The Soil Physics Contributions of Edgar Buckingham

John R. Nimmo* and Edward R. Landa

ABSTRACT

During 1902 to 1906 as a soil physicist at the USDA Bureau of Soils (BOS), Edgar Buckingham originated the concepts of matric potential, soil–water retention curves, specific water capacity, and unsaturated hydraulic conductivity (*K*) as a distinct property of a soil. He applied a formula equivalent to Darcy's law (though without specific mention of Darcy's work) to unsaturated flow. He also contributed significant research on quasi-empirical formulas for *K* as a function of water content, water flow in capillary crevices and in thin films, and scaling. Buckingham's work on gas flow in soils produced paradigms that are consistent with our current understanding. His work on evaporation elucidated the concept of self-mulching and produced sound and sometimes paradoxical generalizations concerning conditions that favor or retard evaporation. Largely overshadowing those achievements, however, is that he launched a theory, still accepted today, that could predict transient water content as a function of time and space. Recently discovered documents reveal some of the arguments Buckingham had with BOS officials, including the text of a two-paragraph conclusion of his famous 1907 report on soil water, and the official letter documenting rejection of that text. Strained interpersonal relations motivated the departure of Buckingham and other brilliant physicists (N.E. Dorsey, F.H. King, and Lyman Briggs) from the BOS during 1903 to 1906. Given that Buckingham and his BOS colleagues had been rapidly developing the means of quantifying unsaturated flow, these strained relations probably slowed the advancement of unsaturated flow theory.

Edgar Buckingham tremendously advanced the understanding of water and air in unsaturated soils during 4 yr at the BOS, which culminated with his famous paper of 1907 (Buckingham, 1907). He introduced the concept of potential into soil-water flow and used an equation equivalent to Darcy's law to quantify flow in unsaturated soil. Topics of his investigation included soil gas flow and aeration, evaporation from soil and the effectiveness of self-mulching (i.e., retardation of evaporation by a thin surficial layer drier than the rest of the soil), measurement of water retention curves (the relation between water content θ and matric potential ψ), identification of the retention curve and unsaturated hydraulic conductivity $K(\theta)$ as the two main soil properties for unsaturated flow, and mathematical formulas of the $\theta(\psi)$ and $K(\theta)$ relations (which he proposed and tested to some degree on both experimental and theoretical grounds).

Buckingham (Fig. 1) was born in Philadelphia, PA on 8 July 1867. In 1887, he graduated from Harvard with a bachelor's degree in physics, then worked several years as a graduate assistant in the physics department. He did additional graduate work at the University of Strasbourg and the University of Leipzig, where he studied under chemist Wilhelm Ostwald, who won the Nobel Prize in 1909. In 1893, Buckingham received a Ph.D. from Leipzig. That same year, he began teaching physical chemistry and physics at Bryn Mawr College. During 1897 until 1899 he wrote a textbook on thermodynamics (Buckingham, 1900a). He left Bryn Mawr as an associate professor in the summer of 1899.

After his departure from Bryn Mawr, he spent the next 18 mo vacationing, tutoring prep school students, and working for several months in the copper mining district of Arizona. Few details on this latter episode are available. On 13 Sept. 1899 he had a meeting with Harvard president Charles William Eliot. Within a day, he was summoned to New York City to meet with a Mr. Dodge and a Mr. Douglas (probably William Earl Dodge, Jr., and noted metallurgist James Douglas of the Phelps Dodge Corp.). Two days later, he was on a special train chartered by the American Institute of Mining Engineers, bound for San Francisco. On 15 Oct. 1899 he arrived at a mining camp in Morenci, AZ. Paid \$100 a week beginning when he left New York, he worked an eclectic mix of jobs for the company, including putting up wires for electrical lighting, working as an engine oiler, and analyzing gas samples. He left Morenci late in February 1900. During his year and a half away from formal academic life, he was also courting Elizabeth Holstein, whom he had met at Bryn Mawr. They were married in Texas in 1901. He resumed his academic career as an instructor in physics at the University of Wisconsin in 1901. After one academic year he left Wisconsin for the BOS.

At the BOS from 1902 to 1906, he investigated the dynamics of gas and water in soils, the main subject of this paper. He reported this research in two reports (Buckingham, 1904; Buckingham, 1907). After leaving the BOS, he went to the National Bureau of Standards where he remained until retirement in 1937. In 1923, he was the first NBS researcher given the prized "independent status" (i.e., free of all administrative duties). His work included research on helium production for the military, and technical oversight of NBS support of rocketry studies by Robert Goddard. He served as an adviser to the U.S. Navy on steam turbine and propeller design and lectured on thermodynamics at the Naval Postgraduate School in Annapolis, MD. Buckingham had traveled extensively in Europe during his graduate school days, and had a life-long love of languages, probably influenced by his father, Lucius Henry Buckingham, a noted linguist (National Cyclopaedia of American Biography, 1941c). [His paternal grandfather, Joseph Tin-

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Abbreviations: BOS, USDA Bureau of Soils; NBS, National Bureau of Standards.

Fig. 1. Portraits of Edgar Buckingham (a) at age 20; (b) with daughter Katharine, circa 1905, during the time of his soil-physics work at the BOS; (c) in 1923; and (d) on unknown date. The scar visible on his cheek in (b) was the result of an abscess and surgeries performed to treat it during 1893–1895 (Buckingham 1900b). The photograph (c) was published by Gardner (1986) and (d) was published in the National Cyclopaedia of American Biography (1941a). Photographs (a), (b), and (c) courtesy of Thomas K. Hunt.

ker Buckingham, was a prominent New England editor and publisher whose literary magazine published the works of Henry Wadsworth Longfellow, Edward Everett, and Oliver Wendell Holmes (National Cyclopaedia of American Biography, 1941b).] His linguistic abilities served him well during a 1918–1919 stint as associate scientific attaché to the U.S. Embassy in Rome. He was a great fan of the Boston Symphony and often attended the orchestra's concerts in Washington with a miniature score in hand.

Edgar and Elizabeth Buckingham had a daughter (Katharine Buckingham, 1902–1980) and a son (Stephen Alvord Buckingham, 1905–1980) (National Cyclopaedia of American Biography, 1941a). Katharine graduated from Wellesley and later MIT with a degree in architecture. Stephen went on to graduate studies in physics at Harvard and introduced his sister to fellow physics graduate student Frederick Vinton Hunt (1905–1972). In 1932, Katharine married Frederick, who joined the Harvard faculty after obtaining his Ph.D. in 1934. He went on to do pioneering work in underwater acoustics, coining the term "sonar" during World War II, and rose to become Gordon McKay Professor of Applied Physics and Rumford Professor of Physics at Harvard (Hersey, 1967; Who Was Who in America, 1973, Thomas K. Hunt, personal communication, 2004). Their only child, Thomas Kintzing Hunt (born 1937) obtained his Ph.D. in physics from the California Institute of Technology in 1964 and has done research in low temperature physics, superconductivity, and energy conversion and storage (American Men & Women of Science, 1998). Stephen Alvord Buckingham received his Ph.D. in physics from Harvard in 1934 and worked in the Department of Terrestrial Magnetism of the Carnegie Institution of Washington before joining the Johns Hopkins University Applied Physics Laboratory (APL) in 1942 to work on the development of the radio proximity fuze and antiaircraft guns. His later work at APL involved the design and testing of jet engines and spacecraft (Hersey, 1967; Applied Physics Laboratory, 1980, Anthony W. Buckingham, personal communication, 2004).

Edgar Buckingham was described as "a man of strong personality, outspoken and uncompromisingly truthful" (National Cyclopaedia of American Biography, 1941a). A close colleague at the NBS described him as methodical and went on to note: "Edgar Buckingham was not only a good writer but a good critic. Some thought him too severe. He never hesitated to call scientists and officials 'charlatans' if he disagreed with them" (Hersey, 1967). In July 1937, he retired at the mandatory age of 70, but continued to work at NBS on research problems such as the flow of gases through small orifices. He died in Washington, DC on 29 Apr. 1940, and was interred at Fort Lincoln Cemetery in Maryland. (Buckingham, 1900b; National Cyclopaedia of American Biography, 1941a; Cochrane, 1966; Hersey, 1970, Anthony W. Buckingham, personal communication, 2004.).

Soil physics terminology has evolved since Buckingham's day. Table 1 lists some of the early twentieth-century terms Buckingham used, with equivalent terms used today. In this paper we use the modern terms, except in quotations. Buckingham introduced the symbol ψ for matric potential, still the prevalent notation. Like other soil physicists of his era, he used the term "capillary" rather than "matric," but in his writing this term is clearly not limited to those phenomena of water–matrix interaction that are specifically characteristic of capillaries.

Table 1. Terminology and notation used by Buckingham, with modern equivalents.

Term used by Buckingham	Modern equivalent
capillary potential ψ	matric potential ψ
capillary conductivity λ	unsaturated hydraulic conductivity K
transpiration	pressure-driven, viscous flow of gas
transpiration constant	pneumatic conductivity
current	flux
rinsing	aeration
carbonic acid	carbon dioxide
porosity	volumetric air content (here symbolized θ_{air})

BUCKINGHAM'S WORK AT USDA BUREAU OF SOILS

Soil Physics at the Bureau of Soils

The pattern of events that led to Buckingham's soil physics work is foreshadowed in the Report of the Chief, BOS in the Annual Report of the USDA (Whitney, 1901). Whitney describes the formation of the BOS, an expansion of the Department's soil activities, with a new infusion of money on 1 July 1901 (p. 113; also mentioned in the report of the Secretary, p. XXIX-XL). The "Soil Physics" section (p. 132–135) mentions "investigations on the capillary movement of water in dry and moist soils, begun during a previous year…," including experiments on the rate of capillarity-driven soil water movement in columns of various heights, similar to the experiments Buckingham would supervise in 1905 and 1906. These topics are not mentioned in the two paragraphs under "Future Work," however.

Franklin Hiram King was probably the one who recruited Buckingham to the BOS and soil physics. King had joined the faculty of the University of Wisconsin in 1888 as professor of agricultural physics. In November 1901, King left Wisconsin to join the BOS as Chief of the Division of Soil Management.

King clashed with Whitney in ways that illustrate the interpersonal tensions that led to discord between Whitney and Lyman Briggs (Landa and Nimmo, 2003), Buckingham, and others. King disagreed with the BOS chief's view that soil physical condition rather than nutrient status will almost always determine crop yield. On 30 June 1904 King was forced to resign (Gardner, 1986; Tanner and Simonson, 1993). He returned to the University of Wisconsin, where he remained until his death in 1911. Whitney had rejected three of King's six research reports, which dealt with water-soluble salts in soils. Less than two months after leaving the BOS, King privately published the three rejected papers in a book format (King, 1904). Whitney was upset by the critical (toward the BOS) tone of King's preface to this volume. In October 1904, Whitney attempted to rescind his approval to publish the other three papers. He was overruled by Secretary of Agriculture James Wilson, and these reports were published as Bulletin 26 in April

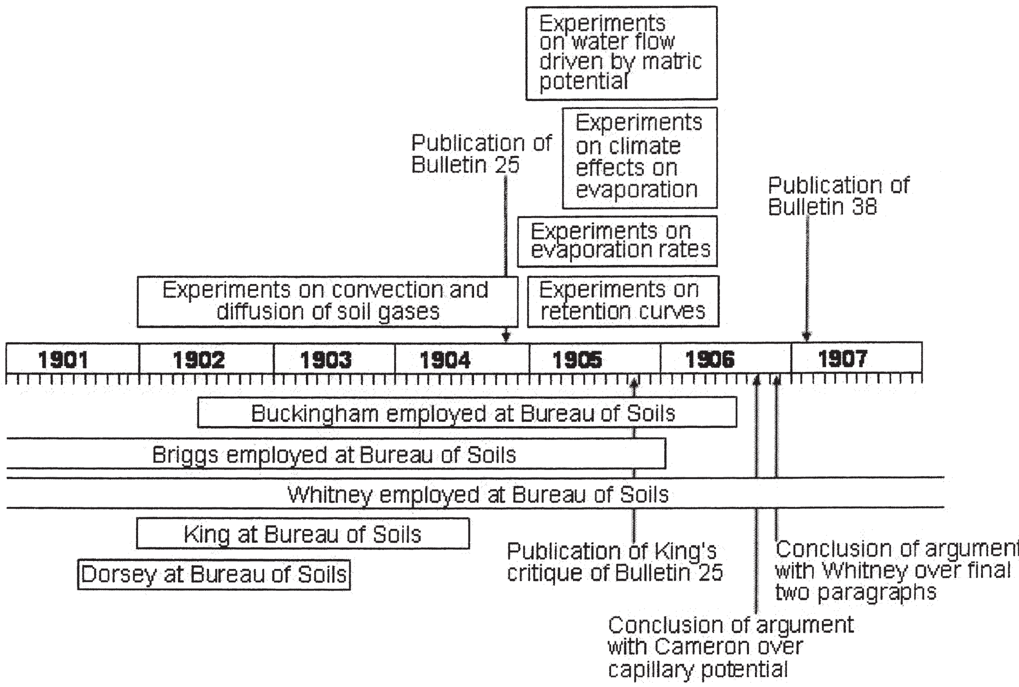


Fig. 2. Timeline of events related to soil physics research at the USDA BOS 1901–1907.

1905 (King, 1905a) (Records of the Bureau of Soils, 1907–1927). The letter of transmittal from Whitney stated that the conclusions expressed on the effects of climate and soil fertility on crop yield did not carry the BOS endorsement. Further details of this conflict, which pitted Eugene W. Hilgard, E. J. Russell, and others against Whitney, and eventually escalated to hearings before the Committee on Agriculture of the U.S. House of Representatives in 1908, are discussed by Gardner (1986), Tanner and Simonson (1993), Amundson and Yaalon (1995), and Fanning and Fanning (personal communication 2004, Milton Whitney–Soil Pioneer, manuscript in preparation). Commenting on this episode in their history of soil mineralogy in the USDA, Cady and Flach (1997) note: "In spite of many attempts by the scientific community to have him removed, Whitney remained director of the Bureau of Soils until his death in 1927. He was a man of strong convictions who rarely changed his mind." Whitney would also do battle with pedology pioneer George Nelson Coffey (Simonson, 1986; Brevik, 1999) who left the BOS after 11 yr of service in 1911; the timing of his resignation may have been related to Whitney's appending a non-endorsing letter of transmittal to Coffey's treatise on soil classification, *A Study of the Soils of the United States*, published by the BOS in 1912.

Buckingham was hired in 1902 to conduct investigations of soil aeration. His overlap with King at the BOS lasted only one and a half years, until January 1904. His overlap with Lyman Briggs, who had been researching soil physics at the USDA since 1896, lasted a little more than 2 yr, until Briggs transferred to the USDA Bureau of Plant Industry at the end of 1905 (Landa and Nimmo, 2003). Figure 2 shows a timeline covering the years 1901 until 1907, with notation of events significant to Buckingham's work.

Another physicist who remained only briefly at BOS was Noah Ernest Dorsey. Like Briggs, Dorsey received his Ph.D. in physics from Johns Hopkins University (1897). He started at the BOS in 1901. In 1903, he went to the NBS where he remained until he retired in 1943, working on measurements of ionizing radiation and the freezing of supercooled water (Dorsey, 1940; Cattell, 1949). His textbook "The Physics of Radioactivity" (Dorsey, 1921) was an important training tool for many early students in radioactivity and radiation safety. His compendium on the properties of water (Dorsey, 1940) is still valued as a reference work by soil physicists today. In 1928, Dorsey followed Buckingham's path to become the second NBS scientist to be granted independent status (Hersey, 1967).

Research on Gas Transport

The movement of soil gases was Buckingham's initial major assignment at BOS. The main practical application was soil aeration, specifically the escape from the soil of carbon dioxide and its replacement with oxygen. Aspects of this topic whose importance was apparent at that time included the relative importance of diffusion and of barometric pumping; the influence of soil texture, "porosity," and compactness; and the quantity of gas exchanged for given conditions of temperature, "porosity," and soil gas composition. As noted in Table 1, Buckingham used the term "porosity" to mean what today would be called volumetric air content, here symbolized θ_{air}.

In BOS Bulletin 25, Buckingham (1904) presented his experimental investigation of convection and diffusion. Measurements focused on the relations between θ_{air}, pneumatic conductivity K_{air}, and diffusion constant D. Buckingham developed new methods for measurement and control of pressures and flow rates. His experiments were done with soil in a rectangular case, instrumented with a pressure-gauge, an "aspirator," gas-pressure regulators, and gas-collecting apparatus. Some related work had been done by King, but very few such measurements had been done before. Bulletin 25 also described some of the methods that did not work, and noted that the method finally adopted for measuring diffusion was "the least unsatisfactory yet found."

Aeration experiments were conducted on four soils, testing different moisture states and packings. The main features of these were the treatment of multiple gases (air and carbon dioxide), collection of gases from the soil, and analysis of their composition. Some of the most important investigations concern convection and diffusion, emphasizing empirical conclusions derived from the experimental results. Buckingham investigated the relation between the diffusion coefficient of air in soil and that of bulk air (i.e., the relation between diffusion through soils and free diffusion). He found the rate of diffusion not to depend significantly on structure, compactness, or water content, and used an empirical formula based on his data to give the diffusion coefficient as a function of θ_{air}. There was close agreement between an extrapolation of Buckingham's empirical formula to $\theta_{air} = 1$ and values of diffusion coefficient that had been previously been measured for free gases without a porous medium. Buckingham called this agreement "accidental" but also "remarkable," and noted it to be "entirely consistent with" diffusion in soil being a slightly modified case of free diffusion.

For the relation between θ_{air} and speed of diffusion, Buckingham's fitting of a power law to his data indicated the ratio of diffusion coefficients to go as the square of θ_{air}. Many other empirical and semiempirical relations have been put forward since that time, mostly with a linear dependence on θ_{air}, but there is still not general agreement as to what formula works best. Buckingham's is commonly among the ones cited in current textbooks (Marshall et al., 1996; Hillel, 1998) and is directly used in current soil physics research (e.g., Moldrup et al., 2004). Buckingham was much ahead of his time in this area; most comparable investigations date from 1940 or later. For the relation between θ_{air} and airflow rate, Buckingham's similar fitting of a power law suggested an empirical constant of approximately 7 as the exponent to relate pneumatic conductivity (K_{air}) to S. That is, K_{air} would be proportional to θ_{air} raised to a power of about 7. He found K_{air}, unlike diffusion, to depend strongly on structure and texture. Buckingham qualified this generalization by noting "It is obvious that in attempting to draw conclusions from experiments on transpiration great caution must be used, and that the porosity must be determined with much greater accuracy than has been done here to make numerical conclusions have any serious significance."

Buckingham's research on the penetration of barometric waves into the soil was perhaps the first investigation of the effectiveness of barometric pressure changes for driving soil aeration. This topic also has been much investigated in recent decades, mostly in the context of convective vs. diffusive transport of gases, and including other convective processes besides barometric fluctuation. Buckingham concluded that the exchange of gases in soil aeration takes place by diffusion and is "sensibly independent of the variations of the outside barometric pressure." Bulletin 25 also includes illustrative examples that treat the rate of escape of carbon dioxide from soil under various conditions, the movement of gases through soils by pure diffusion, diffusion of two gases through a third, the distribution of nitrogen in the soil, rates of diffusion of carbon dioxide and oxygen through nitrogen, the diffusion of other gases through the soil, and the effect of barometric changes on the escape of carbon dioxide by diffusion. Buckingham's concluding remarks, which cover nearly a full page of Bulletin 25, reiterate the principal findings, most notably the quantitative generalizations of gas-flow properties in relation to other soil properties. The tone of these comments is relatively exuberant and seems to convey much pride in the quantitative specificity of the results presented.

Less than a year after the appearance of Bulletin 25, King excoriated Buckingham's publication in *Science* (King, 1905b). King's paper quotes verbatim all nine paragraphs of the concluding section of Bulletin 25. It criticizes Buckingham for basing such conclusions on "the mathematical treatment of a very limited series of laboratory experiments" and charges that they have not "been checked by even a single field observation or experiment," though King did acknowledge that the experiments "have been done with great care." The intensity of King's feelings and the multiplicity of his motivations are apparent in such statements as

> Almost infinite injury is done to the cause of agricultural science and to the growth of the Department of Agriculture along sound and enduring lines by prematurely exploiting results of investigation, striving to get them before the public eye of practical men—congressmen, farmers, merchants and manufacturers—but succeeding in getting them there in the form of untruths, or of partial truths which lead to errors of practice so soon as they are applied.

King's writing demonstrates no awareness of the various qualifications and disclaimers that Buckingham wrote in the text of Bulletin 25 preceding the conclusions. King also mentions Bulletin 22 (Whitney and Cameron, 1903), on the relative importance of chemical nutrients to crop growth, which was highly controversial (e.g., Hilgard, 1903) and whose conclusions were rejected by the soil science community not many years later. King certainly had reason to be angry at Whitney, who had fired him, and to charge Whitney with promoting inadequately tested conclusions had substantial justification. But it is not known why he turned against Buckingham so strongly, only 3 yr after he had helped to hire Buckingham to work under his supervision on topics he held to be of great importance. Perhaps he transferred some of his anger with Whitney to Buckingham, who was still working in Whitney's bureau. Perhaps also, he had somehow come to associate the elucidation of physical processes as done by Buckingham with Whitney's advocacy of an insignificant role of chemical nutrients. Another irony is that King's charges against Bulletin 25 came at almost exactly the same time Whitney was condemning Lyman Briggs for putting "rigid mathematical demonstration" into soil physics research (Landa and Nimmo, 2003).

In contrast, Whitney regarded Buckingham's aeration work favorably. Whitney's (1905, p. 269) annual summary of BOS research includes a paragraph describing the work on aeration in Bulletin 25, including its conclusions on the diffusion of soil gas following the same laws as diffusion in free air, the proportionality of the diffusion coefficient to the square of S, and the dominance of diffusion over barometric fluctuations in driving soil aeration.

Compared with that supported by later research, Buckingham's understanding of soil aeration "underrated convection except in very deep soils" (Tanner and Simonson, 1993). For the most part, however, his generalizations do resemble later ideas, such as the statement that "Gaseous diffusion … is the principal process causing gaseous interchange between the soil and the atmosphere" (Kirkham, 1994, citing Troeh et al., 1982; and Jury et al., 1991). The textbook of Marshall et al. (1996, p. 363) states "Gases and vapors are transported in soil air by convection and diffusion, the latter being the main mechanism." A comparable statement could be based solely on Buckingham's work, perhaps the only difference being that it would call diffusion the "only significant" rather than "main" mechanism.

Research on Soil Water

Buckingham's most celebrated contributions to soil physics, which laid the foundation for the theory of unsaturated flow, are in the third of the three sections of Bulletin 38 (Buckingham, 1907). The preceding sections concern evaporation from soils. The first series of experiments investigated evaporation from water below a layer of soil. In essence this was a study of the effectiveness of an upper layer of soil as a mulch that limits evaporation from the soil below. Buckingham supervised four experiments of durations as long as 441 d. He explained in a footnote that these experiments, like the others in his report, were performed by J.O. Belz and J.R. McLane (Buckingham, 1907, p. 9). The results showed that, especially when capillary flow through the uppermost layer is prevented, soil of various textures can strongly inhibit evaporation. There were not enough experiments, though, to conclusively generalize on the relative effect of texture or tightness of packing. The second series of experiments explored the drying of soils under arid and humid conditions in four experiments that ranged in duration from 17 to 66 d. Figure 3 illustrates typical results. In Buckingham's words,

> The evaporation from the soil under the arid conditions is much more rapid at first, but after about three days have elapsed the rate of loss is less under arid than under humid conditions, so that the total loss under the humid conditions gradually overtakes that under the arid conditions…. It appears that under very arid conditions a soil automatically protects itself from drying by the formation of a natural mulch on the surface.

In this section, as throughout this report, Buckingham discusses the flow of water "in a soil which is not very wet" as taking place through thin films on the soil grains,

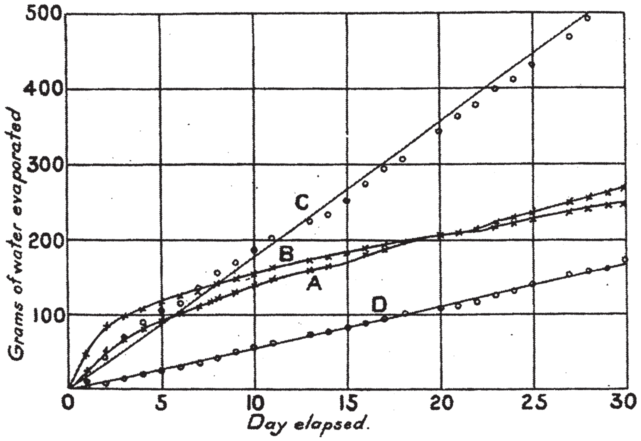


Fig. 3. Water lost over time by Takoma loam soil: soil under humid conditions (experiment conducted at room temperature) (A), soil under arid conditions (experiment conducted with heating of the top 4 cm of the soil column and the air at the soil surface) (B), water under arid conditions (C), water under humid conditions (D) (Buckingham, 1907, p. 21).

a concept that was already present in the soil physics literature (e.g., Briggs, 1897).

In his introduction to the topic of capillary action in soils, Buckingham uses analogies to electric current described by Ohm's law, heat flux described by Fourier's law, and Hagen-Poiseuille flow through a tube. Although he clearly was aware of the work of Hagen or Poiseuille, he does not mention them specifically—perhaps because their formula was intended for the specific case of cylindrical tubes, which he did not find as attractive an analogy to soil-water flow as did later generations of soil physicists.

Though Buckingham repeatedly mentions the analogy of his developments to what was known of electric current and heat flux, nowhere in Bulletin 38 does he mention Darcy or Darcy's law. To understand the implications of this omission and to be able to evaluate Buckingham's progress on this topic requires some attention to the evolution since Darcy's time of what is called Darcy's law. Darcy (1856) presented this law as a quantitative relation between the flow rate of water in saturated sand and the force that drives that flow. Its essence was that this flow rate is directly proportional to the gradient of what we today might call the hydraulic potential (Marshall et al. [1996], p. 79), with the constant of proportionality being the hydraulic conductivity of the sand. Today, various fields in which fluid flow through porous media is important (e.g., soil science, hydrology, fluid mechanics, and chemical engineering) apply Darcy's law in a much expanded range of contexts, including multiphase, gaseous, and unsaturated flow. Its evolution has proceeded in steps, for example Dupuit's introduction of the differential form in 1863. The term "Darcy's law" has come to mean the general statement that the flow rate of a fluid in a porous medium is directly proportional to a force expressible as the gradient of a potential. In Buckingham's time it would not have been applied so generally, but as a choice of analog it still would have been as suitable mathematically as Ohm's or Fourier's laws, and was more closely analogous in

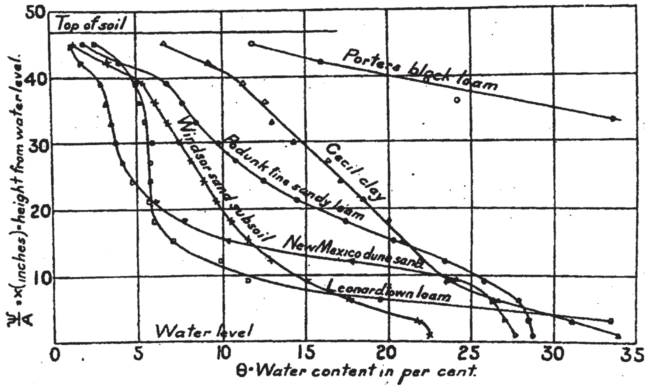


Fig. 4. Measured retention curves for six soils (Buckingham, 1907, p. 32). The symbol A is a proportionality constant depending only on the units chosen for ψ.

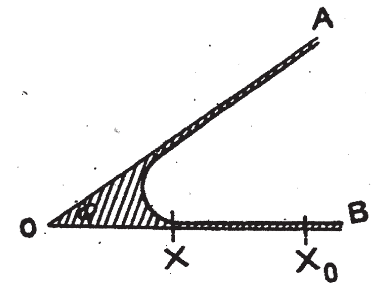


Fig. 5. Buckingham's illustration of capillary water held in a prismatic wedge (Buckingham, 1907, p. 45).

that it treats water flow in a natural porous medium. It is conceivable that Buckingham did not think of his capillary potential as an equivalent of the hydraulic head used in formulating water flow in saturated porous media. Sposito (1986) suggests he simply did not know of Darcy's law. This would explain his neglect of this law that seems to be too closely analogous to ignore. By the standard of later usage one would say he was presenting and applying Darcy's law for the case of unsaturated media. In doing so he played a major role in establishing the generalized version of Darcy's law in our present science. Consequently, when applied to unsaturated flow, this law is sometimes called the Darcy–Buckingham law.

Buckingham introduced the concept of matric potential simply and elegantly: "Let ψ be a quantity which measures the attraction of the soil at any given point for water." After a second definition "Let λ denote the capillary conductivity of the soil," he presented his "formal analogy with Fourier's and Ohm's laws":

$$Q = \lambda\, S \qquad [1]$$

where Q is the flux density (to which he assigned dimensions $MT^{-1}L^{-2}$ rather than the volumetric LT^{-1} favored today) and S is the gradient of ψ. He noted immediately that we should expect capillary conductivity "to be largely dependent on the water content of the soil…." He continued his introduction of the soil water retention relation with clarity and rigor, noting that "ψ depends in some as yet unknown way, differing from soil to soil, on the water content of the soil…." Being nonhysteretic, his formulation represented both θ(ψ) and ψ(θ) as one-to-one mathematical functions, and his writing is ambivalent about whether ψ or θ is best thought of as the independent variable.

Buckingham's desire to measure water retention curves was constrained, but not prevented, by the lack of a direct method of measuring ψ. He devised and successfully tested the hanging column method for soil water retention (Dane and Hopmans, 2002), in which the ψ value corresponding to the water content at a point in an equilibrated soil column is known from its vertical position with respect to a water table. He presented measured retention curves for several soils, six of which are in Fig. 4. He explained differences among soils in terms of pore sizes, much as would be done today. He discussed physical mechanisms that might explain their particular forms and variation among soils. For example, referring to a similar but longer-term experiment than the one illustrated in Fig. 4, he wrote "…the heaviest soil, Cecil clay, holds by far the most water, and the lightest, the Norfolk fine sandy loam, the least." He reported surprising results when measurements were done with steady flow rather than equilibrium, finding soil to be wetter with evaporation rather than drier, and the measured results to depend more strongly on electrolytes than the known electrolytic influence on water properties would suggest. Buckingham noted that the initial water contents were significantly greater for the steady-flow (driven by evaporation) than for the equilibrium experiments. Coupled with his additional observation that the duration of these experiments was insufficient to produce steadiness, this fact could easily have caused the soil to be wetter in the steady-flow (evaporating) soil columns, reasonably explaining this apparent deviation from his (as well as currently accepted) unsaturated flow theory. He concluded the section on water retention with a proposed method for measuring retention curves over a larger range, with an ingenious substitution of multiple closed short columns differing in average water content, for the single long column that would more naturally be indicated.

Buckingham discussed the basic nature of unsaturated hydraulic conductivity in detail, especially its dependence on water content. This discussion included elaborate explanations of how thin-film and filled-pore flow channels conduct water (especially his Fig. 14 and 15, reproduced here in Fig. 5 and 6). He emphasized the geometry of capillary water held in prismatic wedges near particle contacts (Fig. 5). For various reasons, such as its more obvious connection to soil–water hysteresis, the alternative concept of a system of filled and unfilled pores was the dominant conceptual model through most of the twentieth century. In many ways the filled-wedge geometry is a more suitable analog for water in unsaturated soil, as is increasingly recognized in recent years (e.g., Dillard et al., 1997; Tuller and Or, 2001). Buckingham invoked an analogy between capillary and electrical conductivity of soils, though he glossed over or failed to see that frictional effects cause fluid flow to depend differently on channel geometry than electrical effects. Although measurements of unsaturated hydraulic properties were essentially unheard of before his work, Buck-

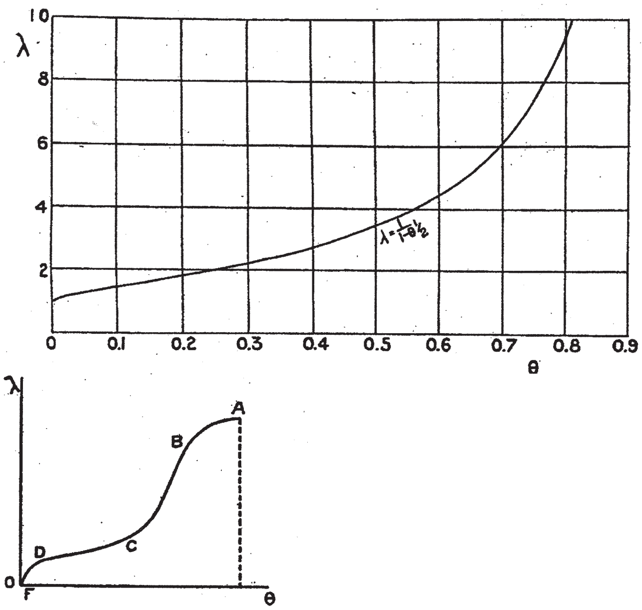


Fig. 6. Hydraulic conductivity relation as a function of water content, (above) by Buckingham's semiempirical formula (Buckingham, 1907, p. 46) and (below) as a sketch with characteristic segments of the curve labeled A-F (Buckingham, 1907, p. 43).

ingham also noted what today is an obvious generalization, that experimental data are very hard to get in soils that are either nearly saturated or very dry.

Buckingham devoted considerable effort to deriving a functional form of $K(\theta)$. He considered several types of channel geometry for the water in unsaturated pores, and described two in detail: prismatic wedges and films on monodisperse spheres. He used the term "drops" to mean isolated blobs of liquid water (e.g., pendular rings of liquid at grain contacts) connected to the rest of the liquid phase only by thin films. Somewhat at odds with later thinking on this subject, Buckingham stated that "…the total resistance, and therefore the total capillary conductivity of the soil, will be determined almost entirely by the films and only to a minor degree by the shape and size of the capillary drops." The modern conception of the isolation of "drops" is similar to Buckingham's, but the water content threshold below which such isolation is effective differs somewhat; models based on filled capillaries are commonly applied down to low values referred to as "residual" water content (e.g., Mualem, 1976). Buckingham (1907, p. 43) noted that evidence that would have permitted him to say whether this threshold was generally at high or low water content was not available. Appropriately, in this first effort of this type, he limited his analysis to evaluating the basic functional form, rather than proceeding to a practical calculation of K from θ. Figure 6 shows the formula he suggested for this purpose.

Later in his text, Buckingham presented an elaborated version of his equivalent of Darcy's law for unsaturated soils, introducing within it the specific water capacity ($\partial\psi/\partial\theta$) so that the problem could be conceived in terms of fluxes and gradients of a single variable, θ:

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

As the unsaturated hydraulic conductivity is analogous to thermal or electrical conductivity, the specific water capacity is analogous to specific heat in heat flow (Narasimhan, 1999). Buckingham stated that it was the nonconstant nature of the conductivity and specific water capacity that distinguishes the formula from the "Fourier-Ohm law":

> If we knew the mathematical forms of ψ and λ as functions of θ, and of θ as a function of x, it is possible, though not probable, that we could give a complete mathematical treatment of the subject. Since we have no such information, we shall turn at once to the consideration of some of the experiments.…

The experiments related to conductivity in Bulletin 38 actually measured a quantity proportional to soil-water diffusivity. Samples of 11 soils were packed in columns in two layers, each of the same soil but different water contents. The amount of water that flows from wet to dry in a given amount of time was measured, and the results expressed as the fraction of the initial water content difference that flowed. Buckingham's description of difficulties associated with direct measurements of unsaturated K would ring true with anyone who has attempted similar measurements in the last 100 yr:

> …the difficulty of keeping one end of a soil column at a low fixed water content…
>
> …the very long time needed for the establishment of the steady state.
>
> …exact duplication of the mechanical condition of granulation and packing is so far from possible as to require averaging data from many experiments…

Buckingham generalized concerning soil type that flow is somewhat less in heavy soils. Concerning time duration, he noted that

> …there is no certain increase of [fraction of water that flowed] from one to fifteen days and that about two-thirds of the change has occurred in the first hour….It thus appears that the very great initial gradient of water content…produces a sudden translocation of water and a readjustment and great diminution of this gradient….

Concerning the water content dependence of soil-water diffusivity for two soils, results for one of which are in Fig. 7, Buckingham observed that speed of flow reached a minimum "at somewhere about one-half to two-thirds of the optimum water content…." and also that "the water content must be reduced to very low values before the speed of flow…falls to anywhere near zero if it ever does so." He interpreted this observed variation using his unsaturated form of Darcy's law (2) and suggested that the flow minimum occurs because for a portion of the Q vs. water content curve, the increase in $d\psi/d\theta$ with decreasing water content overcompensates for the decrease in K. In other words, the two ingredients of the diffusivity [$K(\theta)$ and $\partial\psi/\partial\theta$] combine such that their product is not monotone, just as we would understand this effect today. Buckingham's inferred shape of the

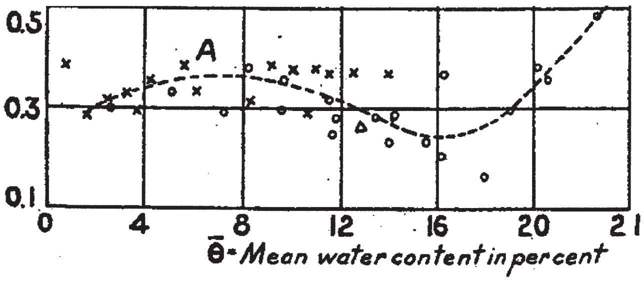


Fig. 7. Data from Buckingham's experiments measuring water flow driven by a difference in matric potential. The ordinate is the mean change in water content of a dry and a wet sample of soil brought into contact in a column, divided by the initial difference in the two water contents. This quantity correlates with the flow rate induced by a difference of water contents, in effect representing the soil-water diffusivity. The results here for a Podunk sandy loam suggest that the diffusivity has a minimum at about 16% water content by weight. The symbol A labels these results as being from experiments of 4-d duration. The different point symbols correspond to minor experimental variations. (Buckingham, 1907, p. 59.)

$d\psi/d\theta$ vs. θ relation implies a reasonably shaped retention curve with an inflection point.

Bulletin 38 ends abruptly, with no summary or conclusion on the topics of capillary flow or capillary action in general. This is ironic, given that the last 22 pages of this report present a major portion of the key concepts, formulations, and experimental methods that would dominate the field of unsaturated flow for a century and perhaps longer. The first two sections, on the evaporation experiments, end with brief summary statements on their main observations. An obvious explanation for the lack of a concluding statement for the third section is that Buckingham was rushing to finish this report in the last few weeks before his departure from the BOS (and essentially, from soil physics research) on 14 Aug. 1906. His last evaporation experiment had ended just 6 wk earlier. The last part of the third section is not as neatly constructed as preceding ones (e.g., there are obvious redundancies), as if written more hastily. Another possibility is that consciously or not, Buckingham may also have been trying to avoid criticism of the sort that King directed against Bulletin 25. Since King's criticisms applied to the extensive concluding sections of that report but far less to its main text, Buckingham may have been motivated to preclude such selective reading by simply omitting any concluding summary.

EVENTS AFTER BUCKINGHAM'S DEPARTURE FROM THE BUREAU OF SOILS

Landa and Nimmo (2003) documented that there was no significant delay in the publication of Bulletin 38 as was proposed by Philip (1974, 1988); on the contrary this report was expedited through the approval and publication processes. This evidence, as well as the evidence published by Gardner (1977, 1986) concerning the lack of animosity between Lyman Briggs and Buckingham, clearly establishes that there is no support for the notion that Briggs tried to suppress Buckingham's work, bullied him out of soil physics, and thereby caused the slowdown of soil physics research that continued for two decades after 1907. Ironically, the absence of the alleged 2-yr delay in publishing Bulletin 38 is self-evident from the text of Bulletin 38 itself, a fact that since at least the 1970s has escaped notice by all commentators on Buckingham's work. This includes the senior author of this paper, who did not realize it until his rereading of Bulletin 38 in April 2004, when he already knew the alleged delay did not occur. The experiments that were the foundation of the research presented in Bulletin 38 were conducted in 1905 and 1906, ending on 2 July 1906, according to Buckingham's published text. Thus the publication date of 14 Feb. 1907 affords no possibility of a 2-yr delay.

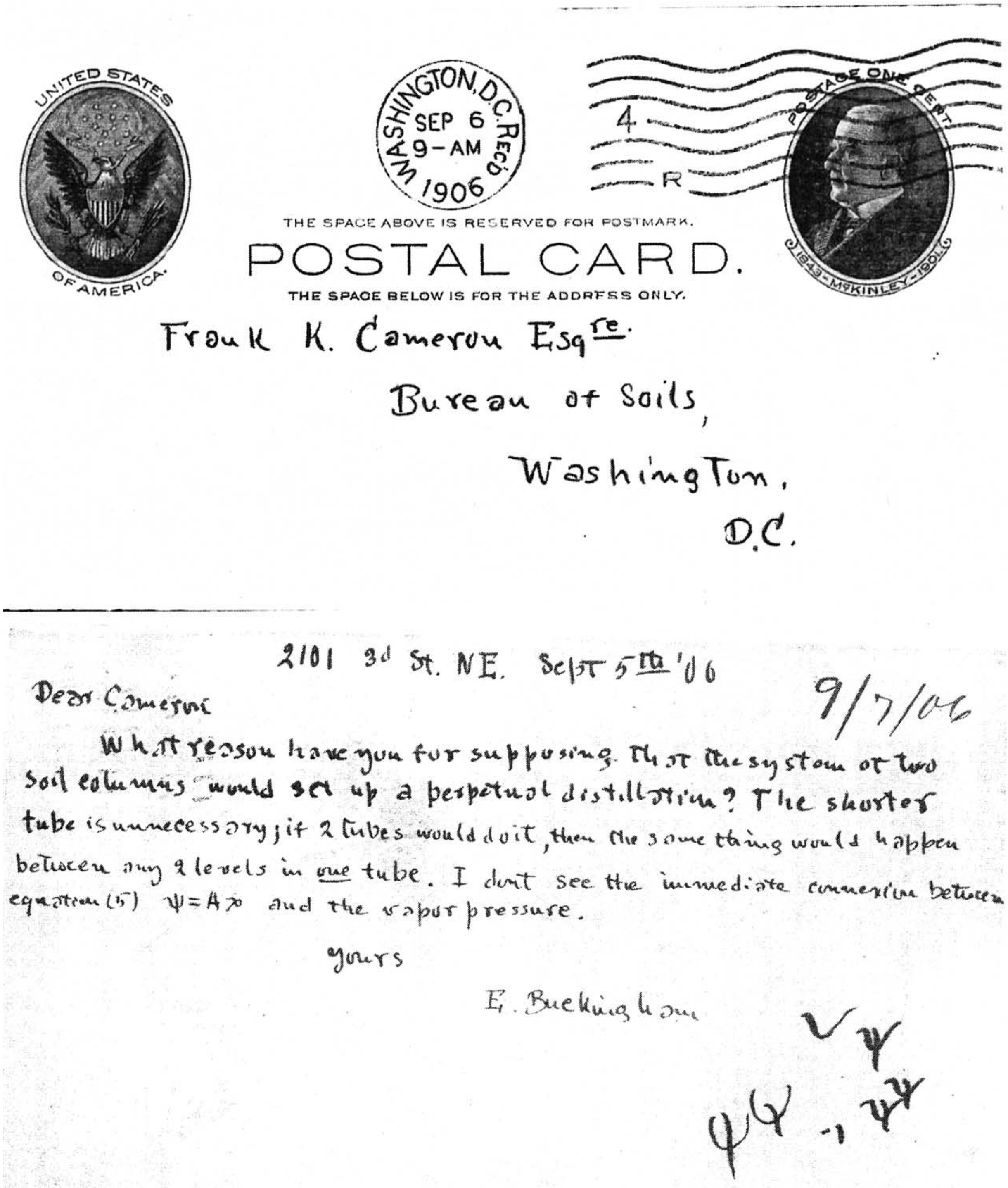
After Briggs left the BOS on 27 Dec. 1905, Buckingham's immediate supervisor was Frank Kenneth Cameron (1869–1958). Cameron received his Ph.D. in chemistry from Johns Hopkins University in 1894, and headed the soil chemistry laboratory at the BOS from 1899 to 1915, when he left for a consulting career. In 1926, he joined the chemistry faculty of the University of North Carolina, where he remained until retirement in 1946. Milton Whitney remained Chief of the BOS. Thus Cameron and Whitney were the ones overseeing the publication of Buckingham's Bulletin 38.

Dispute with Cameron over Alleged Contradiction

Three rounds of correspondence between Cameron and Buckingham between 31 Aug. and 14 Sept. 1906 concerned a perceived contradiction between Buckingham's theory and fundamental laws of thermodynamics. Figures 8 and 9 show two of Buckingham's responses in this series. In his initial letter addressed to Buckingham at the NBS, Cameron proposed a hypothetical experiment involving vapor-phase transport of soil water. His point concerned the difference in potential at the tops of two open soil columns whose lower ends are submerged in pooled water within a closed chamber (diagram on the left side of Fig. 9). Cameron said that the different ψ values, predicted from the column height according to Buckingham's theory, would drive vapor flow from the shorter to the taller one. Accumulated excess moisture would flow in the liquid phase down the taller column, through the pool, and up the shorter column to evaporate again, establishing perpetual motion. His unstated implication is that therefore Buckingham's development contains a fatal flaw. Cameron's letter requested a speedy reply, and expressed impatience to get the manuscript to the printer.

On September 5, Buckingham replied curtly with a postcard (Fig. 8), not answering the question, and refusing to see any reasonable objection. In a tone that might be sarcastic, he implicitly criticizes Cameron's objection for inelegance, as it could be raised with a simpler illustration than Cameron used (one column instead of two). He might have been feigning ignorance of the real issue Cameron raises, or he might have been disinclined to give it serious thought.

Cameron's reasoning comes from a fairly thorough


UNITED STATES OF AMERICA

WASHINGTON, D.C. REC'D SEP 6 9-AM 1906

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POSTAGE ONE CENT

1843-McKINLEY-1901

THE SPACE ABOVE IS RESERVED FOR POSTMARK.

POSTAL CARD.

THE SPACE BELOW IS FOR THE ADDRESS ONLY.

Frank K. Cameron Esqre.
Bureau of Soils,
Washington,
D.C.

2101 3d St. NE. Sept 5th '06

9/7/06

Dear Cameron

What reason have you for supposing that the system of two soil columns would set up a perpetual distillation? The shorter tube is unnecessary; if 2 tubes would do it, then the same thing would happen between any 2 levels in one tube. I don't see the immediate connection between equation (5) $\psi = A\pi$ and the vapor pressure.

Yours

E. Buckingham

Fig. 8. Front and back of 5 Sept. 1906 postcard from Buckingham to Cameron. It appears to be annotated later, possibly by Cameron, with "9/7/06," likely the date of receipt, and doodle-like pennings of two styles of the Greek letter ψ.

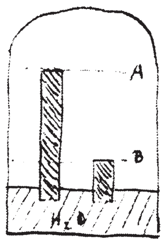
understanding of Buckingham's theory and the relevant thermodynamics of vapor and liquid transport. He may not have deduced that both the water vapor pressure and the water content (expressible, e.g., as relative humidity) of the air within the closed chamber would vary over the space between his imposed boundary conditions, a mistake that would be easy to fall into. If he erroneously assumed that the relative humidity was uniform, then the greater absorptive ability of the surface at A would create an imbalance favoring condensation over evaporation, while the converse would occur at B. Of course in reality, the relative humidity will be less at A than at B, and will compensate for the difference in absorptive ability.

Cameron's immediate response (September 7), took a less formal tone and spelled out his objection in excruciating detail. He noted again that he is "very anxious to get the manuscript off." On September 10, Buckingham

2101 3d street N.E.
Washington Sept. 10th '06
9/11/06

Dear Cameron

Your letter of the 9th has just reached me tonight; the answer to it is as follows:



The tendency to take up water is greater in the dryer soil at the level A than in the moister soil at the level B, as indicated by the equation (5) $\psi = Ax$. This means simply, in other words, that the vapor pressure is less over A than over B, which is in accordance with the usual line of reasoning, the water surfaces at A being more concave than those at B, because there is a greater height, i.e., weight, of water hanging from them. The whole arrangement, when set up as you have suggested, will be in equilibrium just as two capillary tubes would be if distillation both had the same diameter and both were short enough that the water rose clear to the top.

It might all be worked out by an isothermal cycle: evaporate a given mass of H_2O at A, compress & lower to B and condense on the shorter column; take account of the two (different) latent heats, the work of compression, and the work of gravity. But as we haven't the data regarding the latent heats we should only get an approximate result so that it isn't worthwhile — too much like A.A. Noyes!

Yours
Edgar Buckingham.

Fig. 9. The 11 Sept. 1906 letter from Buckingham to Cameron. At upper left is Buckingham's sketch of the thought experiment proposed by Cameron, which Cameron proposed would generate perpetual motion according to Buckingham's new theory of unsaturated flow.

replied with a handwritten letter (Fig. 9) including a sketched figure probably resembling the one, now lost, that Cameron refers to on August 31. He gave a serious but awkward answer to Cameron's question, concluding with an outline of how the issue could be resolved quantitatively, with allusions to thermodynamic complexities of marginal relevance. He correctly noted that this issue with columns of soil is equivalent to a system of simple capillary tubes. His answer discusses variations in vapor pressure within the chamber, but in terms of what it is immediately adjacent to the surfaces of the columns and not explicitly noting that the concentration of water molecules in the air near A will differ from that near B. Buckingham's skill for explaining physical phenomena demonstrated in Bulletin 38 and other publications is not fully apparent here. Cameron probably was not aware of any implicit assumption of uniformity of water vapor distribution, and it may not have occurred to Buckingham that Cameron could be making such an assumption.

A letter from Cameron on September 11 indicates that he did not fully understand Buckingham's response, but he would argue no further:

> I am sorry to say that I cannot help feeling a little doubtful about the matter, but as you seem to be convinced that it is all sound and safe, and are the one who has got to take the medicine any how we will let it go at that.

Again Cameron said he was "very anxious to get the matter off my hands…." He mentioned other prepublication tasks and asked Buckingham "whether you prefer to prepare them yourself or intend to shove that off on me." On September 14, Buckingham sent a postcard assuring Cameron that there are no inconsistencies in his formulation related to the point Cameron raised. Concerning the tasks to be done he wrote "I will attend to it," and he wished Cameron an enjoyable vacation.

Dispute with Whitney over Concluding Remarks

In November 1906, Buckingham wrote a concluding discussion that he intended for publication as the final portion of Bulletin 38. On November 14, Buckingham sent the two new paragraphs to Whitney with a corrected version of the manuscript. Whitney replied on November 17:

> I deem it wise to omit the paragraphs under the heading "Conclusion." They are very brief and merely state that the problem is very difficult but not hopeless and that this bulletin furnishes a starting point for further development. These facts are patent in the paper itself and I think it would weaken rather than strengthen the paper to reiterate them as the sole positive conclusions which you would care to draw from the work.

In a letter on November 20 Buckingham replied

> I think you make a mistake in omitting my concluding remarks, but as the responsibility goes with the authority I can of course only express an opinion.

Preserved in the National Archives, the handwritten text of this unpublished conclusion (Fig. 10) reads:

> The foregoing pages contain a discussion of the nature of the problem presented by the investigation of the laws of capillary conduction of water through soils, together with a description of a number of experiments. The problem is too difficult to permit of any rigorous theoretical discussion on the basis of our present experimental knowledge, and the experimental difficulties, particularly the time-consuming nature of the work, are such that in spite of the amount of labor already expended the positive results obtained so far are rather meagre. Some of the theoretical and experimental difficulties have been pointed out and this paper may well serve as a starting point for further investigations.
>
> Such an investigation, if it is to be anything more than a collection of facts with purely empirical generalizations, must comprise separate investigations of the water holding power of soils or their capillary potentials, and of their capillary conducting powers; for a knowledge of these is essential in interpreting the results of the third section of the work namely the study of the flow of the water itself. The nature of the experimental difficulties may best be seen by noting that in the absence of an efficient soil hygrometer we are in much the same position as would be a physicist who without any knowledge of Fourier's work and with no thermometer at his disposal should try to investigate the subject of thermal conductivity. The problem is difficult but not hopeless the main obstacle being the vastness of the amount of careful experimentation that is needed.

These paragraphs present Buckingham's vision of future research that would bring his theoretical framework to practical fruition. The second paragraph indicates how clearly Buckingham perceived that the problem of water movement in soils depended on static properties (water retention relations) as well as dynamic properties (hydraulic conductivity). He also clearly saw that experimentation was the key to further fundamental advances, borne out by later developments of the tensiometer and psychrometer ("an efficient soil hygrometer").

When Bulletin 38 appeared, the pro forma letter of transmittal, dated 27 Nov. 1906, was signed by Whitney in his role as Bureau Chief. The four paragraphs that Cameron wrote for the descriptive preface have a consistently upbeat tone and summarize several of the major developments presented in the paper.

In the annual reports of the Chief of the BOS (Whitney, 1908, 1909), in contrast to the treatment of Buckingham's work on soil aeration in 1905, there is no direct mention of Bulletin 38 or the soil moisture studies in it. This omission suggests again that Whitney failed to see the importance of Buckingham's work, even though he thought that the agricultural productivity of soil was more dependent on soil physical properties than soil fertility.

Buckingham's Later Work Related to Soil Physics

In the succeeding three decades of Buckingham's illustrious career as a physicist, he never returned to topics of soil physics. He did do research on fluids, for example in a paper on flow in pipes (Buckingham, 1921). That paper, however, is mainly relevant to liquids that include a large proportion of tiny solids, such as pigments in paints, as opposed to water or air in soils. Possibly Buckingham's most celebrated achievements are in the field of dimensional analysis, especially his famous Pi theorem (Buckingham, 1914). Many concepts of this theorem were incorporated into similitude analysis, a major topic of soil physics since Miller and Miller (1956) introduced it to this field.

DISCUSSION

Buckingham's Influence on the Course of Soil Physics Research

After Bulletin 38, rapid progress toward a quantitative understanding of unsaturated flow terminated abruptly. Over a period of decades, however, techniques Buckingham said would be necessary, such as tensiometry, were

Conclusion

The foregoing pages contain a discussion of the nature of the problem presented by the investigation of the laws of capillary conduction of water through soils, together with a description of a number of experiments. The problem is too difficult to permit of any rigorous theoretical discussion on the basis of our present experimental knowledge, and the experimental difficulties, particularly the time-consuming nature of the work, are such that in spite of the amount of labor already expended the positive results obtained so far are rather meagre [redacted]. Some of the theoretical and experimental difficulties have been pointed out and this paper may well serve as a starting point for further investigation.

Such an investigation, ~~should~~ if it is to be anything more than a collection of facts with purely empirical generalizations, must comprise ~~the~~ separate investigations of the water holding power of soils ~~which~~ or their capillary potentials, and of their capillary conducting powers; for a knowledge of these is essential in interpreting the results of the third section of the work namely the study of the flow of water itself. The nature of the

Fig. 10. First page of Buckingham's intended conclusion to Bulletin 38, written in November 1906.

developed, and his theory of unsaturated flow eventually was applied as the basis for quantitative prediction of such flow. Buckingham's matric potential concept was used at Utah State College (now Utah State University) in the 1920s, as Richards (1931, p. 318) explains:

> Buckingham (1907) was among the first to attempt a detailed analysis of capillary flow. He assumed capillary attraction to constitute a conservative force field and defined a capillary potential, the gradient of which was equal to the capillary force. Some years later Gardner and his associates [1922] pointed out that the Buckingham potential was closely related to the pressure in the water films and showed that porous clay apparatus could be used for its measurement.

Twenty-four years passed between Buckingham's publication of Eq. [2] above and the publication of Richards' equation, which simply folds the continuity equation into a generalized Darcy's law equivalent to Buckingham's equation with gravitational potential explicitly included. Buckingham's theory implicitly contains all that is needed to compute dynamic unsaturated flow in space and time, if done iteratively for the coupling of the flow with the change in K and driving force resulting from changing water content. Richards' equation made the mathematical procedure more practical. As to why the next steps in this research topic took so long, it can be said that Buckingham was ahead of his time, as Gardner (1986) suggests, but it also seems likely that the rest of the world would not have taken so long to catch up with him if more of the brilliant soil physicists of the very early twentieth century had not been so effectively encouraged to leave the field.

Even though he invented numerous ingenious devices to obtain the experimental data he needed, neither of Buckingham's soil physics papers has any apparatus diagrams. Bulletin 25 has no figures of any kind, with quantitative results appearing in the form of tables. Bulletin 38 has 23 figures in its 61 pages. Buckingham's verbal descriptions of his apparatus, however, are complete to the degree that a mental or physical picture can be constructed from them. This type of omission may have been more common 100 yr ago than it is now, but USDA reports at that time were often richly illustrated, not only with photographs and artistically crafted drawings and paintings of crops, but sometimes with highly detailed apparatus drawings. One example is that of Briggs (1898) which was reproduced on the cover of May–June 2003 issue (Vol. 67, no. 3) of the Soil Science Society of America Journal. The absence of apparatus drawings means that the extent and to some degree the importance of Buckingham's experimentation is not apparent without a fairly thorough reading. For a twenty-first-century readership this lack of illustrations would likely have an adverse effect on the breadth of recognition of such work, and one can wonder if it was a factor in the scarcity of attention paid to Buckingham's work in the first few decades of the twentieth century.

Scientific Issues that Remain Contentious

Repeatedly in Bulletin 38 Buckingham directly or indirectly addresses the phenomenon of water flow "through the thin films in which a part of the water is distributed over the soil grains." He did this in connection with liquid water being transported through the soil to evaporate at the surface, as well as with what he believed was the most important mechanism of capillary conduction of water in unsaturated soil. Some of his statements accord with current understanding, for example "it is to be expected than in very dry soils capillary flow will be slow." Others seem oddly to support both sides of the current contention over whether there is a water content below which liquid flow ceases (Luckner et al., 1991; Nimmo, 1991). Buckingham gave the opinion that "A soil can probably not be made so dry as to lose its power of capillary conduction of water entirely…." but also, in connection with the dependence of hydraulic conductivity on water content, he suggests there is a finite water content at which liquid flow ceases (p. 42–43).

CONCLUSIONS

Strained interpersonal relations motivated several departures from the BOS (King, Briggs, Buckingham, and others). Given that this involved the work that was rapidly developing the means of quantifying unsaturated flow, these strained relations probably had serious adverse effects on the advancement of unsaturated flow theory. Ironically, given statements to the contrary that were prevalent in the late twentieth century, no evidence has turned up that suggests animosity between Buckingham and Briggs.

Buckingham's 4 yr as a soil physicist were astoundingly fruitful. With both experimental and theoretical investigations, he addressed several major topics, including gas flow, evaporation, and water flow, each of which as a specialty could occupy a whole career. Major elements of unsaturated-flow research today were originated by Buckingham or are related in some way to his work, for example the concept of matric potential, the concept of soil–water retention curves and specific water capacity, unsaturated hydraulic conductivity as a distinct property of a soil and a function of water content, quasi-empirical formulas for K as a function of water content, the importance of water in capillary crevices and in thin films, the application of Darcy's law to unsaturated flow, and from his later years, scaling. Buckingham's work on gas flow in soils produced paradigms that for the most part are still consistent with our understanding of these phenomena. His work on evaporation elucidated the concept of self-mulching and produced sound and sometimes paradoxical generalizations with respect to conditions that favor or retard evaporation. Largely overshadowing those achievements, however, is that he launched a theory, still accepted today, that could predict transient water content as a function of time and space.

ACKNOWLEDGMENTS

We are grateful to Edgar Buckingham's grandsons Anthony W. Buckingham and Thomas K. Hunt, and to Keith Martin (National Institute for Standards and Technology) for information on the Buckingham family. T.N. Narasimhan, Markus Flury, and Mary Beth Kirkham contributed thorough reviews that led to substantial improvements in the text.

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