Edgar Buckingham became involved with soil physics for 5 yr at the turn of the twentieth century. His general goal was to advance understanding of moisture movement and evaporation from soils to improve irrigation and crop management. Specifically, he was interested in elucidating why evaporation from near the soil surface in arid areas during summer months was self-limiting (Buckingham, 1907; Narasimhan, 2005). Based on carefully conducted evaporation experiments from soil columns, and influenced by Fourier’s heat equation, Buckingham formulated a conceptual model for soil-moisture movement and presented his ideas a century ago in his celebrated work *Studies on the Movement of Soil Moisture* (Buckingham, 1907). The history, content, and relevance of this contribution has been addressed by many (e.g., Nimmo and Landa, 2005; Narasimhan, 2005).

On the centenary of Buckingham’s seminal contribution, the purpose of this paper is to reexamine the central ideas of Buckingham’s paper and reflect on how his conceptual model for moisture movement in soils has withstood time.

**Buckingham’s Central Ideas**

Buckingham performed a large number of soil-column experiments to understand evaporation from the soil surface. Some of these experiments lasted for as long as 441 d. One set of the experiments was designed to simulate capillary rise of water from the water table to the land surface, before evaporating under solar heat. These experiments provided him an observational base to develop a conceptual model for moisture flow in soils. Buckingham’s ideas on soil evaporation have been discussed in Narasimhan (2005).

Buckingham was a well-trained physicist, who had earlier written a book on thermodynamics (Buckingham, 1900). In his work on soil-moisture movement, Buckingham was influenced by Fourier’s work on heat flow (Fourier, 1822) and Ohm’s work on galvanic current (Ohm, 1827). Besides Fourier’s Law and Ohm’s Law, he knew of Poiseuille’s Law for water flow through capillaries (Poiseuille, 1846). Nevertheless, if he were to have solely relied on the mathematical forms of Fourier and Ohm, he would simply have used heat and electricity as metaphors for soil moisture. Instead, Buckingham innovatively sought a dynamical model that would account for the energetics of soil-moisture movement. In this he was likely inspired by Maxwell (1872), who, in his *Theory of Heat*, had used the notion of a fluid poten-
tional. Lyman Briggs, Buckingham’s colleague in the USDA laboratory, had already drawn on Maxwell’s treatise in applying ideas on capillarity to soils (Briggs, 1897).

Having decided on a dynamical approach, Buckingham looked for a mechanical potential that would be mathematically analogous to temperature. This potential had to serve two functions. First, it needed to have a well-defined relation to moisture content of the soil, so that the slope of the relation would be soil-moisture capacity, analogous to specific heat. Second, the spatial variation of the potential had to drive moisture in the direction of decreasing potential. Implicit here is the notion that heat (an extensive quantity) is analogous to the quantity of moisture. Accordingly, Buckingham (1907, p. 29) stated, “We shall assume that if we could, by purely mechanical means, pull a definite mass of water away from a definite mass of moist soil of a given moisture content, we should have to do a definite amount of mechanical work; and if we then let the water and the soil come together again in obedience to their mutual attraction, we should, in principle at least, and if we could construct appropriate mechanism, be able to get back the same amount of work that we had to do in separating the water from the soil. This amounts to assuming that the attractive forces between the soil and the water are conservative, or that they have a potential.” Thus, Buckingham assumed that the hydrophilic forces between water and soil were reversible, and consequently, that the postulated potential is a conservative energy potential.

Buckingham’s next task was to establish a relation between capillary potential and moisture content. Unfortunately, he did not have any direct way of measuring capillary potential. He ingeniously got around this difficulty by noting that in a vertical hydrostatic unsaturated soil column, gravity and capillary forces will exactly balance each other at every location, and that elevation above datum in such a soil column is a proxy for capillary potential. Accordingly, he showed that capillary potential and elevation above water table are related by a constant multiplier, A. This reasoning enabled him to present the first-ever soil-moisture retention curves (Fig. 1).

One can recognize that the slope $d\theta/d\psi$ of these curves, where $\theta$ is water content and $\psi$ is capillary potential, is analogous to specific heat. However, Buckingham noted that, unlike specific heat, which is considered to be independent of temperature in Fourier’s model, $d\theta/d\psi$ is a strong function of capillary potential. He also noted that equilibration of moisture content and capillary potential may take a long time and that “It appears probable, on the whole, that in all the experiments mentioned, where the duration was not more than about two months, the final state of equilibrium had by no means been reached, and that such experiments should be run much longer” (Buckingham, 1907, p. 38).

The next task of experimentally establishing a moisture conductivity was more challenging because Buckingham had not found a way of measuring capillary potential. Therefore, he was content to merely formulate a conceptual framework for conductivity in an unsaturated soil.

In Buckingham’s visualization, the water phase in a partially saturated soil formed menisci at the contacts between soil grains, with the curvature concave toward the nonwetting air phase, assumed to be under atmospheric pressure everywhere. On the convex side of the menisci, water-phase pressure was less than atmospheric, with the pressure difference between the air phase and the water phase increasing with increasing meniscus curvature. Away from the contacts, water was visualized as forming a thin film on the soil-grain surface. At high water saturations, Buckingham imagined significant quantities of water forming continuous pathways for “water-in-mass” through water-filled capillaries. With decreasing wetness, however, some of the capillary pathways would be replaced by films of water on the soil grains connecting neighboring menisci. If neighboring menisci had different curvatures, water would flow along the films from the meniscus with large radius to one with small radius, with atmospheric pressure forcing water out of the films into the drops. Under moderate saturations, there would be some water-in-mass flow through connected capillaries and film flow elsewhere. At low saturations, film flow will dominate. At even lower saturations, films may break, thus disrupting connections between neighboring menisci and causing practical cessation of any liquid-phase flow.

This visualization led Buckingham to conclude that capillary conductivity $\lambda$ will be a strong function of water content $\theta$ in a soil. He conjectured that the relation would have the shape indicated schematically in Fig. 2. Between A and B, flow occurs dominantly through saturated capillaries. Between B and C,
capillary flow and film flow coexist. Between C and D, flow is exclusively through films. Between D and F, films progressively break up. Buckingham was careful to recognize that the slopes and the lengths of the different segments will vary from soil to soil. Assuming that in moderately saturated soils, resistance will be dominated by the films, Buckingham derived the following mathematical form for the \( \lambda - \theta \) relation:

\[
\lambda(\theta) = \frac{\alpha \beta}{\sqrt{\theta_1 - \sqrt{\theta}}}
\]  

where \( \alpha \) and \( \beta \) are constants depending on pore geometry and \( \theta_1 \) is saturated moisture content. For \( \alpha \beta = 1 \) and \( \theta_1 = 1 \), this curve was shown to have a shape compatible with Fig. 2, concave upward.

Although Buckingham had experimental values of soil-moisture capacity in the form of the slope \( \frac{d\psi}{d\theta} \) of the moisture retention curve, and a conceptual understanding of capillary conductivity, \( \lambda \), he was quite skeptical about combining these into a diffusion equation for transient soil-moisture movement by analogy with Fourier's heat equation. Buckingham's skepticism arose from his recognition that the mathematical power of the heat equation came from Fourier linearizing the differential equation by assuming that both thermal conductivity and specific heat were independent of temperature. This was physically reasonable because thermal conductivity and specific heat are but weakly dependent on temperature, especially over small temperature variations. Clearly, the dependence of soil moisture capacity and capillary conductivity on moisture content were found to be so strong that Buckingham concluded that a diffusion equation for soil moisture movement could not be linearized.

It is interesting that Buckingham did not present a diffusion equation for soil-moisture movement. He had all the physical and mathematical information necessary to write down what Lorenzo Richards would do almost 25 yr later. Instead, he expressed his perception this way: “If we knew the mathematical forms of \( \psi \) and \( \lambda \) as functions of \( \theta \), and of \( \theta \) as a function of \( x \), it is possible, though not probable, that we could give a complete mathematical treatment of the subject” (Buckingham, 1907, p. 51).

In summary, four ideas can be identified as being central to Buckingham’s work. These are the concept of a capillary potential, the soil-moisture retention curve, the concept of capillary conductivity, and the recognition that soil-moisture movement cannot be represented by a linear partial differential equation such as Fourier’s heat equation.

**Current Understanding**

**Capillary Potential and Soil-Moisture Retention**

The concept of capillary potential, first conceived by Buckingham a century ago, continues to play a fundamental role in modern theory of soil-moisture movement. Yet Buckingham did not present a method for physically measuring that quantity. Subsequent introduction of the tensiometer by Gardner et al. (1922) enabled the measurement, in natural soils, of a quantity variously referred to as moisture suction or moisture tension, or matric potential, which helped Richards (1931) formulate the nonlinear partial differential equation that is widely used today. It is therefore of philosophical interest to examine how Buckingham’s abstract concept of a capillary potential relates to what is observationally quantified with the tensiometer.

Buckingham recognized that to satisfy the needs of an equation of motion, a potential must be a conservative quantity in that its integral must identically vanish over a closed path in space. Accordingly, Buckingham assumed that capillary potential, defined as work done against the water–solid attractive forces, was a reversible process. He stated: “This amounts to assuming that the attractive forces between the soil and the water are conservative, or that they have a potential. It is obvious that a rigorous treatment of the subject, with no restrictions imposed on either the water content or the soluble salt content of the soil, would have to use thermodynamic reasoning. But the simple conception of a mechanical potential will suffice for present purposes, though it is not impossible that with more comprehensive experimental data available, we should have to use thermodynamic potential or free energy” (Buckingham, 1907, p. 29).

It is useful here to compare Buckingham’s concept of a mechanical potential for an unsaturated soil with the analogous concept for saturated groundwater flow. In “The Theory of Ground-Water Motion,” Hubbert (1940) defined an energy potential \( \Phi \) with dimensions of energy per unit mass as

\[
\Phi = gz + \int_{p_0}^{p} \frac{dp}{\rho(\rho)}
\]

where \( g \) is gravitational acceleration, \( z \) is elevation above datum in the gravitational field, \( p \) is water pressure, and \( \rho \) is density of water. The integral on the right-hand side denotes change in the amount of stored elastic energy in a unit mass of a slightly compressible fluid as it is moved in a pressure field from \( p_0 \) to \( p \). Hubbert pointed out that in order that \( \Phi \) be conservative and path independent, \( \rho \) must be a function exclusively of pressure, assuming that the groundwater system is isothermal, and having chemical composition that remains spatially constant. Hubbert illustrated the concept with a pressure-versus-volume diagram and a thought experiment involving extraction of a unit mass of water from a location of elevation \( z = 0 \) and pressure \( p_0 \), and transporting that mass to a elevation \( z \) and pressure \( p \). Here, the \( p \)-versus-\( p \) relation constitutes the equation of state for water, a homogeneous substance. Implicit in this equation of state is the assumption that the density-pressure relation is fully reversible and that density equilibrates instantaneously to any change in pressure, without time lag.

With Hubbert’s conceptualization of potential as an example, we may examine Buckingham’s capillary potential. While Hubbert’s potential pertains to water, a homogeneous substance, Buckingham’s capillary potential is specific to a heterogeneous water–solid–air system. Hubbert’s potential pertains to work involved in “pulling a definite mass of water” existing at pressure \( p \) or density \( \rho \) from a mass of water. But capillary potential pertains to work involved in “pulling a definite mass of water away from a definite mass of moist soil of a given moisture content.” Whereas Hubbert’s energy potential solely involves the permeant, water, capillary potential involves a complex heterogeneous system involving water as well as soil grains.

We may now consider the nature of mechanical work involved in the two cases. In a water-saturated soil, the work
involved in transporting a unit mass of water from pressure \( p_0 \) to \( p \) involves elastic energy associated with a slightly compressible fluid. This elastic energy constitutes the integrand \( dp/\rho \) in Eq. [2]. It could also be represented equivalently as \( V^*dp \), where \( V^* \) is volume per unit mass of water (specific volume). In a partially saturated soil, the work involved in transporting a unit mass of water from a given moisture content to another involves surface tension at the water–air interface. By definition, surface tension represents energy stored per unit area of the interface. Therefore, to quantify the work involved in removing from or adding a unit mass of water to a definite mass of soil at a given moisture content, one has to sum up the energy stored in the many discrete curved menisci contained in the definite mass of soil at the location of interest.

The theory of capillarity is based on Laplace's equation,

\[
p_{\text{air}} - p_w = \frac{2\gamma \cos \theta}{R}
\]  

where \( p_{\text{air}} \) is air-phase pressure, assumed to be atmospheric, \( p_w \) is water-phase pressure, \( \gamma \) is surface tension, \( \theta \) is contact angle, and \( R \) is the radius of the capillary. If atmospheric pressure is taken to be the datum and set to zero (gage pressure), then, \( p_w \) is less than zero. It is seen from Eq. [3] that the energy stored in the interface is a function of water-phase pressure, pore radius, and contact angle.

Buckingham made an important assumption that the work involved in pulling a given mass of water away from a moist soil is fully reversible in order that capillary potential may be conservative. This assumption was shown to be unrealistic for natural soils in an important contribution by Haines (1930), who experimentally established hysteresis in the soil-moisture retention curve. In explaining hysteresis, Haines contributed the fundamental insight: “[T]he mode of moisture distribution in soil does not give reversible conditions but leads to two main values of capillary pull. The case of falling moisture tends to be governed by a higher value of pressure deficiency as determined by the narrower section of the pores, while conditions of wetting or increasing moisture tend to be governed by a lower value depending on the wider sections of the pores. In other words, it is found that a granular system, of which soil is typical, will in general offer a greater capillary pull against the extraction of water from its pores than it can engender when absorbing water into them” (Haines, 1930, p. 98).

Haines' observational inference of irreversibility of work done has important implications. In a natural soil, it is to be expected that pore geometry will be spatially variable; this would be manifested in spatial variations in the sizes and distribution of menisci. Under such conditions, a given water-phase pressure will be associated with a higher moisture content when water is removed or drained in comparison to addition or imbibition of water. Because natural soils are invariably subjected to periodic changes in wetting and drying cycles, and in view of Buckingham's observations that soil-moisture retention curves can take many months to equilibrate, effects of hysteresis must normally be expected to be present in such soils. Also, spatial variations in mineralogy, especially organic content, will cause local changes in contact angle. An important factor that contributes to irreversibility of work done is heat of wetting, that is, the liberation of heat when a dry soil imbibes water (Edlefsen and Anderson, 1943). For these reasons, the integral of work done along a closed path in a natural soil will not be zero. In other words, a conservative capillary potential, as conceived by Buckingham, cannot exist.

An advantage in defining a potential is that it helps combine gravity and pressure effects into a single quantity. In groundwater systems, for example, one commonly combines elevation head and pressure head to arrive at the single quantity, hydraulic head. Hubbert's theoretical work showed that this summation of gravity and pressure effects is possible only if a conservative potential can be shown to exist. However, in nonisothermal systems or in systems in which salt concentrations vary significantly in space, where density is a function of temperature or salt concentration in addition to pressure, one cannot combine gravity effects and pressure effects into a single quantity, such as hydraulic head. In such systems, one is constrained to estimate separately fluid fluxes due to gravity and pressure variations, and combine them to get the total flux. In view of this, if a conservative capillary potential does not exist in a natural soil, then can gravity effects be combined with pressure effects? Finding an answer to this difficult question must involve, among other things, the behavior of water density when water is present under tension in capillaries and as thin films under tension on surfaces.

The foregoing discussion shows that as one passes from the compressive water regime of a saturated soil to the tensile moisture regime of an unsaturated soil, the mechanical nature of water changes drastically. This was discovered independently in the soil mechanics literature. Terzaghi (1923) studied the deformation of water-saturated clays under conditions of drainage, and formulated a theory of soil consolidation. Central to his theory was the concept of effective stress. For the simple case of vertical loading with no lateral strain, Terzaghi defined effective stress as

\[
\sigma' = \sigma - \rho
\]  

where \( \sigma' \) is effective stress, \( \sigma \) is total stress or external stress, and \( \rho \) is water pressure. This equation implies that a decrease of \( x \) units of water pressure causes an \( x \)-unit increase in effective stress. Bishop and Blight (1963) experimentally investigated the applicability of Terzaghi's effective stress principle to unsaturated soils under conditions of drained loading. They discovered that whereas any change in water pressure is fully converted into a change in effective stress of equal magnitude in the saturated zone, such was not the case in an unsaturated soil. Only a fraction of the change in water pressure in the unsaturated state was converted to effective stress. To account for this, they modified Terzaghi's effective stress equation to read

\[
\sigma' = \sigma - \chi \rho
\]  

where \( 0 < \chi < 1 \) is an empirical parameter that is a function of water saturation or moisture content. They found that \( \chi \) falls rather rapidly with saturation, as shown in Fig. 3.

In those parts where a soil pore is completely filled with water under compression, one can readily visualize water pressure interacting mechanically with pore deformation by way of a change in pore size. If the pore is filled with air and is surrounded by water films and menisci, however, water pressure will not any-
That is, solute transport in liquids is a binary diffusion process. In liquids, the solute moves in the direction of its decreasing concentration. This is analogous to pure diffusion involving random movement of unattached molecules. As yet, little is known about this mode, which involves bulk movement of the solvent–solute mixture in a given direction. Remarkably, similar differences in modes of gas transport had been established a decade earlier in Scotland.

Graham (1833) studied the simultaneous diffusion of several gases through a porous material at constant pressure and proposed that the diffusion of a gas under its own concentration variation is inversely proportional to the square root of its density. This finding is referred to as Graham’s Law. A decade later, Graham (1846) investigated the flow of gas mixtures through capillary tubes and found that this bulk movement, which he referred to as tranpiration, was driven by spatial variation of total gas pressure and did not conform to the law that he had proposed earlier. Essentially, Graham had established two distinct modes of gas transport. He had also discovered in his earlier work that the two modes were coupled together during diffusion of gas components in opposite directions, and that due precautions must be taken to maintain constant total pressure so as to eliminate bulk motion (tranpiration) and investigate pure diffusion. This subtle observation was overlooked for nearly a century until the coupling was experimentally confirmed by Kramers and Kistemaker (1943).

In view of the foregoing, it is reasonable to infer that water movement associated with molecular diffusion (commonly referred to as osmotic water transport) is a mode of transport that is different from the bulk movement of water and dissolved solute. Capillary moisture conduction in soils, it is fair to assume, involves viscous flow accompanied by transport of any dissolved solutes in the direction of bulk water movement. Fick’s work suggests another complicating factor. If, as Fick pointed out, concentration gradients exist along the axis of a pore and along the plane of cross-section of a pore because of preferential flow of water along the walls of the hydrophilic pore surface, the flow will be organized in some complex fashion, with separation of the solvent and segregation of the solute. Under these conditions, it is hard to imagine what the relationships might be between capillary potential and osmotic potential, and whether they can simply be summed up so as to define a total potential. Indeed, the mode of water movement in binary diffusion appears to be unique in nature, being neither viscous flow nor analogous to pure diffusion involving random movement of unattached molecules. As yet, little is known about this mode, except for the insightful speculations of Dutrochet (1827) and Fick (1855). Discussions with Ronald Gronsky, a specialist in electron microscopy, indicate that it may be physically possible to image the movement of the water component associated with

![Graph](image)

Fig. 3. Dependence of the parameter \( \chi \) on water saturation (Bishop and Blight, 1963) (reproduced with kind permission of Geotechnique).
molecular diffusion using high intensity tunable soft X-ray beams that are part of the Advanced Light Source machine (Gronsky, personal communication, 2006). Until we know clearly the specific attributes of viscous flow, diffusional transport, and water movement associated with binary transport, we may not be in a position to decide if capillary potential and osmotic potential are additive or not.

Hydraulic Conductivity

Unable to experimentally measure capillary conductivity $\lambda$, Buckingham was content to provide conceptual insights into how it may vary with moisture content, $\theta$. He reasoned that moisture movement in soils must involve a combination of water-in-mass capillary flow and film flow. Building on this conceptualization, he presented his conjecture on what the relation between $\lambda$ and $\theta$ might be (Fig. 2). Voluminous soil hydraulic conductivity data now exist not only confirming Buckingham's conjecture of the form of the functional dependence but also showing that the $\lambda$-versus-$\theta$ relation is strongly hysteretic (Mualem, 1976).

In 1856 the concept of a hydraulic conductivity for earth materials was empirically introduced by Henri Darcy (1856) as a linear relationship between water flux and hydraulic gradient. Since then, Darcy's Law has had such a powerful influence in the earth sciences that the relationship between moisture flux and capillary potential proposed by Buckingham is commonly referred to as Darcy's Law, or merely a variant of it. That is, for horizontal flow the equation would be

$$q = \frac{Q}{A} = -\lambda(\psi) \frac{d\psi}{dx} \tag{6}$$

where $q$ is specific flux or flux density, $Q$ is volumetric flow per unit time, and $A$ is the cross-sectional area. One consequence of using Eq. [6] based on Darcy's Law is the perception that one can explicitly calculate $q$ or $Q$ by knowing the gradient $d\psi/dx$. Unfortunately, gradient is not a directly measurable quantity. It is an abstract, infinitesimal concept. What can be measured with an instrument is pressure or tension at a discrete location. To express flux in terms of such discrete observational data, it is useful to dispense with gradient and express flux in the form of Ohm's Law. That is, neglecting gravity in an unsaturated soil,

$$Q = \frac{\psi_{\text{in}} - \psi_{\text{out}}}{R_{\text{inlet,outlet}}} \tag{7}$$

where $Q$ is the steady-state volumetric flow per unit time through a flow tube of variable cross-section $A$, $\psi_{\text{in}}$ and $\psi_{\text{out}}$ are capillary potentials held constant over the inlet and outlet surfaces of a flow tube, and $R_{\text{inlet,outlet}}$ is the hydraulic resistance between inlet and outlet defined as

$$R_{\text{inlet,outlet}} = \int_{x_{\text{inlet}}}^{x_{\text{outlet}}} \frac{dy}{\lambda(y)A(y)} \tag{8}$$

where $x_{\text{inlet}}$ and $x_{\text{outlet}}$ are coordinates of inlet and outlet along a flow line chosen as a curvilinear $x$ axis, and $A(x)$ is the area of the isopotential surface passing through $x$. Note that $\lambda$ is commonly assumed to be a function of $\theta$ or $\psi$ but that in the integral in Eq. [8], $\lambda$ occurs as a function of the spatial coordinate. For this reason, given the boundary conditions $\psi_{\text{in}}$ and $\psi_{\text{out}}$, $Q$ cannot be explicitly evaluated. It can be evaluated only iteratively. Only in the special case where $\lambda$ is exponentially related to $\psi$, and where $A$ is independent of $x$ can $Q$ in Eq. [8] be evaluated explicitly. Conversely, if one desires to estimate conductivity from data on observed fluxes under known boundary conditions, then one has to a priori assume mathematical form for $\lambda$. In this case, the estimates for the dependence of $\lambda$ on $\psi$ are necessarily nonunique.

Thus, the relation between flux and spatial variation of capillary potential in an unsaturated soil is quite complex. The classical laws of Fourier (heat), Ohm (electric current), Fick (molecular diffusion), and Darcy (water in porous media) are all linear flux laws that assume that flux can be explicitly calculated if the spatial difference of the appropriate potentials between inlet and outlet are known for a flow tube of uniform cross-section. Buckingham conjectured that moisture movement in a soil cannot conform to such a linear flux relation. His conjecture has since been proven correct. Hence, it is not appropriate to refer to the nonlinear flux law of moisture movement in soils as Darcy's Law.

Diffusion Equation for Soil-Moisture Movement

Having established a relation between $\theta$ and $\psi$, and having conjectured a relation between $\lambda$ and $\theta$, Buckingham could have readily written down the nonlinear partial differential equation for transient unsaturated flow of water in a soil. That he did not may perhaps be attributed to his belief that even if $\lambda$ and $\psi$ were known as functions of $\theta$, it was improbable that a complete mathematical treatment of the subject could be achieved (Buckingham, 1907, p. 51). There are two aspects to Buckingham's skepticism, one mathematical and the other philosophical.

The first attempts to solve the nonlinear partial differential equation for transient soil-moisture movement were made during the 1950s by Klute (1952) and Philip (1956). In the following five decades, many developments have taken place in the theory of nonlinear partial differential equations. Yet, in applying these developments to soil-moisture movement, success has been limited to a narrow class of problems, with simple geometries (mostly one-dimensional), comprising a single material. Whereas the relationships among $\theta$, $\lambda$, and $\psi$ are characterized by nonlinearity and nonuniqueness (hysteresis), the solution methods have to assume single-valued (though nonlinear) relationships among these variables, with specific functional forms. Solutions generated for such conditions have definitely advanced our understanding of soil-moisture movement by providing semiquantitative insights on patterns of soil-moisture movement. Nevertheless, these methods cannot solve realistic multidimensional field-scale problems characterized by heterogeneities, arbitrary initial and boundary conditions, and $\lambda$-$\theta$-$\psi$ dependences that have arbitrary mathematical forms.

With the advent of digital computers, numerical models have become increasingly available over the past three decades to solve unsaturated flow problems that cannot be handled analytically. These models are better suited for handling multidimensional heterogeneous systems subject to arbitrary initial and boundary conditions. Nevertheless, their utility is hampered by sparsity of data on system geometry, material distribution, initial conditions, boundary conditions, and hydraulic parameters that are appropriate for the field scale. Although computer outputs can provide numbers of great precision, the solutions them-
selves are only of semiquantitative, heuristic value that must be thoughtfully interpreted by a discerning mind.

Philosophically, Buckingham’s skepticism raises the issue of the role of mathematics in the earth sciences. Milton Whitney, who led the Bureau of Soils and who had the vision to bring in talented physicists such as Briggs and Buckingham, believed that soil physics problems were so complex that they should not be handled strictly mathematically (Landa and Nimmo, 2003).

Concluding Thoughts

Our present ability to observe moisture movement in soils is still mostly restricted to the measurement of moisture tension with tensiometers. In dry soils, where tension exceeds an atmosphere in magnitude, devices based on vapor pressure measurements are used. These are the only types of measurements that are available for deciphering forces that drive moisture movement. Additionally, estimation of in situ soil-moisture contents and their temporal variations have become feasible through the use of neutron logging or time-domain reflectometry. Although the design of tensiometers has been refined significantly over the years, moisture tension measured at a location has inherent uncertainties. It represents some average magnitude of the pressures of many menisci that exist in the vicinity of the porous cup. The size of the region sampled by a given tensiometer is a function of the size and properties of the porous cup, as well as the time of equilibration of the instrument. Although moisture contents can be estimated in situ with the help of neutron probes or time-domain reflectometry, these measurements cannot be used to estimate magnitude and direction of fluxes.

Observationally describing the distribution of moisture content and moisture tension in an unsaturated soil in sufficient detail to estimate fluxes, changes in moisture tension, and moisture content is therefore beset with imprecision. Furthermore, Richards’ equation, based on single-valued relationships among λ, θ, and ψ is only an approximate and simplified representation of what is in fact a very complex natural process. Thus, even the best mathematical tools available to us have the ability to only explain patterns of observed behavior of soil-moisture movement in some semiquantitative manner. These tools can provide only clues and insights on expected patterns of behavior. In essence, there are limits to what mathematics can do to describe soil-moisture movement quantitatively. Mathematics cannot be expected to produce results that are more precise than the detail with which earth systems can be observationally described. In this sense, Buckingham’s skepticism remains very much valid a century later.

It is appropriate to conclude with a thoughtful remark attributed to Ansel Adams, the renowned landscape photographer and conservationist: “There is nothing more disturbing than a sharp image of a fuzzy concept.”

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References


Dutrochet, R.J.H. 1827. New observations on endosmosis and exosmosis, and on the cause of this dual phenomenon. Annales de Chimie et de Physique 35:393–400.


