Published online May 13, 2005

Buckingham, 1907: An Appreciation

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ABSTRACT

Nearly a century ago, Edgar Buckingham published a seminal work on the movement of soil moisture that is part of the foundation of modern soil physics. It also constitutes a pioneering contribution in the study of multiphase flow in porous media. A physicist, Buckingham took on an earth science issue of importance to society and produced superb basic science as a byproduct. Buckingham impresses us with his ability to combine experiment and theory and his capacity to intuitively explain difficult ideas to a wide audience. Science progresses both by gradual accretion of knowledge and by sudden influx of ideas. Buckingham's contribution belongs in the latter category. After a brief, four-year rendezvous with soil science, he went on to pursue a long and distinguished career in physics with the National Bureau of Standards. This paper is an appreciation of Buckingham's contribution on soil moisture in the context of contemporary developments in diffusion theory and the rapid growth of science in America at the turn of the 20th century.

> "Furthermore, the other factor in the equation, namely, the gradient S, is not the space variation of a simple and directly measurably quantity like a head of water, an electric potential, or a temperature. It is the gradient of a quantity ψ, the attraction of the soil for water; and ψ depends in some as yet unknown way, differing from soil to soil, on the water content of the soil, . . ."
>
> Buckingham, 1907, p. 28

Edgar Buckingham's "Studies on the Movement of Soil Moisture," published in 1907 as Bulletin 38 of the U.S. Department of Agriculture Bureau of Soils, is an important milestone in the history of soil physics. For the first time, water movement in unsaturated soils was brought within the scope of rigorous physical principles, helping to improve agriculture through quantitative studies of soil moisture. Buckingham's conceptual–physical model of soil moisture continues to provide the philosophical basis that guides crop management and irrigated agriculture. Simultaneously, his work was also a pioneering contribution in the field of multiphase fluid flow in porous media, significantly preceding related work in petroleum engineering. Almost a century later, it is worthwhile to revisit Buckingham's contribution, understand the scientific atmosphere in which he embarked on his work, and reflect on his insights. The motivation is partly to enjoy an assuredly creative scientific contribution and partly to comprehend the intellectual approach that renders Buckingham's work so valuable.

Buckingham's role in the history of soil physics has been discussed by Philip (1974), Gardner (1986), Sposito (1986), and others. The purpose of this paper is to appreciate Buckingham's work on soil moisture movement from a perspective that extends outside soil science. The close of the 19th century in the United States was distinguished by the federal government's decision to support civilian science with public funds and the ensuing rapid growth in agriculture and industry. Also, at the turn of the 20th century, diffusion theory had established itself as a powerful tool of mathematical physics through the extension of Joseph Fourier's heat diffusion model to include electrodynamics; molecular movement in gases, liquids, and solids; viscous transport of fluids in porous media; and to the statistical behavior of random events. These historical developments provide a useful backdrop against which Buckingham's contributions can be appreciated.

HISTORICAL BACKDROP

American Science in Transition

During the 1860s, America was largely rural, and Congress and President Lincoln took several actions toward betterment of the rural population. In 1862, the United States Department of Agriculture was created and the Morrill Act was passed. The latter established Land Grant Colleges in all the states of the Union. In 1863, the National Academy of Sciences was created with the mandate to provide advice to various departments of the government on scientific and technical matters. At this time, governmental support for science was restricted to matters of the military. In 1879, the National Academy of Sciences recommended to the government to more actively support civilian science and, as a first step in the process, to create the United States Geological Survey for studies of the geological structure and economic resources of the public domain. Meanwhile, the expeditions of John Wesley Powell to the American West brought to light a vast land in which rain did not follow the plow, but yet was capable of immense productivity through capital-intensive irrigated agriculture. With governmental support and technological innovations, agriculture saw rapid expansion. In particular, the 1870s witnessed the successful use of a newly introduced dry-farming technique to efficiently produce wheat over thousands of acres of land in the Great Central Valley of California through mechanized farming. The key to this technique was soil water management. Deep plowing after winter rains brought runoff into the subsoil where it was preserved from evaporation by means of a shallow dust blanket created by a special machine that pulverized the surface soil (Hundley, 2001). This alteration of the soil to inhibit evaporation is referred to as mulching.

Both dry-farming and irrigated farming highlighted

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Published in Vadose Zone Journal 4:434–441 (2005).
doi:10.2136/vzj2004.0126

the importance of soil moisture management, motivating the Department of Agriculture to initiate active research in soil physics. In 1894, the Division of Agricultural Soils, which was renamed in 1901 as the Bureau of Soils, was established within the U.S. Department of Agriculture. Lyman Briggs (1874–1963), a soil physicist of much distinction and influence, joined the Division of Agricultural Soils in 1896 and soon began studying the mechanics of soil moisture on the basis of capillary theory, surface tension, and the interactions between capillary forces and gravity (Briggs, 1897). The Bureau was then led by Milton Whitney, who strongly believed that soil physical conditions were more critical to crop productivity than soil nutrient status. Yet, even while appreciating the importance of soil physics and hiring talented physicists to investigate soils, Whitney believed soil moisture problems to be so difficult that they could not be treated in a strictly mathematical way (Landa and Nimmo, 2003). It is worth noting that the first federal laboratory for physical sciences, the National Bureau of Standards, was established only in 1901. It seems probable that the Bureau of Soils offered a welcome opportunity for Buckingham to pursue applied research.

As soil physicists were pioneering a variety of soil moisture measurements, one apparently counter-intuitive field observation that intrigued them was that the soils of arid regions, a little below the land surface, were known to be generally wetter and to hold their moisture for much longer periods than did the soils of humid areas in dry seasons (Frank Cameron in the Preface to Buckingham, 1907).

Developments in Diffusion

By the close of the 19th century, Fourier's (1822) heat diffusion model had established itself as a powerful tool of analysis in physics. Ohm (electrodynamics) and Fick (molecular diffusion) had made use of the heat flow model as a metaphor, by treating electrical potential and salt concentration as being analogous to temperature. Although he did not explicitly acknowledge Fourier, Darcy (1856) employed a mathematical form analogous to Fourier's Law to describe water flow in porous media. Meanwhile, Graham (1833, 1846) experimentally established two fundamentally different modes of gas transport. In gas mixtures, diffusion of individual components was impelled by spatial variations in their partial pressures. In this process, resistance to motion occurred solely from molecular collisions, and the rate of diffusion was inversely related to the square root of density (Graham's Law). On the other hand, in capillary tubes, bulk flow of the mixture occurred due to spatial variations in total pressure. In this process, which Graham referred to as *transpiration*, resistance to flow arose from wall effects and viscous forces.

Maxwell (1860), as a prelude to explaining electromagnetism, went beyond mere analogy and viewed Fourier's diffusion equation in a dynamic sense, giving consideration to motion under the action of forces. He analyzed the motion of an imaginary incompressible fluid through a resistive medium, impelled by forces arising from spatial variation of fluid pressure (Narasimhan, 2003). Such a dynamic approach is more powerful than mere analogy of mathematical form for a rigorous application of the diffusion equation to mechanical systems. The dynamic approach was later employed by Maxwell, Stefan, Boltzmann, and others in the study of diffusion in gas mixtures.

On the mathematical side, a very important aspect of diffusion theory that goes back to Fourier himself is the assumption that the parameters thermal conductivity and heat capacity in the heat equation are both independent of temperature, the dependent variable. This assumption rendered the diffusion equation to be a linear differential equation for which closed-form solutions can be proved to exist under certain conditions. If this assumption cannot be reasonably made, the differential equation is rendered nonlinear. Such differential equations could not be solved exactly in the absence of computers, and approximate methods for solving them did not exist in the early 20th century.

BUCKINGHAM IN THE BUREAU OF SOILS

Edgar Buckingham (1867–1940), with a bachelors degree from Harvard University and a doctoral degree from the University of Leipzig, taught physical chemistry at Bryn Mawr College (1893–1899), published a book on thermodynamics (Buckingham, 1900), and served briefly as instructor in physics at the University of Wisconsin (1901–1902). He joined the Bureau of Soils in mid-1902 as an assistant physicist and a colleague of Lyman Briggs, who was then a physicist and assistant chief. Buckingham performed soil physics studies over the next four years, before leaving in August 1906 for the National Bureau of Standards, where he had a distinguished career as a physicist until retirement in 1937. It was during his tenure at the Bureau of Standards that he published his well-known π-theorem of dimensional analysis (Buckingham, 1914).

At the Bureau of Soils, Buckingham addressed two problems. The first concerned the rate of exchange of carbon dioxide and oxygen between the soil and the atmosphere, and the second, the movement of soil moisture. The gas exchange problem consisted of evaluating whether the exchange process was dominated by gaseous diffusion or by the transport of gas components with pressure-driven bulk movement of air governed by periodic variations in atmospheric pressure. The diffusion part was in fact a problem in binary gas diffusion in that the escape of carbon dioxide generated in the soil is compensated by influx of an equal amount of oxygen. Drawing on the contributions of Loschmidt and Stefan during the 1870s, Buckingham concluded, based on his own experiments, that diffusion plays a far more important role in soil–atmosphere gas exchange than air flow governed by barometric pressure variations. The results of the aeration studies were published as a Bulletin (Buckingham, 1904). The second problem of the movement of soil moisture involved the interrelated phenomena of evaporation of water from depth and capillary movement of liquid water within the soil. This work, published in 1907, constitutes the subject of what follows.

STUDIES ON THE MOVEMENT OF SOIL MOISTURE

General

Buckingham's contribution to soil physics began with a simple observation that had intrigued agronomists and farmers for decades. It was that mulch (a capillary flow inhibitor) at the land surface can significantly reduce evaporation and preserve soil moisture. This observation inspired the successful dry-farming of wheat in California during the 1870s (Hundley, 2001). Investigation of this issue led Buckingham to recognize that strong evaporation at the land surface can lead to a substantial reduction in the supply of water from below because of the innate nature of capillary movement of soil moisture. To explain this inhibition of moisture movement with pronounced evaporation, Buckingham applied his skills as a physicist. The first two parts of Buckingham's work present experimental evidence demonstrating the links between evaporation and the strength of capillary moisture conduction. The third part is an insightful construction of a theoretical framework to approach the complex phenomenon of moisture movement in soils. Buckingham's is a dynamic theory, based on the identification of a conservative potential whose gradient is an impelling force. Buckingham was probably the first to apply the diffusion model, in a dynamic sense, to the flow of liquids in porous media.

Observations on Evaporation and Capillary Conduction

Buckingham conducted four sets of column experiments to estimate evaporation from depth within the soil, purely by vapor diffusion, without any supply of water by capillary conduction. At the bottom, the samples were supplied with moist air from a free water surface or a moist soil. The soils varied in thickness from 1 to 12 inches, and the duration of the experiments were 4, 53, 140, and 441 d. The principal finding from these experiments was that evaporation was highest in the uppermost one or two inches and declined rapidly with depth. The cumulative amount of water lost to the atmosphere annually from depths in excess of 12 inches was insignificant. Because diffusive flux is inversely related to flow length, the decline in evaporative flux with depth was to be expected. Buckingham also noted that the magnitude of evaporation, estimated by assuming that the partial pressure of water vapor varied linearly over the column, was about four times larger than the observed flux. He reasoned that the vapor pressure gradient should be smaller at the bottom where the vapor must be saturated.

The next set of experiments were designed to investigate the rate of evaporation from a soil column, in conjunction with the supply of water from below through capillary conduction. These experiments were conducted with 48-inch columns, with the bottom two inches periodically supplied with water to simulate a stationary water table and the top six inches rendered loose in structure to simulate tilled soil. Two types of evaporation conditions, arid and humid, were studied. To mimic arid conditions, heated air with constant absolute humidity was blown over the columns. Additionally, the upper inch and a half of the soil columns was heated by electrical coils to the same temperature as the heated air. The experiments were run for 17 to 46 d. A few were performed for as long as 328 d. The important finding from these experiments was that under arid conditions, the rate of evaporation was initially rapid and declined noticeably with time. Under humid conditions, however, the rate of evaporation was less variable over long periods of time. Thus, over a long period of time, a crossover point was noticed beyond which humid conditions experienced greater evaporation loss than arid conditions. Buckingham (1907, p. 24) concluded,

> ". . . It appears that under very arid conditions a soil automatically protects itself from drying by the formation of a natural mulch on the surface."

Buckingham devoted the rest of his paper to methodically explain from first principles the validity of this conclusion.

DYNAMIC THEORY FOR MOISTURE MOVEMENT IN SOILS

General

The knowledge gathered from the aforesaid experiments motivated Buckingham to search for a cogent explanation of the observed behavior in terms of classical physics. Briggs (1897) had already done preliminary work in this regard by invoking principles of capillary flow, presumably inspired by earlier work by Maxwell (1872, p. 260–269). Buckingham took the next step of applying the concept of a potential to analyze capillary motion, probably also drawing from Maxwell (1872, p. 189–193), who used the concept of a potential to analyze the flow of a fluid through a porous plug. These ideas, in conjunction with the mathematical form of Fourier's heat equation and his own experimental data, constitute the foundation of the last and most insightful section of Buckingham's bulletin entitled, "Capillary Conduction in Soils."

Central to Buckingham's conceptualization are the premises that in a soil where both water and air coexist, water is attracted and held by the soil surface by capillarity and the drier the soil, the larger the attraction. Spatial variations in this attractive strength induces a current of capillary water to flow in three dimensions, in much the same way as a current of heat or a current of electricity. Formally, this force can be treated as arising from the spatial gradient of a capillary potential, ψ, which could be treated as analogous to temperature in the heat equation. However, there were two limitations to the analogy. First, ψ was not a directly measurable quantity. In his words:

"Furthermore, the other factor in the equation, namely, the gradient S, is not the space variation of a simple and directly measurably quantity like a head of water, an electric potential, or a temperature. It is the gradient of a quantity ψ, the attraction of the soil for water; and ψ depends in some as yet unknown way, differing from soil to soil, on the water content of the soil, . . . " (Buckingham, 1907, p. 28).

Therefore, the use of ψ in the diffusion model had to be justified by independent physical considerations. Second, capillary conductivity, analogous to thermal or electrical conductivity, would not be a constant property of the material; it would depend on the magnitude of the potential. As he stated:

"The analogy, however, is only formal. In the first place, the thermal and electrical conductivities of a given piece of material are independent of the strength of the current, and in general, only slightly dependent on the temperature and other outside circumstances. . . . The capillary conductivity, however, we have every reason to expect to be largely dependent on the water content of the soil, and therefore variable, not only from point to point in the soil, but also with time at any given point." (Buckingham, 1907, p. 27–28).

Subject to these caveats, Buckingham defined ψ as the energy required to pull a unit mass of water from the soil against the preferential attraction of water to the soil surface when both air and water are present in the pores. By definition, ψ increased with decreasing soil water content. In the absence of any direct way to measure ψ, the distribution of soil moisture in a vertical hydrostatic soil column above the water table would indirectly provide an estimate of ψ. For, at any point x above the water table in a hydrostatic column, upward capillary forces are balanced by the downward force of gravity, and a balancing of these yields the simple relation, $\psi = Ax$, where A is a constant, whose magnitude depends on acceleration due to gravity and the units used.

SOIL MOISTURE RETENTION CURVES

Buckingham's first task was to obtain data on the relation between moisture content, θ, and capillary potential, ψ, under hydrostatic conditions. To this end, data were gathered from 48-inch-tall soil columns, with a constant water level maintained about 2 inches above the bottom through periodic addition of water from a side tube. The upper ends were closed to prevent evaporation. All were imbibition experiments, in which the columns initially had low water contents and gradually gained water by capillary attraction. Some of these experiments were of about two-month duration, while others lasted for as long as 325 d.

The first ever soil water retention curves published are shown in Fig. 1, for six soils varying in texture from sand to clay. These curves admirably show the general pattern of the soil moisture characteristic curves that is now part of soil physics textbooks. Note that none of these six curves shows a well-defined capillary fringe or air-entry transition, the small region above the water table where the soil is fully saturated, but with ψ greater than zero. Even in data presented by Buckingham for experiments longer than 320 d in duration, one cannot

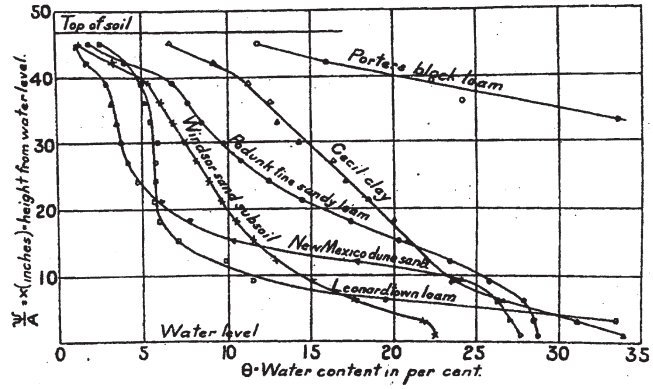

Fig. 1. Water retention curves for six different soils obtained from 48-inch columns after 53 to 68 d. Capillary potential ψ equals elevation *x* times a constant *A* (Buckingham, 1907, Fig. 7).

discern a capillary fringe. This is probably to be attributed to the fact that Buckingham's experiments were all imbibition experiments. A clear capillary fringe will likely be seen only in drainage experiments, as one can infer from our present knowledge of soil-moisture hysteresis.

To further understand moisture retention, many more column experiments were conducted in which water was also allowed to evaporate, with a constant water level maintained at the bottom. The data from these experiments could be understood reasonably well in regard to general patterns that one would expect from capillary mechanisms. But there were difficult-to-comprehend intriguing results. For example, in one experiment with Podunk Fine Sandy Loam, the profile water-content as a function of elevation for two duplicate columns were very nearly the same (Buckingham, 1907, Fig. 9, curves B and C), even though evaporation from one was more than twice that of the other. Buckingham speculated that experiments longer than 320 d may be needed to attain equilibrium. These observations indicated the great difficulty inherent in the experimental study and interpretation of soil moisture movement.

CAPILLARY CONDUCTION

Although Buckingham visualized a flux law for capillary current analogous to that for heat flow, he recognized that it would be far more difficult to measure it experimentally. This was partly because of its dependence on moisture content, partly because of the experimental difficulty involved in maintaining constant low moisture contents at the boundaries of soil samples, and the very long times required for equilibration. Therefore, Buckingham devoted most of his attention to a theoretical–conceptual discussion of how the effective hydraulic conductivity of a soil may vary with moisture content. He did, however, carry out some simpler but difficult-to-interpret experiments to gain insights into the nature of the dependence of capillary conductivity on average moisture content.

Buckingham's conceptual analysis of capillary conduction of water is remarkably insightful and remains valid today, except for minor details. His conceptualization accounted for water movement through water-

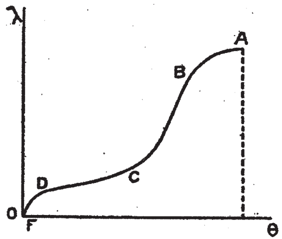

Fig. 2. Schematic variation of capillary conductivity λ with water content θ (Buckingham, 1907, Fig. 14).

filled capillaries as well as through water films. As he stated:

> "... the remaining water being held in the soil by capillary action, partly in drops at the point of contact of the soil grains and partly in thin films on the surfaces of the grains." (Buckingham, 1907, p. 24)

With declining saturation, the water films would become thinner and eventually break. Thus, with progressive decrease in water content, effective hydraulic conductivity would drastically decrease.

Qualitatively, Buckingham postulated a relation between effective hydraulic conductivity, λ, and water content, θ, shown schematically in Fig. 2. Interestingly, in this analysis Buckingham thought in terms of a draining soil rather than an imbibing soil. Between A and B, water saturation is high and water is conducted through water-filled capillaries. A current of water could therefore flow through the soil,

> "... existing always as water-in-mass and without having to flow through surface films on the grains." (Buckingham, 1907, p. 41).

At B, larger saturated capillaries break down and incipient film flow begins, becoming increasingly important with further drying. Between B and C, flow occurs in capillaries and films. Between C and D, film flow dominates, and between D and F films become too thin and break up.

To provide a mathematical form to this conceptualization, Buckingham considered three different geometries of moisture wedges at grain contacts: prismatic wedges, ring wedges, and conical wedges. The prismatic case led him to the following mathematical form for λ(θ),

$$\lambda(\theta) = \frac{\alpha\beta}{\theta_1^{1/2} - \theta^{1/2}} \qquad [1]$$

where α and β are constants pertaining to the geometry of the films, and θ_1 is the saturated moisture content. The shape of the relationship, when $\alpha\beta = 1$ and $\theta_1 = 1$, is given in Fig. 3. This idealization is valid only after commencement of film flow.

As an independent check on his speculation about the nature of the relationship between capillary conductivity and moisture content, Buckingham explored the similarities in the nature of hydraulic conductivity and electrical conductivity in partially water-saturated soils. If one assumes that the soil grains possess negligible ability to conduct electricity, then in a soil of moderate to high saturations, the electrical conductivity will

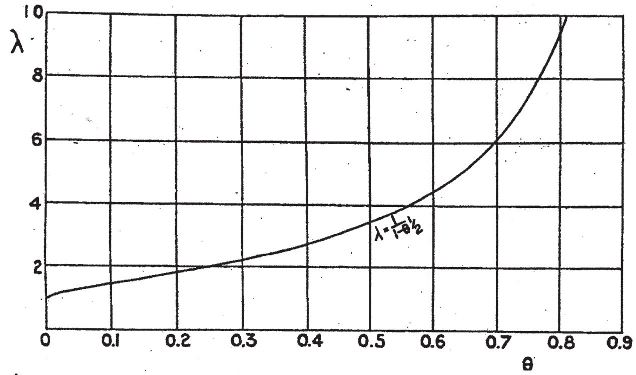

Fig. 3. Hypothetical relation between λ and θ for $\alpha\beta = 1$ and $\theta_1 = 1$ (Buckingham, 1907, Fig. 16).

be dominantly controlled by the geometry and distribution of water films on the soil grains. If so, he reasoned, the form of the curve relating λ and θ (Fig. 3) must be quite similar to the curve relating a soils electrical conductivity with θ. Fortunately, such data were available from other researchers of the Bureau of Soils. The observed relationship between electrical conductance and θ for a sandy loam is shown in Fig. 4. The general similarity between this figure and the relationship between λ and θ shown in Fig. 3 lends support to Buckingham's analysis.

To obtain a better quantitative understanding of capillary moisture movement, Buckingham conducted a number of experiments to find out how the rate of flow of water from a wet to a dry portion of a given soil depended on the nature of the soil and on its mean water content. In a closed tube, two layers of soil, each about 3 cm thick and having different moisture contents, were placed together in contact for a certain period of time, after which they were separated and their water contents measured. Let θ_m be the initial mean water content of the two layers; Δ, the initial difference between the moisture contents of the layers; and *M*, the mean change in the moisture content of the two layers. Then, for each

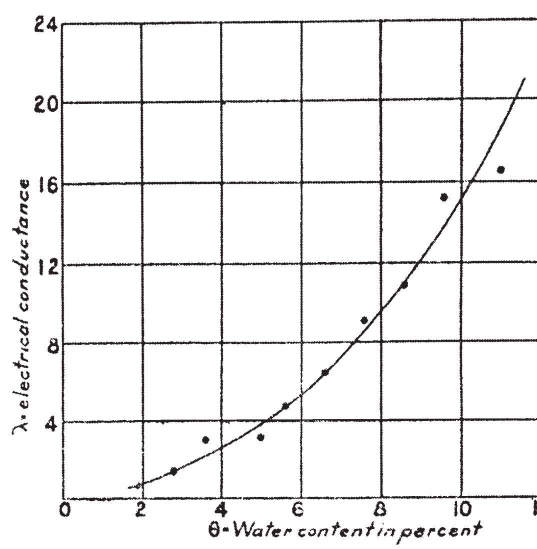

Fig. 4. Relation between electrical conductance and water content for a moist soil (Buckingham, 1907, Fig. 20).

experiment, M/Δ provides a measure of dependence of the hydraulic diffusivity on the mean moisture content. Experiments were conducted on a variety of soils over periods varying from 2 to 13 d. Although the data did not provide much definitive information, two observations emerged. The first was that the quantity M/Δ changed rapidly within the first hour and then changed very gradually over the next several days. The second was that at moderate to low saturations, capillary flow may have local maxima or minima.

APPRECIATION

Until the end of the 19th century, Europe maintained leadership in science. It was with Willard Gibbs (1839–1903) that American science started to establish itself. Buckingham was among those who followed Gibbs and contributed to the emerging eminence of American science. Buckingham's work on soil moisture movement is an example of the transformation of an applied question into insightful basic science in the hands of a talented scientist. While soil science was growing gradually from the contributions of those who devoted their careers to the subject, Buckingham entered the field for a brief period, revolutionized it, and then left it to pursue other interests.

Buckingham specialized in thermodynamics (American Institute of Physics, 2004) and brought his knowledge of basic physics to bear on comprehending the intriguing behavior of capillary water movement in soils. Although he readily noticed the value of the mathematical form of Fourier's Law in quantifying capillary water current, he also recognized that the mathematics of Fourier's linear differential equation was inadequate to describe soil water movement. He expressed capillary current density Q with the following equation,

$$Q = \lambda \frac{\partial\psi}{\partial\theta}\frac{\partial\theta}{\partial x} \qquad [2]$$

and stated:

> "If λ and $\partial\psi/\partial\theta$ were constants, this Eq. [23] would be identical in form with the Fourier–Ohm law, and all the mathematical results from that law would be at once applicable to problems in the capillary flow of water through soils." (Buckingham, 1907, p. 51).

But recognizing that λ and $\partial\psi/\partial\theta$ were not in fact constants in soils, he added, with much foresight:

> "If we knew the mathematical forms of ψ and λ as functions of θ, it is possible, though not probable, that we could give a complete mathematical treatment of the subject." (Buckingham, 1907, p. 51).

Even today, general closed form solutions are not known for the nonlinear diffusion equation. Analytical solutions and asymptotic approximations are available only in some cases involving simple boundary conditions and initial conditions and special mathematical forms of hydraulic conductivity and diffusivity. It is probably because of his skepticism about solving the nonlinear diffusion equation that Buckingham did not take the formal step of writing a partial differential equation for soil moisture movement. Nor did he write down a more general equation of motion combining gravity and capillary potential. He could have, had he chosen to do so; he had defined a potential, a capillary conductivity, and a soil moisture capacity (analogous to specific heat) given by the slope of his moisture retention curves.

In Buckingham's work, one is intrigued by a lack of reference to Darcy's Law. It could well be that Buckingham was aware of Darcy's work but simply did not cite it, just as he did not cite Poiseuille's work, although he exhibits knowledge that the conductance of a capillary tube varies as the fourth power of its radius. There is some merit to this speculation because Buckingham specifically used the phrase "a simple and measurable quantity like a head of water" on p. 28, and Darcy's Law is in fact based on a measurable hydraulic head. Moreover, Buckingham had clearly concluded that the nonlinear diffusion equation was quite distinct in nature from Fourier's linear equation. Sposito (1986) speculates that Buckingham probably was not aware of Darcy's work. Regardless of these speculations, a careful reading of Buckingham's work shows that there are significant differences in the physical mechanisms of flow in Darcy's saturated sand and Buckingham's unsaturated soil. Unlike Darcy, who probably formulated his law by analogy with the mathematical form of Fourier's Law, Buckingham developed a self-consistent dynamic theory.

L.A. Richards, in reviewing advances in soil physics, expressed his admiration of Buckingham's 1907 publication by stating, ". . . I cannot avoid the feeling that during the last 50 years of work on the physics of soil water, we have mainly been filling in the lines" (Richard, 1961, p. 67). Richards suggested that the equation for liquid flux in an unsaturated soil, $Q = \lambda$ (grad ψ + grad ϕ) should appropriately be designated as Buckingham's Law. He elaborated on his suggestion by stating:

> "What is here called Buckingham law for unsaturated flow, has at times past been identified with Darcy law. The proportionality discovered by Darcy between flow and hydraulic gradient for the one dimensional case in saturated sand was extended by others to apply to three dimensional flow in saturated soil. It is clear that to apply a similar proportionality to the far more involved case of unsaturated flow in soil is a very considerable additional step involving many complications for which Buckingham gave the first clear explanation and discussion." (Richards, 1961, footnote, p. 73).

Agreeing with Richards, Swartzendruber (1969) proposed that the equation combining flow in saturated and the unsaturated zones be referred to as Buckingham–Darcy equation. Sposito (1986) refers to the equation as Buckingham flux law.

Hubbert (1940) formally explained Darcy's Law in terms of a potential, defined as energy per unit mass of water in a saturated porous medium. In a correspondence with this author, Hubbert (1974) stated that he was unaware of Buckingham's work. In Hubbert's definition, the fluid pressure component of the potential was associated with the compressibility of water. However, in the case of Buckingham's capillary potential, the component was associated with an entirely different physical phenomenon, namely, intensity of attraction of water by the soil surface. Therefore, connecting capillary potential with the potential relevant to Darcy's hydraulic head is not a trivial issue. As Buckingham defined it, soil moisture moved in the direction of increasing capillary potential, whereas, in a general diffusion-type process, flow is in the direction of decreasing potential. To avoid this inconsistency and unify the equation of motion in the saturated and the unsaturated zones, a change in sign was needed. This change emerged with the invention of the tensiometer by Willard Gardner (Gardner et al., 1922). The tensiometer enabled the measurement of gage pressure of the water phase in a soil, which is a negative quantity. Soil moisture moves in the direction of decreasing gage pressure head. Moreover, capillary potential in an unsaturated soil and fluid pressure in a saturated soil, play very different roles in governing hydraulic capacitance or soil moisture capacity. In a saturated soil, hydraulic capacitance arises partly from a change in porosity, which in turn is governed by variations in skeletal stresses. In a saturated state, fluid pressure and skeletal stress are strongly coupled, while in the unsaturated state, the linkage between capillary pressure and skeletal stress is very weak. In dry to moderately saturated soils, a change in capillary pressure has no effect on the magnitude of porosity. Hydraulic capacitance of an unsaturated soil is dictated by the physics of surface tension rather than porous medium deformation. For these reasons, it can be argued that Buckingham's model for capillary flow cannot be considered merely an extension of Darcy's Law and that it deserves a separate identity as suggested by Richards (1961).

Capillary potential, which was an abstract, nonmeasurable quantity in Buckingham's mind, became a physical reality in 1922, when the tensiometer was invented (Gardner et al., 1922). In the interim, Gardner and Widtsoe (1921) interpreted capillary potential in terms of capillary pressure (pressure in the water phase immediately below the curved meniscus), added gravity, and described capillary water movement in terms of a linear differential equation, with conductivity being constant and assuming that capillary pressure is linearly related to the reciprocal of moisture content. Experimental verification of this equation was not quite successful. Curiously, Gardner and Widtsoe did not cite Buckingham's work. It was left to Richards (1931) to formally express moisture movement in an unsaturated soil in terms of a nonlinear partial differential equation, with conductivity as well as soil moisture capacity being functions of capillary pressure. Assuming the soil matrix to be rigid, the soil moisture capacity in the Richards equation was simply the gradient of moisture content with reference to capillary pressure. Richards made no effort to solve this equation. It was not until the 1950s that the first approximate solutions to this equation would appear with the contributions of Klute and Philip.

The beginning of the 20th century also saw rapid expansion of the petroleum industry and a serious interest among petroleum engineers to understand the flow of oil, natural gas, and water in porous media. The first experimental data on the relationships between effective conductivity of different fluid phases in relation to their saturation began appearing during the 1930s, starting with the contributions of Wyckoff and Botset (1936). It is worth pointing out here that, in interpreting their experimental data, Wyckoff and Botset (1936) make the important assumption that at any given saturation, the ratio between electrical conductivity and hydraulic conductivity is a constant, a reasoning already employed by Buckingham. They stated: "The electrical resistance measurements, from which may be obtained the ratio of the conductivity during any observation to the gas-free conductivity, . . ." This assumption is very similar to Buckingham's perception about the similarity between electrical conductivity and hydraulic conductivity. Thus, Buckingham's work on the dependence of capillary conductivity on phase saturation antedates similar work in petroleum engineering by three decades.

CONCLUDING REMARKS

Buckingham imaginatively applied his science to address a very important problem in agriculture. In so doing, he succeeded in laying the foundations for the study of the flow of multiple fluid phases in earth materials. Such problems are of great importance, not only in soil science, but in many other fields of the earth sciences and engineering. As one reads Buckingham's paper one is impressed with the clarity of ideas and his systematic application of scientific principles. As a physicist in the company of agricultural scientists, Buckingham articulated his findings mostly in written prose, without much reliance on mathematics. His foundational ideas are as valid today as when he proposed them. Soil physics data that have been accumulated since Buckingham's pioneering work reinforce his suspicion that ". . . it is possible, though not probable, that we could give a complete mathematical treatment of the subject" (Buckingham, 1907, p. 51).

In dealing with capillary conduction in soils, it appears, intuition will continue to be as important as mathematics.

Buckingham's "Studies on the Movement of Soil Moisture" is a piece of scientific literature that is at once enjoyable and educational.

ACKNOWLEDGMENTS

Thanks are due to Jacob Bear, John Letey, John Nimmo, and Garrison Sposito for reviewing the manuscript and providing thoughtful comments. Rien van Genuchten and an anonymous reviewer suggested valuable editorial changes. This work was supported partly by the Director, Office of Energy Research, Office of Basic Energy Sciences of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 through the Earth Sciences Division of Ernest Orlando Lawrence Berkeley National Laboratory.

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