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LAWS OF SOIL MOISTURE

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Abstract--Observed regularities in the processes connected with the flow and distribution of water in soils may, if they are sufficiently general, be referred to as laws of soil moisture. The Darcy equation which expresses the proportionality between transmission velocity and the driving force for water in saturated soils is one such regularity that is commonly referred to as a law. Another regularity that applies without exception whenever outflow of free water occurs from soil, is of the nature of a boundary condition, but is here proposed as a law; namely, "Outflow of free water from soil will occur only if the pressure in the soil water exceeds atmospheric pressure." Examples for the application of the outflow law are cited and discussed.

Progress in science and engineering has been based largely on the discovery and use of regularities that occur in the processes of nature. The recognition, verification, and concise statement of these regularities constitute one of the prime objectives of organized experimentation and research. Sometimes we seem to get lost in our forest of experimental facts. When faced with the task of correlating and understanding a maze of seemingly unrelated observations it is comforting to consider the simplifications brought to chemistry by the laws of stoichiometry and the atomic table. It is helpful to think of the tremendous advances made possible in electrical engineering by the Maxwell equations and the brief and concise laws named after Coulomb, Ohm, Faraday, and Ampere.

The important relation of soil moisture to man's welfare has stimulated continuing investigations in agriculture, geology, soil mechanics, ceramics, and allied fields. As a result, a multiplicity of observations and facts have accumulated. Unfortunately these are not very well correlated or understood. Few regularities in soil-moisture processes have been discovered and clearly formulated. It is the purpose of this paper to promote and encourage this process by reference to two general principles. One of these is widely recognized and commonly referred to as a law, the other deserves wider recognition and use by students and investigators and perhaps deserves to be dignified by designating it as one of the laws of soil moisture.

Darcy's Law--DARCY [1856] reported that the rate of flow of water through sand filter beds was described by the equation

$$Q = ks\ (H + e)/e \qquad (1)$$

for the case where the pressure under the filter is equal to the weight of the atmosphere and where Q is the volume of water passed in unit time, s is the area of the bed, e is the thickness of the bed, H is the height of the water on the filter, and k is a coefficient depending on the nature of the sand. As stated, this equation applied to steady linear flow through saturated sand. Water motive forces arising from both gravity and the pressure gradient are taken into account. If we define the transmission velocity $v = Q/s$ and the hydraulic gradient $i = (e + H)/e$ we have

$$v = ki \qquad (2)$$

which is a vector equation applying to three-dimensional flow in isotropic media and is often taken as the general form of the Darcy flow law. The equation expresses the fact that the flow rate is proportional to the water motive force. MUSKAT [1937] has reviewed the conditions under which the law is valid and has given an excellent summary of methods and examples for the application of the law to the solution of practical flow problems. Numerous scientists and engineers throughout the world have used this law as a basis for a rational analytical attack on problems involving the flow of water in saturated soils.

Our definitions and methods for measuring permeability are based directly on the Darcy law. Numerous permeability units for soils have been considered [MUSKAT, 1937; RICHARDS, 1940]. The simple Darcy coefficient k in (1) and (2) is most commonly used in agricultural soils work. The large and rapidly changing effects produced by the interaction of colloidal and organic material and the quality of water make it impractical to take into account small effects such as are due to change in viscosity with temperature. It is seen that k, the permeability, is equal to the transmission velocity when the hydraulic gradient is unity, that is, when the driving force is equal to 980 dynes/gram.

It is surprising, in view of the long and useful history of the Darcy law, that some soil scientists and engineers are even yet reporting laboratory permeability data on the effect of various treatments on the water-transmitting properties of soils under conditions where the hydraulic gradient is unmeasured and unreported.

Practical applications of agricultural research are made in the field, and here the transmission velocity is a more useful, usable quantity than permeability. Permeability can be measured on samples which are transported to the laboratory. The hydraulic gradient which operates in the field, however, is determined by the characteristics and boundary conditions for the whole profile. Consequently, the hydraulic gradient is a soil moisture factor that generally must be measured in the field. Field methods for appraising both permeability and the hydraulic gradient are under active development at the present time and the Darcy law is a unifying and simplifying basis for progress with this work [PILLSBURY and CHRISTIANSEN, 1947; KIRKHAM and van BAVEL, 1948].

Outflow law--It has been recognized by some investigators that a special boundary condition for the pressure of water in soil must be met before water outflow will occur. A general statement of this principle which is here proposed as a law of soil moisture might be phrased as follows: "Outflow of free water from soil occurs only if the pressure in the soil water exceeds atmospheric pressure."

This relation is so simple and obvious as scarcely to need formulation and proof. Newton's first and third laws of motion also appear to be almost obvious, and yet these simple laws, when logically applied, can lead to conclusions which may not be obvious.

The outflow law may be simple demonstrated with a wick siphon as shown in Figure 1. Wet a piece of clean cotton cheese cloth with water and crumple it into a porous roll about three cm in diameter and 20 cm long. Hang the roll over a rod and mount a beaker with the water at the same level as the free end of the wick as shown at A. Surface tension action will cause water in the porous wick to come to pressure equilibrium with water in the beaker. Water at each level in the right hand side will have the same pressure as water in the left hand side of the wick at the same level. Thus water at the free end of the wick will be at atmospheric pressure and no outflow will occur. If the beaker is raised slightly as shown at B, pressure in the water throughout the wick will be raised and drops will begin to form and continue to fall from the free end of the wick.

The outflow law applies to the entry of water into underground tile drains and drainage of

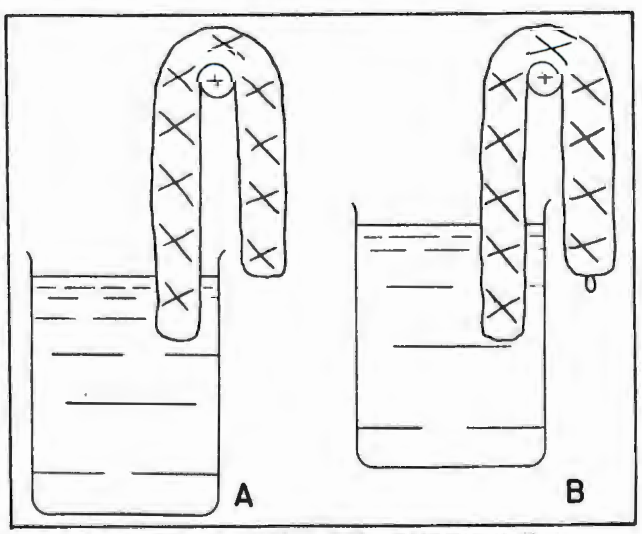

Fig. 1--Demonstration of the moisture outflow law with a wick siphon

water from lysimeters and soil pots used for growing plants. The law applies to the anomalous field drainage case where a shallow soil layer of fine texture is underlain with coarse material. Instead of providing improved drainage, the abrupt transition zone from fine to coarse texture acts like a perched water table because the soil moisture at the lower boundary of the fine-textured layer must come practically to atmospheric pressure before it will move into the coarse material. ZUNKER [1930] has discussed this soil moisture phenomenon.

Applications of the outflow law--Lysimeters constitute an important case for the application of the outflow law. RICHARDS, NEAL and RUSSELL [1939] used tensiometers to study moisture relations in the lysimeters of the Soil Conservation Service Experiment Station at Clarinda, Iowa and state, "Before free water will drain away from a lysimeter it is necessary that the pressure in the soil water at the base of the column shall approach atmospheric pressure." In the same volume, RICHARDS and JOFFE [1939] reported laboratory experiments with soil columns where drainage to a conventional lysimeter funnel and drainage to a tension plate that was used to simulate deep soil percolation were compared. They recognized and stated the zero pressure (zero tension) outflow boundary condition. Earlier statements of the outflow law as applied to lysimeters have undoubtedly been made and the writer would appreciate having these earlier statements called to his attention.

KOHNKE, DREIBELBIS, and DAVIDSON [1940] made a survey of the construction and use of lysimeters and state, "The greatest functional error in all three types of lysimeters probably occurs at the boundary of the lysimeter soil and the air beneath it. When the gravitational water reaches this point it will have to overcome the resistance set up by surface tension before it can leave the soil." These authors indicate that lysimeters have been used for experimental work for more than 260 yr and cite nearly 500 references to publications on lysimeter work. And yet it is only recently [COLMAN and HAMILTON, 1947] that this outflow boundary condition has been taken into account. Anomalous results obtained with different types and different depths of lysimeters in response to different cropping and rainfall conditions can often be explained if the outflow boundary condition and its effect on the moisture regime are clearly understood.

When the outflow law is more generally recognized it is expected that lysimeters designed for hydrological studies will embody porous structures such as proposed by RICHARDS and JOFFE [1939], WALLIHAN [1940], and COLMAN [1946], so as to simulate more closely moisture conditions in the natural profile.

Soil pots which are used in varying sizes for the experimental and commercial growing of plants are, like lysimeters, subject to the outflow law if sufficient water is applied so that drainage occurs. The moisture regime is quite different from field conditions and accounts for the fact that liberal admixtures of sand and peat are made to potting soil by commercial growers in order to increase the size of the soil pores. In view of the outflow law it is clear that special precautions with irrigation are required to avoid abnormal plant responses caused by water logging if tests are to be made with small lots of fine textured soils.

SHAFFER, WALLACE, and GARWOOD [1937] have shown that the outflow law applies at the periphery of porous media in a centrifuge and recognition of this fact made it possible to obtain a theoretical solution of the moisture equivalent centrifuge problem [RICHARDS and WEAVER, 1944].

While the present discussion relates primarily to soils, we must keep in mind the unity of all science. The two laws of soil moisture stated above appear to apply equally well to any liquid in any porous medium which is wetted by the liquid.

Additional laws--Additional laws of soil moisture will be discovered and formulated as our knowledge of soils increases. Some readers may wish now to propose additional laws. For example the movement of water in the root zone for soils that do not have water tables, permanent or temporary, takes place under unsaturated conditions. The original statement of the Darcy law did not include unsaturated flow. The extension of the Darcy equation to cover unsaturated flow for the isothermal case has been made and is in the state of what might be called a working hypothesis. Perhaps at some future time the Darcy law can be generalized to cover both saturated and unsaturated flow conditions.

The complicated interrelation of heat and moisture transfer in unsaturated soil can probably be expressed in simple general terms but as yet little progress has been made in this direction.

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DISCUSSION

E. C. Childs (University of Cambridge, Cambridge, England)--I am in general sympathy with Richards' thesis, and with him, deplore a current tendency to confuse permeability with an observed infiltration rate in unspecified and unreproducible conditions. I should, however, prefer to express Darcy's law in the three-dimensional form

$$v = -k \text{ grad } \phi$$

where ϕ is the hydraulic potential, grad ϕ reducing to Richards' i for one-dimensional flow. My preference is no doubt due to my greater concern with drainage problems which are rarely one-dimensional [CHILDS, 1943, 1945a, 1945b, 1946, 1947a, 1947b, 1948; CHILDS and GEORGE, 1948]. For the rest, I should like to discuss one section only of RICHARDS' paper, that dealing with unsaturated soil. I do not think that Darcy's law itself needs to be generalized; we just have to recognize that the permeability so defined is a function of moisture content (as indeed was demonstrated by Richards' own pioneering work) a function which has received a satisfactory formulation in my laboratory [CHILDS and GEORGE, 1948]. It may then be convenient and possible for some problems to express the rate of water movement in terms of moisture content gradient, that is, by a diffusion equation) since a given moisture profile implies both a known potential gradient and permeability at a given point [CHILDS and GEORGE, 1948]. The complete solution of the problem of water movement down a moisture profile then becomes a matter of solving the problem of non-linear diffusion, perhaps complicated by hysteresis. It seems to me that it is along these lines that progress appears most promising.

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E. A. Colman (California Forest and Range Experiment Station, Berkeley, Calif.)--In order to emphasize the significance and implications of the outflow law which Richards has proposed, I should like to mention some of the information we have obtained from the San Dimas lysimeters [COLMAN and HAMILTON, 1947]. When the large lysimeters of this installation were built we did not cover the tank bottoms with a layer of gravel, recognizing that such a layer would not insure drainage of the soil above to field capacity. Instead the tanks were filled entirely with uniform soil. Later we placed tensiometers in the soil at the seepage outlets (the soil is six feet deep) and measured moisture tensions before, during, and after seepage periods. Over several years of observations we found, as was to be expected, that seepage did not start until moisture tension dropped to zero in these tensiometers, nor did the tension increase again until seepage had stopped.

During the period of these observations we also had tensiometers placed with their porous cups at various levels within the lysimeter soil. These tensiometers showed that during periods of seepage, zero moisture tension was maintained in the soil to a height of three feet above the seepage plane. This suggested that the lower half of the soil in these tanks was virtually saturated through a considerable part of the winter rainy season, a condition which is far from normal for this soil and the vegetation studied, in their natural state.

These and similar observations have led us to believe that lysimeters must be equipped with drainage control devices if results obtained from them are to have application beyond the lysimeters themselves.

Willard Gardner (Utah State Agricultural College, Logan, Utah)--It is to be expected that the curvature of the air-water interface at the bottom of the right-hand part of the tube represented in A of Figure 1, would be zero and the pressure throughout the tube would not be disturbed by placing this end of the tube also in water at the same level as that in the beaker. This should represent the same state of equilibrium as before, the force per unit volume due to the pressure gradient being balanced by the pull of gravity per unit volume.

The water at the end of the tube on the right of B would tend to develop a convex curvature with a slight increase in pressure sufficient to keep the water in the tube even though the interface at this end were slightly below the level of the water in the beaker. The interface, if curved, does therefore have a slight influence on the state of equilibrium. However, were this interface also removed by dipping the end into free water at a level lower than that in the beaker, the water would of course move out of the beaker through the tube however small the difference in elevation may be so long as it does not vanish completely. There exists also a small pressure gradient in the atmosphere that should not be overlooked but it would modify the problem very little to reduce the atmospheric pressure to zero.

Can we not infer all that this proposed outflow law implies? We may infer for example from Newton's second law that if a particle moves in the direction of a constant force that is applied to it the distance it travels is a quadratic function of the time, but we would not be inclined to regard this as a new law.

Don Kirkham (Iowa State College, Ames, Iowa)--In an article "Some tests of the diffusion theory, and laws of capillary flow in soils" [Soil Sci., v. 67, 1949], C. L. Feng and I report data which show that the horizontal capillary flow of water from a free water source into air-dry soil takes place in accordance with the laws $Q = At^{1/2} + a$ and $X = Bt^{1/2} + b$, where Q is the quantity of water absorbed in time t, X is the distance of advance of the wet front and A, B, a, and b are constants, the latter two for practical purposes zero. The equations were designated laws because of their simple nature and because Richards had pointed out, soil moisture laws, if we have them, should be announced. Whether or not the expressions should be called "laws," we are still aware that a more important expression, a law for capillary flow, remains to be discovered. It is hoped this law would relate simply the rate of water movement, moisture content, and driving gradient, all, over a wide range of moisture content. As Richards indicates this law must reduce to Darcy's law when the soil is water-saturated. The law will also have to conform to the laws given above.

Helmut Kohnke (Purdue University, Lafayette, Indiana)--I am glad to see the outflow law so clearly stated by Richards. It may be added that outflow begins at the threshold between tension and pressure. I believe the first time the outlfow law was taken into account in the design of lysimeters was 1936 at the North Appalachian Watershed Experiment Station near Coshocton. A depth of eight feet was chosen to provide adequate moisture tension in the main root zone. Shallow lysimeters with porous bottoms held at certain tensions have the disadvantage of removing water from the soil body that cannot climb up again in vapor or liquid form as it would under field conditions. It seems that a considerable depth is a prerequisite for future lysimeters, The wick experiment as demonstration of the outflow law is extremely clever and simple. I wonder why Darcy's law has not also been expressed in the form of a sentence in this paper as the outflow law has been.

M. R. Lewis (Bureau of Reclamation, Washington, D. C.)--The phenomenon discussed by Richards furnishes an excellent example of delay in formulating the laws governing soil moisture. WIDSTOE and MCLAUGHLIN [1912] found that after free drainage ceased, more moisture remained in a one-foot column of soil than in the upper foot of a three-foot column. VEIHMEYER, ISRAELSON, and CONRAD [1924] found that the deeper the soil column used in the determination of the moisture equivalent the less the average moisture content at the end of equal periods of exposure to the same centrifugal force. PIPER [1933] and others have noted that the field capacity or specific retention of soils cannot be determined by merely draining short columns of soil resting on coarse sands or screens. Undoubtedly such manifestations have been noted over a long period but the law was not clearly stated, so far as the writer knows, before the 1939 reports cited. About 1918, W. G. Sloan and the writer had occasion to make an interesting demonstration of the phenomenon. It was denied that a certain irrigation canal on high land was losing water by seepage and the denial was backed up by a showing that water did not drip from the roof of an unlined horizontal opening a few feet below the bed of the canal. To counteract this evidence a rectangular hole was cut in a strip of blotting paper and one end of this was placed in a tumbler of water while the other end, with the hole, was bent down on the outside. Soon water dripped from the end but none crossed the open space.

There is great need for a clearer understanding of the similarities and dissimilarities of flow in saturated and unsaturated soils and it is to be hoped that progress will be made in developing the applicable laws.

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A. F. Pillsbury (University of California, Los Angeles, California)--This paper serves the admirable purpose of pointing up simple, fundamental, soil-water relationships. Question might be raised as to whether or not the Darcy equation should be called a law because it holds only for laminar flow, and because of the problems related to unsaturation. Also, BUCKINGHAM [1907] appears to be the first to recognize the outflow law, and VEIHMEYER, ISRAELSON, and CONRAD [1924] recognize the saturated condition of the outer face of moisture equivalent samples.

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S. J. Richards (University of California, Riverside, Calif.)--By suggesting the use of the word laws to name the generalizations discussed in its report, the committee may be generating smoke which will hide the fire of the real purpose for writing the report. For example, many workers will prefer to call Equation (2) the Darcy Equation when applying it to unsaturated flow. However, the name used should be subordinated to the idea involved. The ideas suggested are fundamental and useful. They should be stated in terms that will give the greatest distribution among workers.

The outflow law as stated relates only to the moisture close to the horizontal plane at which the outflow boundary occurs. In the discussion of the application the suggestion is made that moisture in soil layers above the location of the outflow is influenced, which is certainly the case. Soil moisture above an outflow boundary may be under a tension, T, equal to the height of the soil, h, above the boundary. (T is here measured in length units of equivalent soil solution.) For the case when the soil moisture is draining downward to an outflow, then the tension at any elevation must be less than the vertical height measured to the outflow boundary.

L. A. Richards (U. S. Regional Salinity and Rubidoux Laboratories, Riverside, Calif.)--The reviewers' comments make distinct contributions toward the appraisal and interpretation of the contributed paper and scarcely need a summarizing statement. However, a few points brought out in the discussion will be briefly mentioned.

Equation (1) was developed by Darcy for a linear, one-dimensional flow case and Eq (2) was developed in the above paper by substituting new symbols in Eq (1). It was not the writer's intention, however, to imply, as Childs apparently does in his comments that Eq (2) does not apply to the three-dimensional case. CHRISTIANSEN [1943] and REEVE and JENSEN [1949] use a flow equation equivalent to Eq (2) for describing non-linear, ground-water, flow patterns under field conditions. The hydraulic gradient i in Eq (2) may be taken as identical with grad ϕ in Childs' equation. The negative sign signifies only a difference in an arbitrary convention of nomenclature between physics and engineering.

The points raised by Gardner are certainly pertinent. Back pressure from positive curvatures of the air water interface will usually exist and will influence outflow. The negative form used in the above statement of the outflow law, namely, "Outflow of free water from soil will occur only if the pressure in the soil water exceeds atmospheric pressure," takes the back pressure effect into account. The effect connected with the pressure gradient in the atmosphere as mentioned by Gardner does not appear to apply if atmospheric pressure mentioned in the above statement is considered at the point of outflow.

The last question raised by Gardner is quite appropriate. What criteria should be satisfied by an observed, formulated and verified regularity in the processes of nature before it may properly be designated as a law? If the relation $f = ma$ can be inferred from the principle of least action, should we cease to refer to this equation as a law? Are the empirical relations mentioned by Kirkham similar to the examples of the quadratic function mentioned by Gardner?

Because the Darcy equation does not hold for turbulent flow and has not been demonstrated to hold for unsaturated flow, Pillsbury and Richards question whether it should be referred to as a law. Following the same reasoning would these men say that since a relativity correction must be applied at high velocities, $f = ma$ should not be called a law?

Certainly these are questions for which there is no brief answer. Obviously it was the objective of the contributed paper to state the outflow boundary condition in clear, concise form for pedagogic purposes. This important relation which has many practical applications does not appear to be widely familiar to soils workers. Whether ultimately it will be referred to as a law or simply as a boundary condition will have little effect on its usefulness. Discussion on whether it constitutes a law might even promote the objective of the contributed paper.

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