

THE USEFULNESS OF CAPILLARY POTENTIAL TO SOIL-MOISTURE AND PLANT INVESTIGATORS¹

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INTRODUCTION

Soils literature contains numerous discussions of the problem of the movement of moisture in the soil and its availability to the plant. In a great many cases, however, the point of view is that of the experimentalist, and the possible advantages that may accrue from a consideration of the generalizations available in the literature of physics and chemistry are almost wholly overlooked.

One investigator, for example, discovers from his experiments that water evaporates more rapidly from a moist than from a dry soil; another discovers that the moisture tends to accumulate toward the rim of a sample in the centrifugal machine; still another finds that a wet clay will absorb moisture from a sand comparatively drier. Many examples of this character may be pointed out as results of experimentation purporting to represent contributions to scientific knowledge. By such experimental procedure and by careful analysis of the resulting data we may succeed anew in working out generalizations from which we may predict with some degree of certainty, qualitatively at least, the way in which soil water will move under certain conditions. If we are to profit by experience we must make these generalizations, but it is quite probable that in many cases such generalizations will be found to conform with those that are already known to the basic sciences.

It is at once obvious that a mixture of mineral fragments of numerous kinds in the presence of organic material and moisture constitutes a complicated system. Rainfall and evaporation, with seasonal and daily variations in the temperature, subject the soil surface to fluctuations so that, in general, the system must be regarded as dynamical, the principal "reactions" being a readjustment of the soil structure and a movement of the moisture. This paper is concerned with methods for studying the phenomena connected with this latter reaction.

Capillary and gravitational forces are always involved as factors determining the conditions of motion or of equilibrium of moisture in the soil. There is much evidence for believing that most soils are "wetted" by water, and hence the adhesive attraction of water molecules for soil grains and the cohesive attraction of one water molecule for another are suppressed to indirect relationship and need not enter into the analysis. Gravitational forces on the elemental

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particles are measured by the masses of the particles themselves, so there remains the single somewhat obscure force of capillarity with which to deal.

By making use of potential functions physicists have developed a dynamical method which has materially aided in studying the flow of heat and electricity. If we adopt this method we can remove many of the difficulties in the field of soil moisture by using what is known as the capillary potential function.³ This function is simply an application of the well-known energy-potential theory. Capillary potential differences have the same relation to the flow of moisture in soil as voltage differences have to the flow of electricity in wires, or as pressure differences have to the flow of water in pipes. This latter is a rather close analogy because the capillary potential at any given point in the water between soil grains is numerically equal to the hydrostatic pressure at that point.⁵

Definitions and discussions of the capillary potential, involving more or less mathematics, are already to be found in available literature, but since potential functions have not been extensively used by workers in the agricultural sciences it has been thought worth while to present a discussion of the capillary potential without the use of detailed mathematical analysis. To aid in making clear the nature of this function the characteristics of the electrostatic, gravitational, and pressure potentials are briefly reviewed. The close relation between the capillary potential and the pressure potential (which in water is numerically equal to the hydrostatic pressure) makes it possible to introduce the capillary function in terms of more commonly used quantities.

This paper also presents some experimental data which show the relation between capillary potential and moisture percentage for several different soils, and attention is called to some of the ways in which capillary potential may be used.

DEFINITION AND CHARACTERISTICS OF POTENTIAL FUNCTIONS

ELECTROSTATIC POTENTIAL

In general, it may be said that potential functions⁶ are more or less artificial creations of the mind, defined and used because they are helpful in studying and accurately expressing the processes of nature. In dealing with electricity we have come to regard potential

³ The capillary potential as a magnitude to be used in the study of soil moisture was first introduced and defined by Buckingham (2) ⁴ in 1906. The methods then known for measuring this magnitude were rather slow and of uncertain accuracy, so the function was of little experimental use. It is an interesting coincidence that in 1906, the same year Buckingham submitted his article, Livingston (13) developed apparatus, called by him autoirrigators, which could be used as a quantitative means of controlling the capillary potential in soil. However, there seems to have been no correlation established between autoirrigators and the Buckingham potential function until about 15 years later, when it was pointed out by Gardner (7) and his associates that porous clay equipment could be used to measure the value of this function.

⁴ Reference is made by number (italic) to "Literature cited," p. 741.

⁵ The capillary potential in water is numerically equal to the hydrostatic pressure only when the units used are such that the density of water is unity.

⁶ In a singly connected, conservative force field the potential at any point is the amount of work required to move a unit mass from an arbitrarily chosen point of zero potential to the point in question. If f as a vector is the externally exerted force on unit mass and ds an infinitesimal vector along the path, then the potential at any point B is, $W = \int_A^B f ds$ where A is the arbitrarily chosen point of zero potential. If there is no force in the field the potential will be constant throughout.

In case more than one force field exists in a region the potential for each field and the potential due to the resultant field or total potential is defined by the above relation. If equilibrium obtains, the forces are balanced and the total potential will be constant throughout the region. The potential at any point is independent of the mass present and is the work that would be required to move unit mass from the point of zero potential to the point in question.

as indispensable. Because the term "potential" is commonly associated with electricity, and because the electrostatic potential is similar in so many ways to the potentials to be discussed in this paper, the characteristics of the electrostatic potential function are briefly reviewed.

If static electrical charges are accumulated at different places in a certain region there will be electrical forces exerted on other charges which are brought into that region and there is said to exist an electrostatic "force field." The field intensity, which is defined as the force on a unit positive charge, has a definite direction and magnitude at every point in the region. It is called a point function because every point in the region is characterized by the direction and magnitude of the field intensity at the point. Now, it is possible completely to represent this force field by means of another point function called potential. The potential is a function such that if its value is known for every point in the region then the direction and magnitude of the field force at any point can be calculated. The electrostatic potential at any given point is defined as the amount of work that must be done against the field forces in bringing a unit positive charge from some reference level to the point in question. The term "work," as here used, has its usual meaning. It is the product of a force times a distance. For example, if a force of 5 gm. moves a body a distance of 2 cm. in the direction of the force, then 10 gm. centimeters of work have been accomplished. Since potential is defined in terms of the work done in moving a unit charge in the force field, then the difference in potential between two points is simply the work required to move a unit charge from one point to the other. Hence, if the potential is known at two different points, then the average component of the field force acting on a unit charge in the direction of the line connecting the two points is simply the difference in potential divided by their distance apart, the force being directed from high to low potential. If we let V stand for the electrostatic potential, then for every point in an electrostatic field V will have a certain definite value. If V is everywhere the same, then it requires no work to move a charge from one point to another and the electric field intensity must be zero, i. e., there are no forces acting. If, however, V changes in value from point to point there will be a direction in which its space rate of change will be a maximum. This change in potential per unit of distance in the direction of the maximum rate of increase of potential is called the potential gradient and is designated by $\text{grad } V$. The field intensity E is everywhere equal in magnitude and opposite in direction to the gradient of V , or

$$(1) \quad E = -\text{grad } V$$

This relation is especially important.

As we proceed, it should be noticed that there is a striking analogy to the electrostatic case between both the way in which the gravitational and pressure potentials are defined and the way in which the gravity and the pressure field force is related to the potential gradient.

GRAVITATIONAL AND PRESSURE POTENTIALS

Bernoulli's equation, which is discussed in almost every college physics textbook, expresses the relation connecting the gravity

energy, the kinetic energy, and the pressure in a moving fluid.⁷ It may be written as follows:

$$(2) \quad gh + p/\rho + \frac{1}{2}v^2 = K$$

where, in the centimeter-gram-second system of units, h is the height in centimeters of a point above a fixed level; g is the acceleration of gravity, 980 cm. per second per second; p is the pressure in the fluid at the point expressed in dynes per square centimeter (in the centimeter-gram-second system the dyne is the unit of force; 980 dynes = 1 gm.); ρ is the density of the fluid in grams per cubic centimeter; v is the velocity of the fluid at the point in centimeters per second; and K is a constant.

We shall first consider systems which are at static equilibrium. Under this condition the velocity is zero and equation (2) becomes,

$$(3) \quad gh + p/\rho = K$$

In applying this equation we shall deal only with the potential and force relations within the region occupied by the liquid. The first term is the expression for the gravitational potential at the point under consideration. It is the work, in dyne centimeters, that would have to be done against the gravity field force in order to raise 1 gm. of matter to a height h centimeters above a gravity reference level. For the systems we shall here consider, the free flat liquid surface will be used as the reference level for the gravitational potential. Let the gravitational potential be designated by ϕ . Then from (3) the value of ϕ at any point in the region is

$$(4) \quad \phi = gh$$

where h is the vertical distance of the point from the free flat water surface level. If the point is above this surface, then h will be taken as a positive quantity. For points below the water surface, h will be negative. (This convention as to the algebraic sign of h will be used in subsequent formulas in which h is used.)

Equation (4) shows that the gravitational potential is proportional to the vertical distance from the reference level and that it increases with the height. This means that vertically upward is the direction of the potential gradient. The gravity force per unit of mass, F_g , is vertically downward and is equal in magnitude to the space rate of change of the potential, i. e., $F_g = -\text{grad } \phi$.

The second term in equation (3), p/ρ , may also be interpreted as a potential, defined for every point throughout the region occupied by the liquid. This is the potential due to the internal stress of the material and is called the pressure potential. It has been designated by the letter π ⁸. At any point in the liquid,

$$(5) \quad \pi = p/\rho$$

⁷ Bernoulli's equation is valid for steady irrotational motion of a uniform frictionless fluid.

⁸ The more general expression (17, p. 149) for the pressure potential at a point B is, $\pi = \int_A^B dp/\rho$ where A is the arbitrarily chosen point of zero pressure potential. This expression holds for both positive and negative pressures and is valid through varying densities. When ρ is constant the above integral reduces to p/ρ where p is the difference in pressure between A and B .

When dealing with the gravity potential, the work done in raising a unit mass against gravity may be thought of as being stored in the mass as gravity potential energy, but the term "pressure energy," which is ordinarily associated with the p/ρ term in Bernoulli's equation, is inaccurate and should be avoided (θ).

where p is the value of the pressure at that point. In the case of water, ρ is equal to unity, and hence for this liquid π is numerically equal to the pressure. It is a matter of common observation that if a horizontal tube is filled with water and there is a difference in the pressure at the two ends, the water will flow from the high to the low pressure end. Let us consider a unit cube of liquid in such a tube in which there is a difference in pressure of 1 dyne per square centimeter per unit of length in the horizontal direction. When this condition exists the pressure force on one end of the cube will be 1 dyne greater than the pressure force on the other end and there will be a resultant force of 1 dyne per cubic centimeter, tending to move the water in the direction of the decrease in pressure. It should be noticed that under the conditions of this example the pressure potential has a gradient of one potential unit per centimeter in the direction of the increase in pressure. Hence, the property of the electrostatic potential set forth in equation (1), is also a property of the pressure potential, i. e., the field force, F_p , due to the pressure in the liquid is equal to the negative potential gradient or, $F_p = -\text{grad } \pi$.

In working with potential functions the potential gradients and potential differences are the significant quantities, and these are independent of the place chosen as the reference level or place of zero potential. That is, if a different reference level were chosen the potential would take on a new value for every point, but the size and direction of the potential gradient at any point or the difference in potential between any two points would remain unaltered. For the systems considered in this paper, and for soil-moisture work generally, it will be found convenient to choose the same reference level for both the gravitational and the pressure potential, i. e., the region of zero hydrostatic pressure or the free flat water surface.

With the pressure at the free flat water surface chosen as the zero reference level for π , then the value of π at all other places is simply equal to the difference in pressure between the flat water surface and the point in question. If at a given point the pressure is less than at the surface, then π is negative, and vice versa.

Let us consider a system in which both the pressure and gravity force fields are acting. If a capillary tube is dipped into a free surface (fig. 1) the water will rise in the capillary tube and come to rest. When the water is at static equilibrium the forces on each little element of water must be balanced. Hence, there must be some force

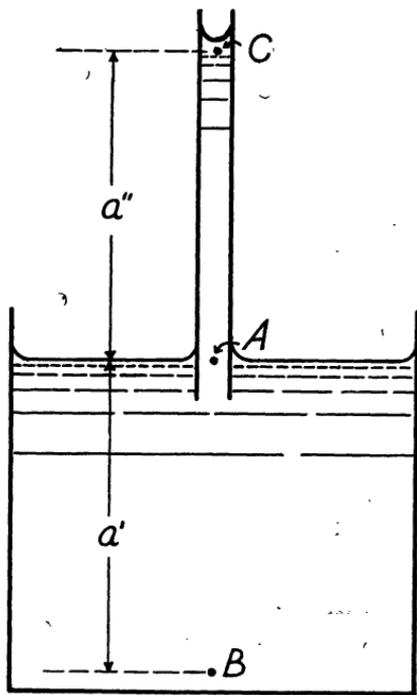


FIG. 1.—Capillary tube dipped into a free water surface

acting in the liquid to neutralize the force of gravity. The forces that are acting may be derived by considering the potentials which are involved. Since the water is at rest, equation (3) must hold. Consider first the gravitational potential. For all points at the same level as A , which is at the level of the free flat water surface, $\phi = 0$. At all other places in the liquid $\phi = gh$. That is, at C , $\phi = ga''$, and at B , $\phi = ga'$. The gravitational potential at this latter point is negative because a' is negative. From the expression $\phi = gh$, it is easily seen that all points in the same horizontal plane have the same gravitational potential. The potential gradient is always perpendicular to the equipotential surface, and in this case is vertically upwards. This is the opposite direction to gravity which is the field force of this potential.

$F_g = -\text{grad } \phi = g = 980 \text{ dynes} = 1 \text{ gm.} = \text{gravity force per unit of mass.}$

According to the convention here adopted, the pressure potential π is also zero at all points at the same level as A , where the hydrostatic pressure is zero. At other levels $\pi = p/\rho$.

The expression for the hydrostatic pressure in a liquid is $p = -\rho gh$, where ρ , g , and h have the same meanings as previously used. Substituting this value for p in the expression above gives $\pi = -\frac{\rho gh}{\rho} = -gh$.

Therefore, at the point B , $\pi = -ga'$. Because a' is negative the value of π at B is positive and is numerically equal to the hydrostatic pressure in the liquid at that level. At the point C , $\pi = -ga''$. π is negative at C because g and a'' are both positive quantities. The negative sign indicates that the water at the point C , just under the meniscus, has a negative pressure, or that it is under tension. Thus, the pressure and the pressure potential are positive at B , decrease to zero at A , and become more and more negative with increasing height in the capillary tube.

The equipotential surfaces of the pressure potential are horizontal because all points at the same level have the same hydrostatic pressure. However, the gradient of π is vertically downward because that is the direction in which π increases. The field force due to pressure difference is in the opposite direction to the gradient, and hence acts vertically upward. Pressure and gravity are the only force fields acting in a system such as Figure 1, so if the water is in static equilibrium the pressure and gravity forces on each little element of water must be balanced. There must be at every point a force due to a pressure gradient which is just equal and opposite to the force of gravity.

If at every point in the region just considered we add together the value of π and ϕ we shall have a new point function which we shall call Φ , the total potential.

$$(6) \quad \pi + \phi = \Phi$$

Φ has the same properties as the two potentials of which it is composed. $\text{Grad } \pi$ is a measure of the forces set up due to the internal stress of the water, $\text{grad } \phi$ is a measure of the force due to gravity, while $\text{grad } \Phi$ is a measure of the resultant of both of these forces acting on a unit of mass at any given point. Since the system we have just considered is at static equilibrium the resultant of all the forces

acting on each little particle of the liquid must be zero, and hence there must be no gradient of the total potential. This is the condition set forth by equation (3), and it is easily seen to be true, for

$$(7) \quad \pi + \phi = -gh + g\bar{h} = \Phi = 0$$

everywhere in the system. At the water surface $\pi=0$, $\phi=0$, and therefore $\Phi=0$. Everywhere else π is just the negative of ϕ , so that they add up to zero. Thus the space occupied by the water in the system is an equipotential region for Φ , and because of the reference level convention that has been adopted, Φ is everywhere equal to zero. When this condition obtains the gravity and pressure forces

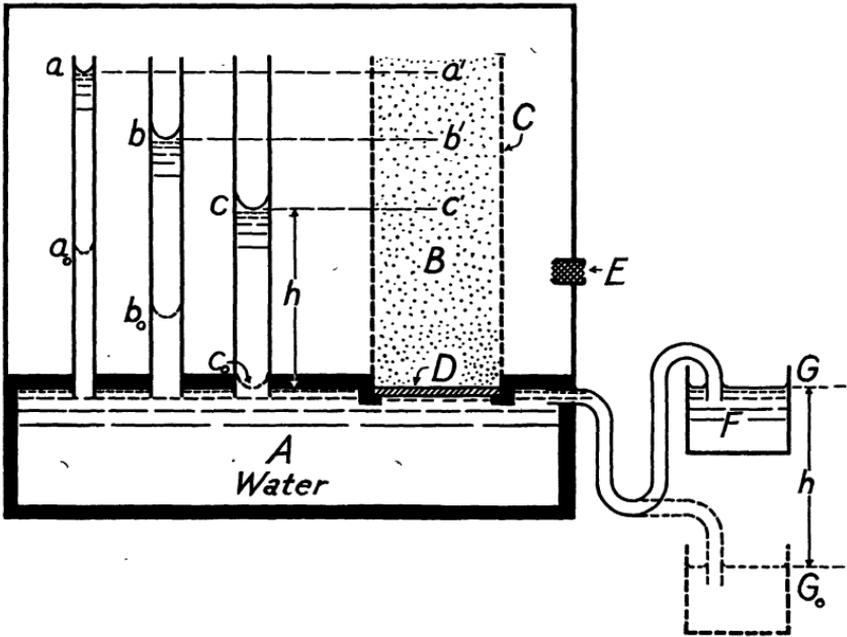


FIG. 2.—A system to aid in studying the moisture relations in a soil column. See text for complete explanation

are just balanced and, neglecting friction, a very slight impulse would be sufficient to move a little mass of water anywhere in the system.

As an example more closely related to the soils problem let us consider the forces and potentials in the system illustrated in Figure 2. A is a water tank fitted with capillary tubes as indicated. B is a column of soil supported by a cylindrical sieve, C, and closed at the bottom with a porous clay plate, D, readily permeable to water. The vertical tubes are inclosed in a case which is provided with a porous plug opening, E, to maintain atmospheric pressure within, but to prevent the loss of water vapor from the chamber. When the tank, A, is filled, and the water in the auxiliary tank, F, is so adjusted that the free water surface is maintained at the level, G, then water will rise in the capillary tubes and soil column and will reach an equilibrium distribution, provided the temperature everywhere in the system is maintained uniform.

To simplify the problem, let us here assume that pure water and washed soil are used. When the system has come to equilibrium under isothermal conditions, let us say that the water has risen in the capillary tubes to the heights a , b , and c , respectively. These heights will be determined by the radii of the tubes and the surface tension of the water according to the formula $h = \frac{2T}{rg}$ where g is the acceleration of gravity, r is the radius of the tube, and T is the surface tension of the water (c. g. s. units implied).

The configuration of the region occupied by the water in the soil is not definitely known, but it is probable that in moist soils the water forms a continuous and connected configuration which spreads out in thin films over the surface of the soil grains and collects into wedges where the grains are in contact or are very close together. It is the relation between the potentials and the forces in this water configuration that we are particularly interested in.

In Figure 2, all points in the liquid at the same level as G—the level of the free water surface—have $\pi = 0$, $\phi = 0$, and hence, $\Phi = 0$. We shall consider the pressure and gravity force relations in the soil-water configuration quite analogous to those existing in a capillary tube. The forces and potentials may be analyzed by the same method that was used for the system shown in Figure 1, and at equilibrium—according to equation (3)— Φ must have the same value everywhere in the region occupied by the water.

It is well known that the vapor pressure of a liquid depends on the curvature of the liquid surface (3). When equilibrium exists in the system of Figure 2, the water surfaces in the soil at a' must have the same curvature as the capillary meniscus at a , for if such were not the case there would be a difference in the vapor pressure at the two points. This would result in distillation and in the motion of water in a cycle, which, according to the second law of thermodynamics, is impossible under isothermal conditions.

As was shown above, π has the same value for all points in the capillary tubes or soil column which are at the same height above the free water level, G. This means that the pressure in the liquid at all these points is the same. That this is the case may be indicated by the following different method of reasoning. When equilibrium obtains, all the liquid surfaces at the same height have the same vapor pressure and hence the curvature of the air-water surfaces in the soil at a' , b' , and c' is the same as that at the corresponding heights, a , b , and c , in the capillaries. (Pure water and constant temperature are assumed.) The difference in pressure on two sides of a curved liquid surface is given by the well-known formula

$$(8) \quad p = T (1/r_1 + 1/r_2)$$

T is the surface tension of the liquid in dynes per centimeter and $(1/r_1 + 1/r_2)$ is the expression for the total curvature of the surface.⁹ The surface tension and curvature have the same values at both a and a' , and since the pressure in the vapor at a and a' is prac-

⁹ r_1 and r_2 are the radii of curvature of the two curves formed by the intersection of two planes (principal planes) at right angles to each other and passing perpendicularly through the water surface at the point where it is desired that the curvature be known.

tically equal to the pressure in the water at the flat surface (neglecting the pressure difference in the vapor between a and D due to the weight of the column of gas between these two points), then the value of the pressure difference in the liquid between the points a and D , and a' and D , is given by equation (8) and is numerically equal to π . Hence, the value of π when determined in this manner will be the same for all points at the same level because the surface tension and curvature are the same at all these points.

The above reasoning holds, of course, only for pure water in an isothermal equilibrium system. However, if we still retain the assumption that ρ is equal to unity, then the value of π in soil water is correctly given by equation (8), even if isothermal equilibrium conditions do not obtain.

CAPILLARY POTENTIAL

The preceding discussion of potentials was given primarily as a preparation for introducing and defining the capillary potential, which we shall designate by the letter ψ . The value of this function at a given point in moist soil was originally defined by Buckingham (2) as the work that would have to be done against the "capillary field force" in transferring a unit mass of water *from the soil to free water* at zero hydrostatic pressure. Subsequent writers (4, 8), however, have defined this function as the work done against the capillary field force in moving unit mass of water *from the flat water surface to the point in question*. This definition gives ψ the opposite algebraic sign to that used by Buckingham. This latter definition is more in accord with the way potentials are ordinarily defined and is the definition that will be used in this paper.

Just what is meant by "capillary field force" is rather obscure. If we interpret this expression, as Buckingham indicated, as simply the mechanical force involved in the attraction of moist soil for water, then we may consider it as the force set up in the soil water configuration due to pressure differences or due to a pressure gradient. When this is understood, it is easy to see that the capillary potential and the pressure potential are the same. That is,

$$(9) \quad \psi = \pi$$

No one questions the significance of the pressure potential when studying the flow of water through pipes or the motion of ground water where the soil is saturated, but in soil which is not saturated, the pressure in the water is negative, and for studying the flow of water under such conditions neither the pressure potential nor the capillary potential has been very much used.

That the pressure is negative makes little difference. The potential functions should be as useful in soil-moisture work as they have been in dealing with electricity or heat. Failure to use capillary potential when making a detailed study of the flow of water through soil is almost as inconsistent as not taking advantage of the well-known equation of Fourier¹⁰ when studying the flow of heat at temperatures below zero, because the distinction between positive and negative pressures is almost as arbitrary as the distinction between positive and negative temperatures.

¹⁰ Fourier's equation for the flow of heat will be discussed further on in the paper.

Because of its descriptive fitness, capillary potential will be used for regions such as moist soil where the hydrostatic pressure is negative; but it should be understood that the two terms, capillary potential and pressure potential, are interchangeable. The place of zero hydrostatic pressure has been chosen as the reference level. The capillary potential will therefore be negative in moist soil or wherever the hydrostatic pressure is negative.

MEANS OF CONTROLLING CAPILLARY POTENTIAL

With the proper arrangement of porous clay apparatus the capillary potential in soil which is in contact with the porous surface may be accurately controlled. Let us refer again to Figure 2. When the water surface in the auxiliary reservoir is at the level G, the meniscus in the largest capillary tube, *c*, is at a height *h* centimeters above G. This height corresponds to a capillary potential of $\psi = -gh = -980h$ dyne centimeters per gram. (This is equivalent to a tension of $980h$ dynes per square centimeter in the water at *c*.) Now if the reservoir, F, is lowered so that when the system again comes to equilibrium the new free water level is *h* centimeters lower than before, then the meniscus in each capillary tube will be depressed by this amount. Under the new conditions the curvature of the water films in the soil on the porous plate is the same as that which previously obtained at the height *h* centimeters above the plate, because this curvature is the same as the curvature of the water meniscus now at *C*₀. The value of ψ in the soil on the plate is negative and is numerically equal to *g* times the vertical distance down to the new free flat water surface. It is evident that with the initial conditions (free water level at G) the curvature and pressure relations obtaining at any point in the soil column would be unchanged, if, at some position lower in the soil column, a horizontal porous plate were interposed, the plate being mounted in such a way that its under side could be kept in contact with a column of water reaching down to the free water surface. When using the centimeter-gram-second units, the capillary potential in soil which is in equilibrium with water through a porous plate is numerically equal to the difference in pressure in the water under the plate and the atmospheric pressure. This pressure difference may be determined by means of a water or mercury manometer. With porous clay apparatus of sufficient strength and fineness of porosity, pressure differences as high as 1 atmosphere may be maintained in this manner.

In the system illustrated in Figure 2, the conditions of uniform temperature, pure water, and static equilibrium throughout the system were assumed. These conditions of course would be impossible to attain in any actual soils experiment. Nevertheless, the methods used in this example for deriving the capillary and gravitational field forces from their corresponding potentials may be quite generally applied.

When the soil moisture is not at static equilibrium with free water, then the relation $\psi = -gh$ no longer holds. For liquids of constant density ψ is defined by equation (5), i. e.:

$$(10) \quad \psi = p/\rho$$

For soil-moisture work generally we may assume ρ equal to unity¹¹ because the errors involved in measuring ψ will be greater than those introduced by this assumption. Equation (10) then becomes

$$(11) \quad \psi = p$$

where p is simply the pressure difference between the reference level and the point in question (c. g. s. units implied).

APPARATUS FOR MEASURING CAPILLARY POTENTIAL

When the tension in the soil water is less than 1 atmosphere, the value of ψ in a given soil may be accurately determined by a direct method. The apparatus shown in Figure 3, called a capillary potentiometer, has been used in this laboratory for various soil experiments. It consists of a porous cup, A, sealed onto a glass tube which is connected by heavy pressure tubing to a mercury manometer, B. The porous cup and the manometer are filled with water, a rubber stopper is inserted at C, and the cup is imbedded in soil. When water moves from the cup into the soil, the mercury rises in the manometer and the pressure within the cup is reduced. This process continues until the soil water and the cup water have the same pressure. The difference between this pressure and atmospheric pressure is numerically equal to the capillary potential of the soil and may easily be determined by properly reading the manometer.

When using equations (2) and (3) the pressure difference should be expressed in dynes per square centimeter and would correspond to a potential in dyne centimeters per gram (work per unit of mass). However, for practical purposes these units give large numbers with which to deal. The capillary potential may be conveniently expressed in terms of the length of the water column which the tension in the soil water would be able to support. If the length of the water column is given in centimeters, then the potential units would be gram centimeters per gram and would correspond numerically to the tension in the liquid expressed in grams per square centimeter.

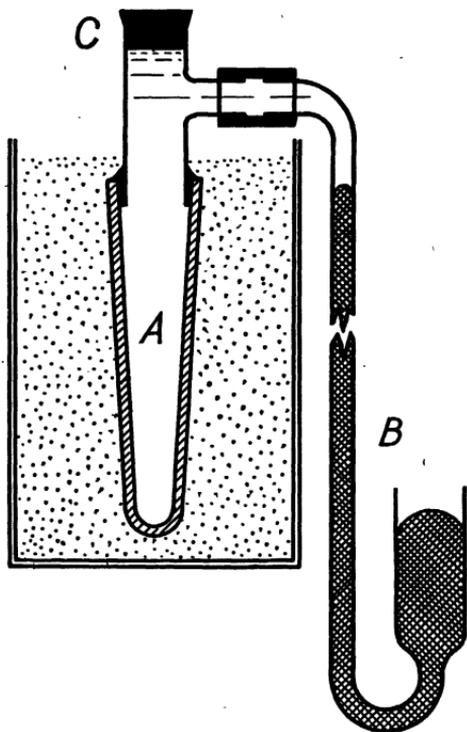


FIG. 3.—A capillary potentiometer. See text for complete explanation

¹¹ ρ is sometimes used to represent the mass of water per unit aggregate volume of the soil (5, 6, 8), but in this paper ρ is used only to represent the mass per unit volume of water or soil solution.

FACTORS DETERMINING THE CAPILLARY POTENTIAL

As was seen from considering Figure 2 and the definition of ψ , the equilibrium value of the capillary potential in a soil column at a given height above a free water level is a constant, independent of soil structure, temperature, or dissolved material in the soil solution. The percentage of moisture in the soil at this height, however, varies with all of these factors.

ψ is a magnitude determined by the pressure in the water. Because of our choice of the pressure reference level, water is said to be under tension when its pressure is less than atmospheric pressure. (The pressure in water at a free flat water surface is the same as atmospheric pressure.) The difference in pressure between the water under the little curved surfaces of the soil solution and the atmosphere is given by the formula (8) $p = T \left(\frac{1}{r} + \frac{1}{r_2} \right)$. If we could measure the

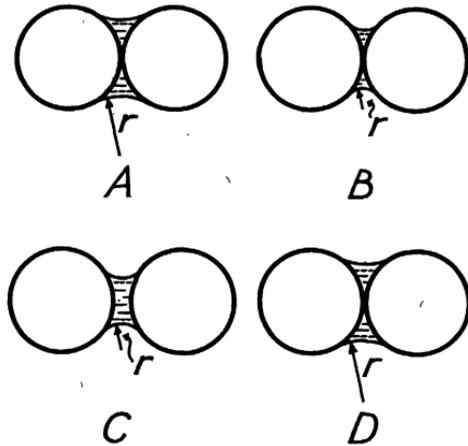


FIG. 4.—Water wedges between spherical soil particles. Decreasing the amount of water between articles (A) increases the curvature of the water surface (B); pressing the particles closer together (C) decreases the curvature (D)

surface tension and surface curvature of soil water, then we would be able to calculate the value of ψ at any point. This would be unnecessary for certain values because, as was seen earlier, the potential can be measured directly by means of the capillary potentiometer.

Let us now see how the value of ψ in a given isolated mass of moist soil is affected by the temperature, moisture content of the soil, dissolved material in the soil solution, size of soil particles, and state of packing. Any change which increases the surface tension or the curvature will decrease ψ , and vice versa.¹²

For a mass of soil with a certain state of packing and water content, decreasing the temperature or increasing the amount of dissolved salts in the soil solution will increase the surface tension and hence decrease ψ . The other factors—moisture content, size of soil particles, and state of packing—will affect the value of ψ through their effect on the curvature. As is indicated in Figure 4, A and B, if the amount of water collected between two soil grains is decreased, there will be an increase in the curvature of the water surfaces, hence a decrease in ψ . That is, the drier the soil, the more negative the capillary potential will be. Also, if equal weights of a fine and a coarse soil have the same moisture percentage, the fine soil will have more surface and more contact points between soil particles. There will be less water collected at each of the contact points, and it would be expected that the fine soil will have a lower potential than the coarse soil even though their moisture percentages are the same.

¹² The magnitude of ψ will be spoken of in the algebraic sense. That is, -5 is greater than -10 , or, as a further example, ψ increases if it changes successively from $-10, -5, 0, 5, 10$, and so on.

The compactness of the soil also influences ψ . Referring again to Figure 4, C and D, if two particles of soil are pushed closer together the curvature of the water surface will be decreased. If comparatively dry soil is sufficiently compressed, water will run out under the force of gravity. During this process of compressing the soil (until the water is just ready to flow out) the moisture percentage, expressed on the dry-weight basis, remains unchanged, but ψ changes from a low negative value to zero.

For a magnitude that has as many influencing factors as ψ it is desirable to hold all the factors constant except one and see how the magnitude varies when this one factor is changed. In studying the capillary potential the moisture percentage of the soil seems to be the factor best suited for this purpose. If the contact angle between

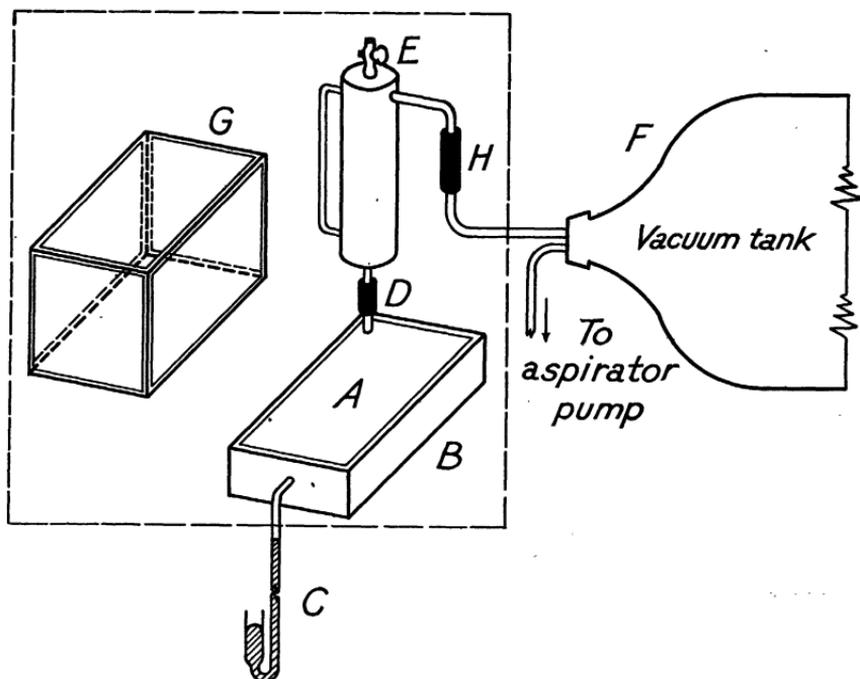


FIG. 5.—The arrangement of the apparatus for determining the capillary potential in soil. See text for complete explanation

water and the soil particles is zero, we should expect that for a given soil, having a certain temperature and state of packing, there would be a certain definite value of ψ for each value of the moisture percentage. All the experimental data thus far collected seem to support this conclusion.

MOISTURE PERCENTAGE EXPERIMENTAL DATA

As was pointed out earlier, the value of ψ in soil which is in equilibrium with water through a porous plate is numerically equal to the difference in the pressure in the water under the plate and atmospheric pressure. By making use of this fact the apparatus shown in Figure 5 served to determine the moisture percentage-capillary potential curves for several types of soil. The porous plate, A, was specially made for the purpose, and is 9 inches long, 5 inches wide, and about one-fourth inch thick. It is mounted in the cast aluminum case, B,

and an air-tight seal is effected by means of plaster of Paris and a soft wax. The mercurial manometer is connected at C. A $\frac{3}{8}$ -inch copper tube is sealed in to the porous plate at D and a vacuum rubber connection made to the water reservoir, E. To put the apparatus in operation the manometer is supplied with mercury and the capillary cell and reservoir are filled with water. The corner of the plate at D is slightly raised so that any air which accumulates within the cell may pass upward through the water in the reservoir. By means of an aspirator pump the pressure in the vacuum tank, F, is reduced until the mercury stands at the desired level in the manometer. The soil for the experiment is then spread on the plate to the desired depth and covered with the glass cage, G. The soils used were air-dried and reduced to a fine powder by means of a small hand grinder.

Four of the complete units shown in Figure 5 were used. That part of the apparatus within the dotted line was mounted in an air thermostat, the air being well stirred by an electric fan. For the data here presented the temperature was maintained at 16.1° C. During the course of the experiments, continuous thermographic records were kept, and except for short intervals when samples were taken, the temperature fluctuations were less than one-tenth of a degree centigrade. The interior of the case was kept dark to avoid the temperature effects of light observed by Linford (12). When the apparatus was ready the plates were covered with a $\frac{1}{2}$ -inch layer of soil, the glass cover cages installed, and the thermostat closed. The dry soil absorbs water from the porous plate until the soil moisture is in pressure equilibrium with the water under the plate. Since the maximum distance the water moves through the soil is one-half inch, this equilibrium is rapidly approached. The carboy pressures were adjusted so that the mercury levels in the manometers remained constant from two to four days to permit the soils to reach equilibrium. At the end of this time 40 to 50 gm. soil samples were taken from the plates and the pressures set at some new values. The moisture determinations were expressed as percentage of water for dry weight of soil. The data for four different soils are given in Table 1 and Figure 6.

TABLE 1.—The moisture percentage and capillary potential values of four soil samples

[The moisture is expressed as percentage of water for dry weight of soil and the corresponding capillary potential is given in gram centimeters per gram]

Bennet sand		Greenville loam		Trenton clay		Preston clay	
Moisture	Potential	Moisture	Potential	Moisture	Potential	Moisture	Potential
20.9	4	39.6	5	67.3	4	66.5	6
11.7	26	34.2	29	52.5	27	60.4	22
9.5	54	30.2	55	45.2	53	57.8	31
7.6	82	27.0	84	43.0	54	51.5	58
6.9	110	22.8	144	40.5	82	46.3	85
6.2	150	20.5	222	38.0	103	42.4	143
5.7	240	19.4	269	33.6	125	40.2	196
5.3	348	19.0	304	30.7	216	33.0	287
5.1	301	17.5	371	28.4	286	31.6	438
4.9	427	17.0	429	27.2	380	31.2	362
4.8	452	16.4	489	26.2	467	29.4	527
4.7	492	15.5	556	26.2	558	29.0	650
4.1	684	15.2	656	24.5	800	28.7	729
4.0	596	15.0	715	24.3	612	28.5	664
3.9	692	14.6	796	24.2	735	28.4	611
3.7	801			24.0	745	28.3	784
				23.8	555	27.7	776

Since ψ is negative, the fourth quadrant is used for plotting. The soils used were: A, a loose sandy loam; B, a clay loam; C, a heavy subsoil clay; D, a fine clay from Preston, Idaho. (The porous plates were made from Preston clay.) The potential units used in plotting are gram centimeters per gram, and correspond numerically to the length in centimeters of the water column which the tension in the water would be able to support.

If large soil tubes 26 feet high were filled with these soils at the temperature and state of packing here used, and with their lower ends dipped into free water were allowed sufficient time for the water to come to static equilibrium, then the distance above the flat water level would correspond numerically to the potentials, and

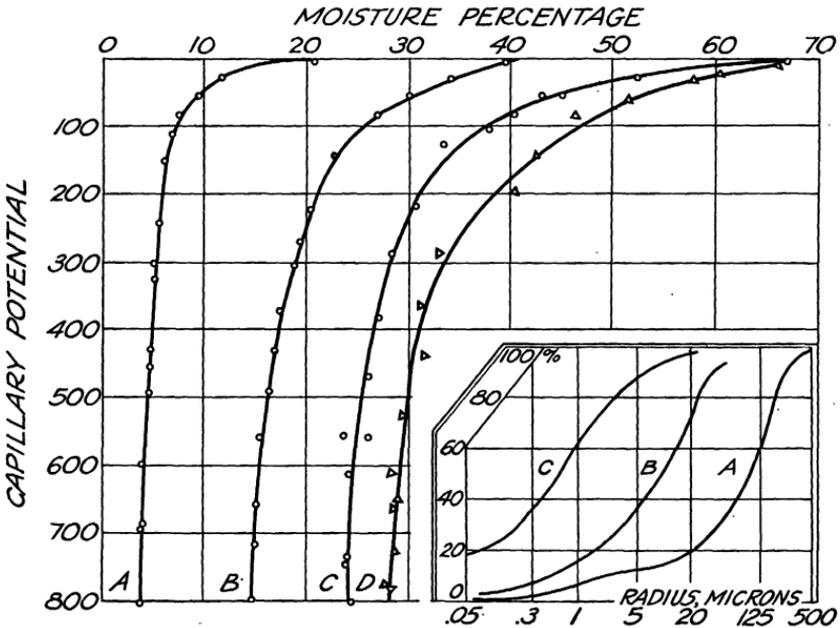


FIG. 6.—Capillary potential-moisture curves for: A, Bennet sandy loam No. 629 from the Uinta Basin; B, Greenville clay loam from the college farm; C, Trenton subsoil clay No. 1232; D, clay from Preston, Idaho. The inset shows the mechanical composition of soils A, B, and C, the ordinates showing the percentages of material of smaller radius than the corresponding abscissas

the moisture percentages at any height up to 800 centimeters (26 feet) for the different soils could be determined from the curve.

The mechanical analyses for soils A, B, and C, as given by Thomas (19), are shown in the inset, Figure 6. The effect of the size of the soil particles on the moisture content of soils at any fixed potential is very evident.

Because of the short distance the water has to move and the relative ease of duplicating the soil structure, the apparatus here described for determining the relation between ψ and moisture percentage has some advantage over methods previously employed. The capillary conductivity seems to be less for clay than for sand, and the greater scattering of the experimental points from the smooth curves for the clays C and D indicates that for these soils two to four days was not sufficient time for the water to reach

equilibrium. Another source of error for this method lies in the fact that the mercury levels in the capillary cell manometers fluctuate with the atmospheric pressure. Continuous barographic records were kept to aid in compensating for barometric changes. For the low potential points the manometer (fig. 5, C) was replaced by a rubber tube reaching down to free water at the desired level. With this arrangement barometric fluctuations do not influence the value of ψ in the porous plate.

APPLICATION OF CAPILLARY POTENTIAL THEORY

MOISTURE GRADIENT EXISTS

From the discussion given with Figure 2 it is clear that when moisture in a vertical soil column is at static equilibrium with a free water table, there must be in the water a gradient of the capillary potential having such direction and magnitude that the capillary or pressure forces just balance gravity. This means that the tension in the soil liquid must increase with the height above the water table. If the surface tension remains sensibly the same throughout the column, then, according to equation (8), the curvature of the air-liquid surfaces of the soil solution must increase with the height above the water table. As is indicated in Figure 4, this may be accomplished by having a looser state of packing, or by a decrease in the moisture content with increasing height above the water table. Experiments by King (10), Buckingham (2), Israelsen (8), and others indicate that the moisture gradient is necessary in order to make possible the proper capillary potential gradient for static equilibrium.

That this moisture gradient will exist under equilibrium conditions is still reluctantly accepted by some soils workers (20). The fact that this moisture gradient is not common in the field is easily explained. There is abundant evidence to show that the motion of water in dry soils is very slow. Under field conditions the seasonal and diurnal fluctuations of temperature, evaporation, precipitation, irrigation, and ground water, or drainage conditions make it unlikely that equilibrium is very closely approached in any actual case. Even if equilibrium were attained, the curves (fig. 6) indicate that for a deep-water table in the coarser soils the moisture gradient is so small that precise moisture-determination methods would be required for its detection. If static equilibrium were attained in a loam soil such as B, Figure 4, then a moisture gradient somewhat similar to that shown by the curve would be expected.

SOILS NOT AT MOISTURE EQUILIBRIUM—CAPILLARY FLOW

Thus far we have considered only soil-water systems which were assumed to be at static equilibrium. The preponderance of evidence indicates that for actual cases in the field this condition is exceptional. Soil moisture is generally in motion. It is in the study of the dynamics of capillary flow that the potential theory is particularly useful. The reader is especially referred to the lucid nontechnical discussion given by Buckingham (2) on this phase of the subject; also to the more recent work of Gardner (5, 6) and Israelsen (8). This application of the potential theory is of prime importance because it offers a direct method for getting at the fundamental factors which determine

capillary flow. Because the above-cited literature is available this phase of the subject will be reviewed but briefly in this paper.

We have seen that grad Φ , the gradient of the total potential, is a measure of the total "water-moving" force or the net resultant force (per unit of mass) which tends to produce motion of the soil water. Darcey's equation states that the velocity of the water is proportional to the force which is producing the motion, hence we may write,

$$(12) \quad v = -K \text{ grad } \Phi$$

where v is the velocity and K is the proportionality constant. Both the velocity and grad Φ are vector quantities because they have definite directions as well as magnitudes. Grad Φ is in the direction of the greatest rate of increase of potential. Since the water moves in the opposite direction the negative sign is used in the equation.

Equations similar to (12) are very useful in studying the flow of heat and electricity. Pointing out some of these similarities will aid in understanding equation (12) and help to attach a physical meaning to the constant K .

Fourier's law for the flow of heat is

$$(13) \quad q = -C \text{ grad } \theta$$

where q is the velocity of flow, or the quantity of heat crossing unit area perpendicular to the flow in unit time. The temperature, represented by θ , is a point function and may be spoken of as the thermal potential. Grad θ is the change in temperature per unit of distance in the direction of the greatest rate of increase in temperature. C , called the thermal conductivity, is a constant for a given kind of material. It is the amount of heat that would flow through a unit cube of the material in unit time if two opposite faces had a temperature difference of 1 degree. Qualitatively every one knows that a bucket of hot water will cool off faster in cold air than in warm air. This is because there is a greater temperature difference causing the heat to flow out through the walls of the bucket. Also the water would cool faster in a metal bucket than in a wooden one, because metal is a better heat "conductor." Equation (13) is a quantitative expression of these relations and simply states that the conductivity times the temperature gradient is equal to the heat velocity, or the quantity of heat transferred across unit area (perpendicular to the motion) per unit of time.

A similar expression has been found to hold for the electrical case. Ohm's law for steady electrical currents in metallic conductors may be written,

$$(14) \quad i = -C' \text{ grad } V$$

where i is the current density, C' the specific conductivity, and grad V is the change in potential per unit distance.

From analogy with (13) and (14) we may call K in (12) the specific capillary conductivity and define it as the amount of water which will flow in one second across a unit area in the soil, perpendicular to the direction of flow, when Φ changes at the rate of one unit per centimeter. However, the above analogy should not be pushed too far.

The thermal and electrical conductivities for a given piece of material are independent of the strength of the current and are in general only slightly dependent on the temperature and other outside influences, but the capillary conductivity K will depend on the kind of soil, its moisture content, and state of packing.

It is true, of course, that before equation (12) can be usefully applied in actual problems this transmission constant will have to be studied for a large number of soils under different conditions, but this procedure seems to be our best chance for reducing the phenomena of capillary flow to a quantitative basis. This method has met with splendid success with heat and electricity and it should not be any more difficult to make reliable capillary potentiometers than it is to construct good thermometers or voltmeters.

For soil-moisture conditions where the tension in the liquid is not greater than 1 atmosphere, porous clay apparatus offers a convenient means for measuring and studying the capillary transmission constant. One experiment has been attempted in this laboratory with this end in view, but the experiment was unsuccessful because the apparatus was not of the proper design. However, with a short column of soil properly arranged between two capillary cells such as those shown in Figure 5, it should not be difficult to obtain a steady and measurable capillary flow from one cell to the other. The capillary potential gradient would be determined by the pressure difference in the water in the two cells and the moisture content of the soil could be determined from the capillary potential-moisture percentage curve for the soil.

The gradient of Φ may be computed from the relation

$$(15) \quad \text{grad } \psi + \text{grad } \phi = \text{grad } \Phi$$

Grad ϕ is a constant numerically equal to g . Potential gradients are vector quantities and must be added according to the parallelogram law which is used for the addition of forces. The resultant direction and magnitude of grad Φ determines the direction and velocity of the soil-water movement. When grad Φ and the velocity of flow, v , are known, the conductivity, K , may be evaluated by substituting in equation (12).

Three common cases of capillary water motion are: (a) Movement of precipitation or irrigation water downward through a comparatively dry soil, (b) motion of water upward from a saturated level or water table, and (c) motion of water in a horizontal direction. In case (a), grad ϕ and grad ψ are such that both the gravity and capillary forces tend to move the water downward. This downward motion will continue (provided there is no surface evaporation) until the soil is drained dry or until the soil moisture comes to equilibrium with an impermeable layer or a saturated water table. In case (b), the gradient of the capillary potential ψ has such direction and magnitude that there is a resultant upward "water-moving force." If there is no evaporation or transpirational loss of water from the surface the state of static equilibrium will ultimately be reached. However, when surface loss occurs, the capillary potential gradient is maintained and the upward flow continues. When the moisture content of soil is low the capillary conductivity is very small and

it requires large potential gradients (comparatively wet soil in contact with the dry) to produce an appreciable flow. Movement of water in a horizontal direction, case (c), is due entirely to a horizontal component of grad ψ . If undisturbed, the motion will continue until all points at the same level have the same potential.

THE AVAILABILITY OF SOIL MOISTURE TO PLANTS

The problem of the availability of soil moisture to plants becomes very much simplified when considered in terms of the potentials. The term "availability" involves two notions, namely, (a) the ability of the plant root to absorb and use the water with which it is in contact, and (b) the readiness or velocity with which the soil water moves in to replace that which has been used by the plant.¹³

CASE (A)

For a plant which is growing in moist soil it is necessary for the root to absorb water from the little films and wedges among the soil particles. If the tension in the soil water is sufficiently high it is reasonable to suppose that the osmotic forces acting through the root-hair membranes may not be great enough to enable the plant to use even that soil water which is in contact with the root. The capillary potential is a measure of this tension in the soil water and, hence, should be a good index to the "security" with which the water is held by the soil. The term "security" as it is here used relates only to the pressure differences involved. Of course, it is possible for a plant to be in a wet soil and still be wilted and suffering from physiological drought if the salt content of the soil solution is sufficiently high. The effect of dissolved material on the availability of soil moisture which is in contact with the root could be expressed by adding to ψ the value of the osmotic potential as used by Linford (12). For a more complete index to soil-moisture condition it would be possible to use thermodynamic potential or free energy (11).¹⁴ However, the capillary potential as here defined will be found useful over a wide range of soil-moisture conditions.

CASE (B)

The other factor in the availability of soil, namely, the rate at which water flows in toward the root, is concisely expressed by equation (12). The rate of flow across unit area perpendicular to the direction of movement is simply the conductivity times the potential gradient. Small potentiometers may be inserted at different points around a root system and without disturbing the plant the soil-moisture conditions can be carefully followed. If the conductivity and capillary potential for the soil have been investigated,

¹³ The above discussion assumes the position of the root to be fixed. It is probable that the ability of the plant root to extend itself is an important factor in determining the "availability" of water in relatively dry soils.

¹⁴ When there are abnormally large amounts of soluble material in the soil water, or for dryer soils, where the water is in such thin films that it ceases to have the properties of a liquid, then it would be advisable to use a function such as the free energy or thermodynamic potential. This function may be thought of as a sort of total potential which can be used in any kind of system and which would take account of the energy relations due to all of the factors such as pressure, gravity, osmosis, changes of state, chemical reactions, etc.

then the direction and velocity of the water movement can be approximated, if not accurately determined. Potentiometers, like the one illustrated in Figure 3, can be used to measure ψ only when the tension in the liquid is between 0 and 1 atmosphere. It seems likely, though, that the optimum soil-moisture conditions for most of the agricultural plants lie well within this range.

The "old problem," as expressed by Livingston and Hawkins (15), that the commonly used methods of designating or describing soil moisture condition are "not ideal for ecological or agricultural inquires," is frequently expressed in the literature. Because of the difference in the security with which water is held by a fine and a coarse soil it is obvious that expressing the water content as a percentage of the dry weight of soil is not satisfactory. Expressing the moisture content of soil as a fraction of the moisture-holding capacity gives a better idea as to the availability of the moisture to the plant, but this method has the disadvantage that for a given soil the moisture-holding capacity will depend on such things as the temperature, the state of packing of the soil, and the length of time which is allowed for the soil to drain or to reach equilibrium. Also, when it is desired to maintain constant moisture conditions for potted plants over a period of time it is necessary to resort to the rather uncertain procedure of adding water to keep the pots up to the desired weight.

Because of the significance of the capillary potential concerning the "security" with which the water is held by the soil and also because of the ease with which the potential can be measured and controlled for experimental purposes, this function seems to have advantages over any of the magnitudes now used for designating or controlling soil-moisture condition as a factor in plant environment.

MEASUREMENT OF ψ IN DRY SOILS

Under ordinary conditions, such as in pipes, glass tubes, etc., it is difficult to subject water to very great tensile stress. If the lower end of a tall vertical cylinder with a carefully fitted piston were submerged in water and the air removed from beneath the piston we could, by raising the piston, make the water stand in the cylinder to a height of 28 to 32 feet, depending on the barometric pressure. If we attempt to increase this height by further raising the piston the water simply breaks into the vapor phase because the liquid will not stand any further decrease in pressure or increase in tension. There is evidence, though, that if proper conditions are obtained the tension may be increased for beyond this value. Some workers believe it is possible for water to support tensile stresses as large as 10,000 atmospheres. The conditions in a dry soil are such that the water is under extremely high tension. When the tension is greater than 1 atmosphere, then the ordinary potentiometers can not be used for measuring ψ .

Since the vapor pressure of the soil water depends on the surface curvature of the soil solution, the vapor pressure of the soil can be measured and the corresponding capillary potential can be calculated

if the vapor pressure of the soil solution at zero curvature is known.¹⁵ Calculations based on vapor-pressure data and the wilting coefficient given by Thomas (18) indicate that wheat plants can grow and absorb soil moisture which is under tensions as high as 26.4 atmospheres before wilting occurs. This is the moisture condition that would have existed if the soil had been at equilibrium with a water table 896 feet lower.¹⁶

The measurement of ψ in comparatively dry soils might also be accomplished with apparatus having membranes by means of which the tremendous forces of osmotic solutions could be utilized. Some experimental work has been done in this laboratory toward the perfection of osmotic apparatus similar in form to the cells in Figure 5, and in which a copper ferrocyanide membrane was supported in a thin clay plate. However, as yet, no satisfactory cells have been produced.

POSSIBLE IMPROVEMENTS IN APPARATUS

There is need for improvement and perfection of apparatus for use in connection with capillary potential measurement and control. More rugged and accurate potentiometers would be desirable for the purposes of field work. Pressure gauges could be used instead of manometers. The potentiometer should be provided with a sensitive means of detecting any motion of water from porous cup to the soil and should be arranged so that the cup water pressure can be reduced by hand until the outward flow ceases. Also, for certain kinds of work, the porous clay surface could be mounted as a section in the side of a metal pipe so that the instrument could be inserted some distance in soil without seriously disturbing the plant roots or soil structure. There is need for a recording potentiometer which can make continuous records. Capillary potential records taken over a period of years would furnish interesting information about the seasonal and yearly variation in the moisture condition of lower soil layers.

There is need also for improvement and commercial development of porous clay soil pots which will give satisfactory soil-moisture control for plant experimental work and possibly even for general use. Figure 7 shows a design that has been made up in this laboratory. A is a porous clay cup, shaped like an ordinary flower pot. It is

¹⁵ For a system such as that shown in Figure 2 it is evident that at each height above the water table there is a definite value for the vapor pressure as well as for the capillary potential. If there were a uniform concentration of soil salts dissolved in the water throughout the system, the vapor pressure everywhere would be reduced but the capillary potential gradient in the soil water and the pressure gradient in the column of vapor would still remain. In a column of water vapor the pressure, p , at any point, is given by

the exponential $p = p_o e^{-\left(\frac{\rho_o g h}{p_o}\right)}$, where h is the distance of the point above the level where the vapor pressure and density are, respectively, p_o and ρ_o . If the vapor pressure of the water-saturated soil (zero hydrostatic pressure in the soil solution) is known, then the capillary potential in the soil at any other moisture content may be calculated from the vapor pressure of the soil by using the above formula.

Thomas found that wheat plants wilted when the vapor pressure, p , in Greenville soil was 2.330 cm. of mercury. This is 0.046 cm. less than the vapor pressure of the saturated soil at the same temperature. Thus, taking p_o as 2.376 cm. of mercury and ρ_o as 23.11×10^{-6} gm. per c. c., we can calculate h from the above formula. Solving for h , we have

$$h = -\frac{p_o}{\rho_o g} \ln \frac{p}{p_o} = \frac{2.376 \times 13.6 \times 980 \times 2.3 \times .0085}{23.11 \times 10^{-6} \times 980} = 27,336 \text{ cm}$$

This is numerically equal to the capillary potential (expressed in gram centimeters per gram) because the soil would have to be at this height in a soil column to be at equilibrium with the free flat surface of the soil solution.

¹⁶ To avoid misunderstanding, it should be emphasized that even though wheat plants may be able to use soil water under tensions as high as 26.4 atmospheres, it is quite certain that water from an 896-foot water table would be "unavailable" for plant use because the rate of water movement would be too slow to supply the needs of the plant.

sealed into the can, B, by means of plaster of Paris and soft wax. A tube is fitted into the can at C and is connected to a pipe that reaches down to a free water surface. When the can and tube are filled with water and a stopper is inserted at D the capillary potential of soil in the pot will be determined by the height, h . This is essentially the same principle as that used by Livingston for his auto-irrigators (14). The type of apparatus here described has the advantage that the porous water-supplying surface is relatively larger and leaves the inside of the pot free to be occupied by the plant roots and soil. The porous clay material described in this paper was molded and fired in the laboratory. It is likely that with improved

methods it would be possible to make the capillary cell unit A and B in Figure 7 out of one piece of fired clay, thus eliminating the sealed joint.

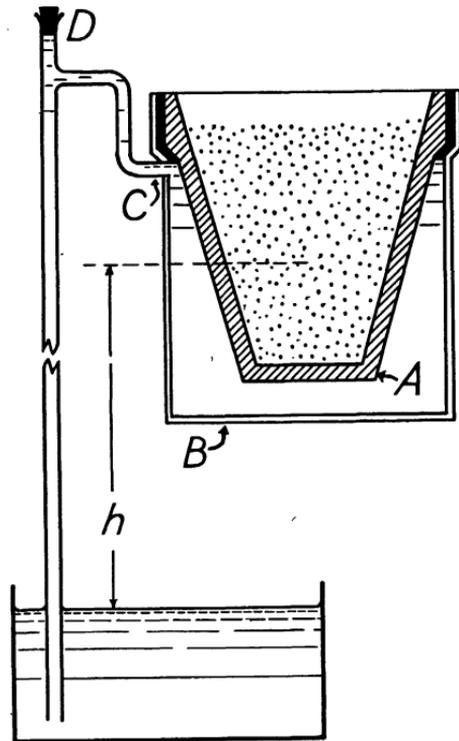
There is need for the perfection of osmotic cells or other forms of apparatus for the measurement of ψ in dry soil. It is possible to extend considerably the range of usefulness of the apparatus shown in Figure 5. If the soil on the plate were covered with an air-tight case so that by supplying air pressure in this soil chamber the pressure differences between the air in the soil and the soil solution could be greatly increased. The value of ψ would be correspondingly decreased and determinations could be made at varying pressures.

FURTHER EXPERIMENTAL DATA NEEDED

The capillary potential has as yet been only slightly used or applied in experimental work.

The following are some promising fields for experimentation

FIG. 7.—Apparatus used for controlling the capillary potential for potted plants. See text for complete explanation



that should yield valuable information: (1) Detailed experimental study of the capillary transmission constant for different soils with various states of packing and moisture content; (2) more complete study of the relation existing between capillary potential and soil-moisture content, mechanical composition, state of packing, temperature, and soluble salts; (3) study of optimum growth and germination potentials for different plants and experimentally determining whether or not ψ is a more significant quantity than those now used for designating and describing soil-moisture condition as a factor in plant environment.

SUMMARY

Studies on the movement of soil moisture and its availability to plants have been largely experimental and there is need of a comprehensive, guiding theory. The energy potentials and dynamical

methods which have been found so useful in studying electricity and heat may be equally well employed in soil-moisture investigations.

A discussion is given on the nature and use of potential functions, and the electrostatic, gravitational, pressure, capillary, and total potentials are defined.

It is shown that, when the proper units are used, the value of the capillary potential in soil which is in moisture equilibrium with water through a porous clay wall is numerically equal to the difference in pressure in the water and atmospheric pressure. The capillary potential is therefore a measure of the pressure in the soil solution.

The factors determining the capillary potential in a moist soil are discussed and experimental data are given which show the relation between this function and the percentage of moisture for four different soils.

The flow of moisture through soil can be expressed as simply the capillary conductivity times the potential gradient, i. e., $v = -K \text{ grad } \Phi$. (This is analogous to Ohm's law for electricity and Fourier's law for heat.)

Application of the potential theory to soil-moisture movement is made for the following cases: (1) Flow of moisture downward through soil after rainfall or irrigation, (2) flow of moisture upward from a saturated water table, and (3) movement of moisture in a horizontal direction.

The availability of soil water to plants involves two factors, viz, the "security" with which the water is held by the soil and the readiness with which moisture flows in to replace that which has been used by the plant. The capillary potential is a direct measure of this "security" factor. The rate of moisture flow toward the roots is quantitatively expressed in terms of the transmission constant and potential gradient by the above equation.

A new form of porous clay apparatus is described which can be used in controlling soil water for potted plants.

The capillary potential offers a means of quantitatively expressing soil-moisture phenomena and has advantages over the commonly used methods of designating soil-moisture condition as a factor in plant environment.

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