phase to those in the liquid phase.

Cary and Mayland [1972] investigated salt and water movement in unsaturated frozen soil. Flux equations for water and salt, which included coupling coefficients for both flows, were proposed. It was emphasized that frozen unsaturated soil should not be considered as a static system. Not all the soil water freezes at temperatures commonly experienced in the field. Liquid films remain between the solid and ice phases, between the solid and air phases, and between the ice and air phases. Soluble salts are forced into these films. Liquid water and vapor tend to move from warmer to cooler areas. Much of the flow is in the liquid films. Thus solutes will also be carried from warmer to cooler regions.

Joshua and de Jong [1973] measured the coupling coefficients between heat and moisture flow. The results were analyzed by using the theoretical framework of irreversible thermodynamics and the Philip-de Vries theory. The agreement between the thermodynamic theory and the Philip-de Vries theory was satisfactory between 0.3- and 15-bar soil water suction. At suctions below 0.1 bar the Philip-de Vries theory predicted more coupling than was observed. Future work on coupled flows should consist of careful experiments on a variety of soil materials under a range of conditions to test the validity of the transport equations that have been proposed.

A more mechanistic approach to the analysis of osmotic flow in clays and soils has been taken by *Kemper et al.* [1972]. A theory was advanced to explain the nature and mechanism of osmotic flow in such media. According to the theory, solution concentration differences in incompressible media are translated into a hydraulic pressure gradient which moves the solution to the high-concentration side. Similar concentration differences in compressible media cause electro-osmotic movement of solution to the high-concentration side. The concepts outlined are relatively untested, and further investigation is necessary.

The effect of temperature on the pressure head, water content, and conductivity relationships of two silt loam soils was studied by *Haridasan and Jensen* [1972]. The temperature dependence of the pressure head-water content relation could not be explained on the basis of changes in surface tension of air-water interfaces. The observed increase in hydraulic conductivity at a given water content due to an increase in temperature was almost entirely accounted for by the decrease in viscosity of water.

The effect of solutes on the hydraulic properties of various materials has been examined by several investigators. *Elgabaly and Elghamry* [1970] measured hydraulic conductivity of kaolite as affected by adsorbed cations; *Naghshineh-Pour et al.* [1970] studied the hydraulic conductivity of several soils in relation to electrolyte composition; and *Shainberg and Caiserman* [1971] and *Shainberg et al.* [1971] studied the hydraulic conductivity and swelling pressure of Na/Ca montmorillonite systems. The hydraulic conductivity of axially loaded soils during cyclic calcium-sodium exchanges was measured by *Waldron and Constantin* [1970]. All these results shed partial light on the kinds of effects to be found, but a systematic treatment and coherent account of the effects of solutes on hydraulic properties are still lacking. In view of the recent increased interest in modeling of solute and water movement there is added motivation for obtaining better knowledge of these effects.

A very thorough experimental study of the soil water, chloride, and heat transport in the upper 10 cm of a bare field soil has been conducted by Jackson and his associates at Tempe, Arizona [*Jackson et al.* 1973; *Nakayama et* *al.*, 1973]. The time and depth patterns of soil water flux in this zone of the soil profile clearly displayed the dynamic nature of the flux. The applicability of theories of coupled heat, salt, and water flow to this situation is being examined.

Carter et al. [1971], in a noteworthy and monumental effort, studied the effect of irrigation return flow from an 82,030-ha (202,700-acre) tract into the Snake River. They sampled water diverted from the river and sampled return flow at many sites. They found that about 50% of diverted water was returned, that it was higher in nitrates and soluble salts than when it was diverted, but lower in PO_4-P. About 30% of the PO_4-P present in diverted water was returned. Applied fertilizer apparently did not leach. Subsurface drainage water contained about twice the concentration of soluble salts originally present in the irrigation water. NO_3-N concentrations increased several fold (to 3.24 ppm) in subsurface drainage water but were considerably below drinking water standards (10 ppm).

In most analyses of water flow in unsaturated soils it has been implicitly assumed that solutions of the flow equation are stable, i.e., that small perturbations in flow patterns will tend to disappear. With this assumption it is possible to describe infiltration by numerical and analytical techniques of solution of the soil water flow equation. The water content profile in the transition zone between the wet and dry regions depends on the hydraulic conductivity and water retention characteristics of the soil. Various experimental observations [*Hill and Parlange*, 1972; *Smith*, 1967; *Crosby et al.*, 1968; *Tabuchi*, 1961] and theoretical considerations [*Saffman and Taylor*, 1958; *Wooding*, 1971] show that the stability assumption is not always justified. When infiltration occurs in a layered soil in which the upper layer is finer and less conductive than the coarser layer beneath, the wetting front becomes unstable and breaks into narrow wetting columns or 'fingers.'

The Green and Ampt model of infiltration [*Green and Ampt*, 1911] has recently been employed by *Raats* [1973*a*] to develop criteria for stability of the wetting front in uniform and nonuniform soils. Instability due to an increase of air pressure ahead of the wetting front was observed by *Peck* [1965] and is predicted by the theory developed by Raats. Instability is also indicated by Raats' theory during infiltration of nonponding rainfall into soils with a narrow range of pore sizes and during ponded and nonponded infiltration into soils in which the conductivity increases with depth.

The stability of the flow is of fundamental importance in problems involving recharge to the water table and movement of pollutants. If the front is unstable, one-dimensional solution of the water flow equation cannot be used to predict the percolation. Stability considerations should play a large role in soil water flow studies in the future.

In the period since 1970, investigators have continued to take advantage of the increasing power of the digital computer to study flow of water in porous media. Recent studies have advanced knowledge of flow processes by studying increasingly less simplified systems. Two phenomena receiving increasing attention are the interrelation of air flow and water flow and flow in a swelling medium.

Much work on describing two-phase (air and water) flow systems has taken place at Colorado State University. Concentrating on the infiltration process, *Brustkern* [1970] employed a Buckley-Leveritt approximation from oil technology to approximate the effect of air on infiltration. The four equations (flow of air and water and conservation of mass for air and water) were programed for finite difference solution by Phuc [*Phuc and Morel-Seytoux*, 1972]. His results agreed in principle with those of Brustkern, indicating significant reduction in infiltration capacity under conditions of limited vertical distance to an impermeable boundary. A characteristic drop and rise in infiltration rate when air counterflow occurs (exits at the surface) was also shown [*Morel-Seytoux*, 1973]. A different mathematical approach was used by *Noblanc and Morel-Seytoux* [1972], in which the flow process was studied by considering zones in which certain simplifying assumptions could be made without major error. The resulting procedure allowed numerical solution involving an integral equation and matching solutions at the solution zone interface.

Excellent experimental demonstration of the nature of the effect of air flow on infiltrating liquid flow was given by *McWhorter* [1971]. Analytical solution for horizontal flow and approximate solutions for vertical flow under several boundary conditions were also developed. The experimental work included a careful study of infiltration into various closed column lengths of sand. Shorter columns exhibited the theoretically predicted early drop and recovery of infiltration rate.

It seems fair to say that characterizing hydrodynamics of two-phase porous media flow involves (1) obtaining information on those conditions in which the gas phase cannot be neglected and (2) obtaining efficient methods to calculate water movement, almost always the item of practical interest in those cases. The physics of the role of two-phase flow are rather easily described in partial differential terms. It is the recognition of sensitivity, relative magnitude of effects, and efficiency of methods of calculation that now concern the investigators. From the progress to date, it appears that continuing study will better show (1) which soil conditions will necessitate two-phase calculations for infiltration and drainage computations, (2) those assumptions about the properties of the soil and soil air to which calculation of time and extent of air counterflow are most sensitive, and (3) mathematical approximations and simplifications for modifying older infiltration rate formulas to account for air effects.

Progress has been made in characterizing the effect of a swelling soil medium on its pattern of imbibition of water [*Philip*, 1971*b*, 1972; *Smiles*, 1974; *Groenevelt and Bolt*, 1972; *Sposito*, 1973]. Again the theoretical description of water movement and distribution in a soil whose swelling nature is well defined by a relation of void ratio, porosity, and pressure can easily be laid out in partial differential relations. Useful in this respect is the use of a material coordinate system which expands with the swelling media. Results to date have demonstrated that swelling acts counter to gravitational effects, thus reducing vertical infiltration to a phenomenon more resembling capillary rise. The key to use of results to date is, of course, the ability to characterize the swelling relations of the soil. Problems of complexly stratified swelling systems are yet to be dealt with.

In the field, soil water flow occurs in a cyclic manner with periods of drainage, redistribution, and evaporation alternating with periods of wetting. The flow involves the phenomenon of hysteresis. The boundary conditions are time dependent. Analytical methods for solution of the water flow equation under these circumstances are not available, although certain bounds and limits on the behavior of the solution can be developed [*Philip*, 1973]. Numerical solution techniques offer the possibility of examination of some of the detailed flow behavior of flow systems with time-dependent boundary conditions. Soil water pressure head and the development of the profiles of water content were examined by a numerical solution scheme for the Richards equation of soil water flow [*Klute and Heermann*, 1974]. Hysteresis in the water content-pressure head relation was incorporated into the solution procedure. An arbitrary sinusoidal variation of pressure head at the soil surface was imposed. The wave forms of water content, pressure head, and flux exhibited a progressive increase in phase lag and decrease in amplitude with depth. The highly nonlinear soil water flow system introduced a high degree of harmonic distortion into the response of the system to the applied boundary condition. Further work along these lines should (1) examine the behavior of the profiles in a range of soil materials, (2) make use of better methods of representing and incorporating hysteresis into the solution scheme, (3) utilize a periodic boundary condition involving evaporation, and (4) investigate the possibilities (if any) of analytic approaches to problems of this kind.

One of the significant developments in the soil water research of the past 4 yr was the application of the integral method to the solution of the soil water equation. This is a quasi-analytic method in that solution by successive approximations is necessary. The number of approximations required is few, however. *Parlange* [1971*a*, *b*, *c*, 1972*a*, *b*, *c*, *d*, *e*, 1973] and *Parlange and Aylor* [1972] applied the method to a variety of flow situations including one-, two-, and three-dimensional adsorption and infiltration under both steady and transient conditions.

Knight and Philip [1973], however, found that the second- and higher-order approximations in Parlange's method do not satisfy continuity requirements. As a consequence, higher-order approximations oscillate with increasing amplitude about the exact solution. They conclude that the utility of Parlange's method is that of the first approximation and that the method cannot be applied to the two- and three-dimensional cases unless they are radially symmetrical.

For the one-dimensional absorption case, *Philip and Knight* [1974] developed a quasi-analytical solution similar to Parlange's but preserving continuity in higher-order approximations. The next few years will probably see continuing development of these methods.

An analytical, as compared with a numerical, solution of the flow equation for a particular application is quite valuable in that it yields a general description of the flow situation of interest. That is, one may study with relative ease the effects of making changes in hydraulic boundary condition and of changing dimensions of the flow regions. A number of analytical solutions have appeared recently. For example, *Raats* [1970, 1971, 1972], *Philip* [1971*a*, 1972], and *Zachmann and Thomas* [1973] have developed such solutions for steady seepage from point and line sources, cavities, and basins. *Warrick* [1974] and *Lomen and Warrick* [1974] have contributed solutions for unsteady flows from point and line sources. These solutions yield matric flux potential, stream functions, and total hydraulic head distributions for flows of significance to furrow and subsurface irrigation. These solutions also provide a basis for the discussion of leaching under irrigation.

Warrick [1970], *Morin and Warrick* [1973], *Warrick and Lomen* [1974], and *Selim and Kirkham* [1972*a*, *b*] have approached hillside seepage from an analytical standpoint. Under saturated conditions there may be several alternating zones of infiltration and exfiltration from the top to the bottom of a slope.

Raats [1973*b*] has reported on steady upward and downward flows. He demonstrates a maximum upward flux for a given depth of water table and also describes the two types of downward flow that can occur in the zone immediately above an interface between two soil layers.

Analytical models cannot be developed for all porous media flow situations, and so it is often necessary to rely on numerical methods. Recent years have seen noteworthy progress in the application of the finite element method to porous media flow problems [*Guymon et al.*, 1970; *Guymon*, 1972; *Cheng and Li*, 1973; *Rubin and James*, 1973; *Neuman*, 1973].

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