RELATIONS BETWEEN WATER AND SOIL

by

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PREFACE

This account is written from the standpoint of the agricultural use of soils. It touches also at some points on work done in other fields concerned with fluids in porous media. Soil is hardly to be considered as a single type of porous material since it can include inert sands on the one hand and reactive clays on the other. Hence some of the work done by the petroleum technologist on fluids in porous rocks, by clay technologists on water in clays, and by engineers concerned with soil as a foundation material is relevant to the present discussion.

Many terms have by now come into use in the general field of research on fluids in porous media. In facing the problem of what terms to use, I have been helped by reports on terminology published in the Proceedings of the Soil Science Society of America in Vol. 16 (1952) pp. 85-88, Vol. 20 (1956) pp. 430-440, and Vol. 22 (1958) p. 270 and by discussions on terminology of soil moisture and salinity initiated (but not yet published) by the International Committee for Horticultural Congresses.

I should like to thank Mr. G. V. Jacks of the Commonwealth Bureau of Soils and Dr. H. L. Penman of Rothamsted Experimental Station, England, for early discussions on the scope of this account and I am indebted to Dr. Penman and Dr. J. N. Luthin (while on a visit from the University of California), and Mr. J. W. Holmes, Mr. C. G. Gurr, Dr. E. L. Greacen and Mr. G. B. Stirk (Division of Soils), for reading some parts of the manuscript. I owe much to colleagues of the Division of Soils for many discussions and to Dr. J. P. Quirk (University of Adelaide) and Dr. K. L. Sutherland (Division of Industrial Chemistry, C.S.I.R.O.) for discussion of some of the material on sorption. Translations of a number of the papers referred to here were made by the Translation Section, C.S.I.R.O., Melbourne, and by the Commonwealth Bureau of Soils.

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1. SOIL AS A STORE FOR WATER

I. Introduction: Water and Some of the Properties of Soils

Over a great part of the land surface of the earth, water limits plant growth either because there is too much or too little of it in the soil. The extreme cases are in swampy and arid areas where if crops are to be grown at all they have to depend upon drainage or irrigation. Between these extremes lie the established agricultural lands many of which can be improved by having less water or more in the soil at certain times of the year. A great deal is done to control water in agriculture and, if both water and soil are to be put to the best use, a full understanding of soil-water relations is necessary. Much of the research on retention and movement of water in soil and the use of water by plants is done with this objective.

Water has notable effects upon the soil itself and these may indirectly affect plant growth also. It plays a key part in soil formation. The processes of weathering and profile development (involving organic as well as inorganic parts of the soil) are greatly affected by water. The movement of materials dissolved in water results in horizons of loss and of accumulation which give the soil a distinctive profile and may brand it as fertile or infertile for plant growth. Water is also a responsible agent in soil erosion. Many of the physical properties of soil, such as its structure, strength, and swelling, are greatly affected by it so that soil-water relations play an important role in tillage and in the design and performance of roads and buildings.

The behaviour of water in soil is affected by the size of the particles and the way in which they are arranged. Generally the greater the clay content, the more water will soil retain at a given stage of draining or drying, but the type of clay mineral and the nature of the exchangeable cations also affect retention and movement. The particles may be openly or closely packed together and so leave more or less pore space between them for water and air. They form the porous matrix in which the water is embedded and the way in which they are arranged so as to leave much pore space or little, large pores or small, is clearly just as important in water relations as the size and kind of the particles. The total pore space (the volume fraction occupied by water and air) is fairly easy to determine but the pore sizes have been more troublesome. Water will move through, or drain out of, large pores more easily than small, and so size of pores has to be considered for water storage and movement as well as amount of pore space. The classical approach to pore size was through its particles. Workers trying to find some basis for relating soil properties to permeability, at first determined the geometry of the pore space in ideal systems of packed spherical particles. Later they obtained an effective tube size from the ratio of porosity to surface area of the particles. By this means, irregularly shaped particles could be dealt with; but the method failed when there was a larger range of size and it is unsuited to soils. With the development of methods for finding how water content changes when a suction is applied to the water in the soil, a means ultimately became available for measuring the size distribution of pores in non-shrinking soils.

The theoretical background for water retention, movement and storage in unsaturated soil was originated more than 50 years ago by Buckingham but advances in these, as in most lines of soil-water investigation, were greatly accelerated by developments in techniques for measuring suction which came much later. These have led to a better understanding of the processes by which water becomes distributed through soil and is made available to the plant.

II. Gains of Water to the Store

Soils gain water from rain and irrigation and lose it by drainage, by transpiration from plants, and by evaporation directly from the soil. Some of the processes by which water is gained or lost can be controlled. Control over water entry is mainly through irrigation but man also undertakes treatments which are designed to increase or reduce the amount of rain water entering directly into soil. Soil and water conserving practices which improve soil permeability or which hold the water ponded on the surface until it soaks in, are examples of what is done to increase intake and so reduce loss of water which would otherwise run off the surface.

The amount of water retained in soil which has drained for about two days (while covered to prevent evaporation) is known as the field capacity. This is not a precise quantity but it serves the useful purpose of providing an approximate upper limit to the amount stored for subsequent use by plants. The lower limit is the permanent wilting point and the difference is the range of available water for plant growth. This definition of capacity for water storage has been widely used. In irrigation practice in particular, it has provided a useful basis for determining when water is needed and the amount required to recharge the store. Excessive irrigation, much beyond that amount, is wasteful of water and damaging to the soil.

In order to know at any time the actual stage of drying reached within these limits and so decide how much and when water is needed, it is usual to sum up the position qualitatively from local experience with soils, plants, and climate. Quantitative methods are also in use based on plant behaviour (e.g., changes in fruit size), evaporation measurements, or soil measurements. Soil measurements are of two kinds. If it is desired to know the actual amount of water to be added to the surface in centimetres or inches, in order to recharge the store for a particular soil, then a measure of the water content (as the amount of water in a given volume of soil) may be needed. However, the best common guide to the stage of drying is given by the suction of the soil. Suction is a term referring to the force with which water is held in the soil. For example, if water in a porous cup is brought in contact with moist soil, then the suction which is needed to keep it from entering the soil is equal to the suction of the soil. Both the terms suction and water content will be dealt with more fully in the next section.

In large irrigation areas when watering times are controlled on a regular roster, the watering schedule is not very flexible; but the smaller areas and especially the one-farm units with independent water supply have more latitude. In all cases there is the desire for answers to the question of water needs and a keen demand exists for methods for measuring the changing suction or water content for practical agricultural and field experimental work. A number of methods have been introduced to obviate sampling, and instruments such as tensiometers and gypsum blocks have proved useful for measuring suction in the field. Others with promise, such as the neutron moisture meter, are becoming available for measuring water content. Also, provided plants suffer no restriction in the supply of water to their roots, the amount lost by transpiration can be calculated from meteorological data. If some known starting point such as field capacity is taken, then the deficit of water at any later time can be calculated by this means if other losses can be disregarded. Advantages and limitations of various methods for determining suction and water content in the field will be discussed in a separate section.

III. Losses to the Atmosphere

Evaporative losses can be most easily controlled by removing all vegetative cover. The most widespread use of this means of control is in the fallow periods common especially in cereal farming. There are varying reasons for fallowing but in some regions the storage of water for the next crop is the main one. Much work has been done on treatments to conserve water. Paper, foil, or plastic sheets and various other materials can be used to cover the ground and reduce water loss. A comprehensive review of these and soil treatments has been made by Jacks, Brind and Smith (1955). Treatment of the soil itself usually depends first of all on the removal or prevention of weeds so that there will be no unnecessary withdrawal of water by plants. Loosening of the soil surface can reduce liquid flow to the surface and so create a dry barrier which reduces evaporation. Ordinarily the top soil will dry out any way and the protection will thus be provided in dry weather without loosening the soil. Water is lost from a bare soil by evaporation at approximately the same rate as from an open water surface so long as the soil surface remains wet. When the surface dries out due to the rate of evaporation exceeding the rate of supply from below, evaporation decreases markedly. Penman (1941) considered that when a wet soil is subjected to conditions which induce a rapid rate of drying, the total water lost over a period may be less than would be the case if drying conditions were less severe. With rapid drying a protective dry mulch is quickly formed. He has suggested that, in view of the continued loss with slow drying, cultivations in spring might be effective in reducing loss of water from bare soil. They are ineffective in the summer except by way of weed control. In later work, Gardner (1958) and Gardner and Fireman (1958) show that the rate of loss depends on the rate of supply from below in the liquid phase unless the meteorological conditions for evaporation are themselves limiting.

Lemon (1956) has used surface active agents which, by reducing the surface tension of the water, cause less water to be retained in the surface soil after an irrigation. Hence the dry zone will be established sooner and with less loss of water than otherwise. Results were said to be promising but unproved on a field scale. Earlier Russian work using soap for this purpose, is quoted by Lemon. Russian workers have paid a lot of attention to surface treatments of soil structure to reduce movement in both liquid and vapour phases. Koliasev (1941) and Kolesnik (1948) found that a layered structure of alternate loose and compact soil was effective in reducing the loss of water from the top metre of soil. In Kolesnik's experiments, soil treated in this way conserved more water over the summer and at the time of seeding had 4 cm more to a depth of 1 metre than one which was loosened but had no compact layer. The purpose of the compact zones was to reduce vapour movement and that of the loose zones to reduce liquid movement towards the surface. Burov (1952) showed that the amount of water lost to a depth of 1 metre increased with size of the structural aggregates (and the amount of pore space made up of larger pores) because of wind entry when the pores are too large. Also if they are too fine, liquid loss (and cracking) can become serious. An optimum size of aggregate to prevent evaporation was found by Burov (1954) in field experiments to be 3-0.25 mm. Lumpy (>10 mm) and fine (<0.25) aggregates increased the losses under field conditions and these fractions were best kept below 5 to 10 per cent by weight for Trans-Volga chernozem. Burov suggests that this type of finely crumbed structure could be brought about by pasture leys and proper tillage.

A change in the annual amount of water used by vegetation can have widespread effects on water storage, run-off, and soakage to aquifers. In some circumstances, the burning off of perennial native shrubs so that annual grasses can take over, has been advocated. In California, Veihmeyer (1953) has shown that, in a climate with cool wet winters and hot dry summers, the grasses do not dry the soil out so thoroughly (except near the surface) and there is more water remaining in the soil when the following wet season begins. The practice may be opposed on other grounds such as erosion (*see* discussion of Veihmeyer's paper, *Trans. Amer. Geophys. Un.* 35, 652-658) but there is no doubt that the principle is sound so far as the water regime alone is concerned. The effects of clearing perennial native shrubs and trees and substituting annual winter-growing grasses, crops, and fallows upon local hydrology can sometimes be unwelcome. Teakle and Burvill (1938) have studied one case of importance in which clearing of native vegetation following settlement for agriculture has resulted in increased seepage of water to the valleys. In this case the soils, were naturally fairly saline and the seepage has resulted in serious salting of valleys in a large agricultural region in Western Australia. Similarly Wilde *et al* (1953) found that the clear cutting of aspen stands on podzolized soils in northern Wisconsin caused semi-swamp conditions to develop.

IV. Removal by Artificial Drainage

Excess water in soil is removed artificially by subsoil drainage to a depth chosen on the basis of the type of soil, crop, and climate and the economics of drain construction. In humid areas the depth is often of the order of 100 cm (or less) but in irrigated arid country it is commonly deeper and if soils are permeable to that depth, tile drains are commonly placed at a depth of about 200 cm. The main objectives in draining are to reduce the water content of the soil so that aeration will be adequate and so that dissolved salts will be removed and their movement towards the surface restricted.

The greater depth of drainage for irrigated land gives a better insurance against upward movement of salt and its accumulation near the surface. However, irrigated pastures and crops which wholly cover the surface can be maintained with shallower drainage than that more usually required for irrigated orchards in which part of the ground is bare of vegetation and is not wholly covered by water at each irrigation. Methods of draining irrigated lands have been discussed by Luthin (1957a). Drainage is commonly required in irrigation areas and the need for it is usually to protect against salinity. An extended discussion of the movement of soluble salts is given in Section 8.

In relatively humid areas, the depth of drainage is sometimes rather carefully controlled so that some use may be made of the ground water when the rainfall during the growing season is not sufficient or is so irregular in its incidence that drought periods occur. Nicholson (1949) states that in such cases the optimum depends a good deal on the type of crops being grown (cereals required a lower groundwater level than root crops) and on the seasonal conditions (higher levels better in droughty summers than in moist summers). Because of these variables and the variability of soils, there has been much controversy about the depth at which water tables should be maintained to suit local conditions. Nicholson and Firth (1958) have reported on the effect of depth of the groundwater in a fen peat soil upon crop yields and soil structure. Their results (shown in Fig. 1) generally favour depths of 30 to 35 inches although potatoes and

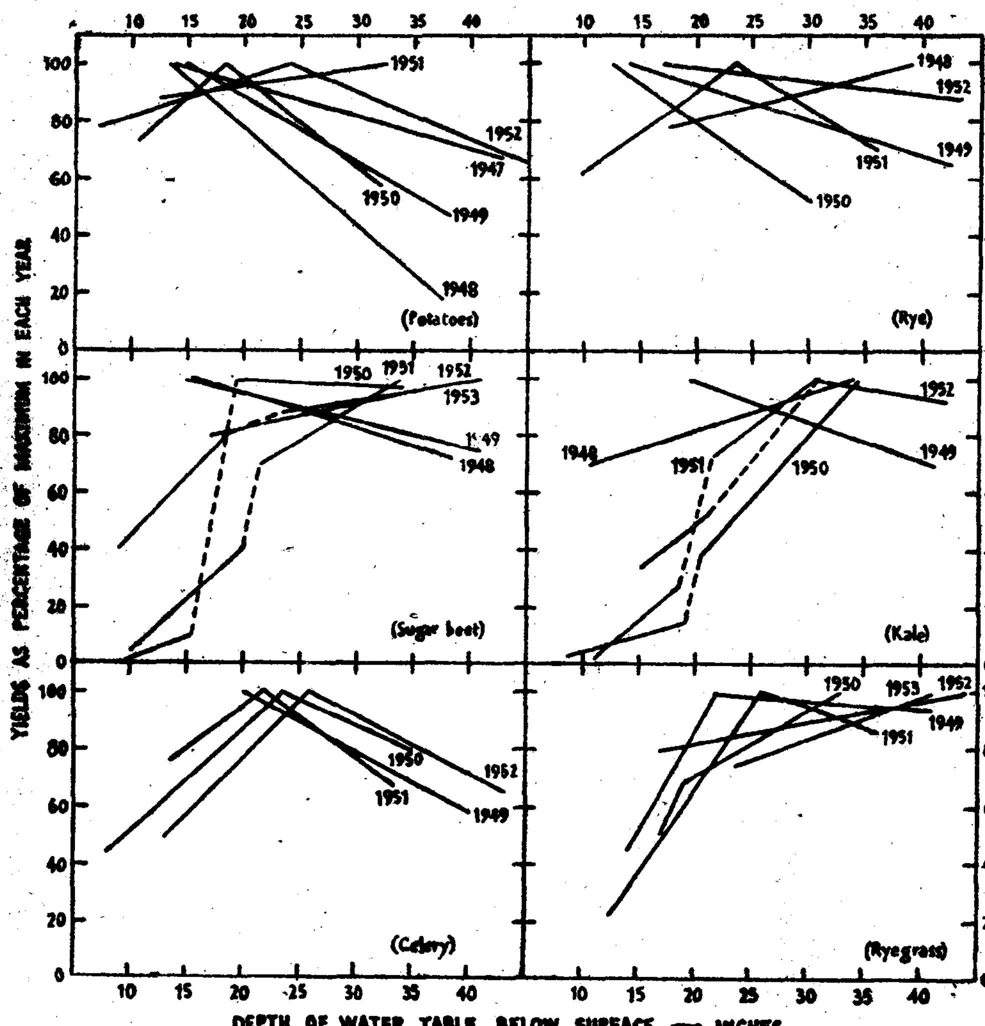

FIG. 1. *Effect of depth of water table on crop yields on a fen peat soil* (*Nicholson and Firth*, 1958).

celery responded to shallower groundwater levels (about 24 inches). There was a progressive deterioration in the physical condition when the water level was kept shallower than 30 inches during successive growing seasons. Reference can be made to Wesseling and van Wijk (1957) and van't Woudt and Hagan (1957) for further details on depth of drainage in these circumstances and on sub-irrigation.

Wind (1955) has measured the contribution from a shallow water table to the root zone by inserting a plastic sheet above the water table. The water content of the soil above the sheet was lower throughout the summer in the soil treated in this way than in untreated soil and Wind found that 15 cm of water was supplied to the untreated soil during the season. For his clay soil, of measured unsaturated permeability, he estimated the relation shown in Fig. 2 for the amount of water (mm/day) contributed to the bottom of the rooting zone in relation to its height above the water table and the suction of water at that height. For example, if the suction is 1 atmosphere at a height of 40 cm above the water table, 3 mm of water per day will be contributed. The accuracy of these results is no doubt limited by the instruments used for measuring water content and suction in the field. Verhofen (1953) as quoted by Wesseling and van Wijk (1957), found a lower rate of supply of 3 cm per year in a soil column. Because rates of supply from below are not great, it is usually necessary under conditions of low rainfall and high transpiration to raise the water table periodically so that the soil will be properly sub-irrigated.

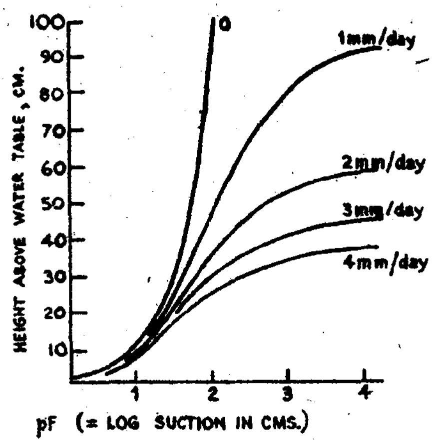

Fig. 2. *The amount of water (in mm/day) contributed by a water table to soil at a given suction and at a given height above the water table (Wind, 1955).*

Loss of production from having a water table too high (so that damage results when there is an unexpected rainy period) can be greater than from having it too low. For adequate aeration, Wesseling and van Wijk (1957) suggest that the fraction, ε_g, of the soil filled with air should exceed 0.1 and drainage should be designed to maintain conditions better than this for most of the time. The way in which diffusion of gases decreases with decreasing air-filled porosity (as caused by increasing water content) is illustrated in Fig. 3 by data of Taylor (1949). It will be seen that when ε_g falls to 0.1, diffusion is greatly restricted. In naturally occurring soil, non-uniformity would usually result in the sealing off of the soil at various planes and aeration could thus be stopped altogether at this stage. There is evidence of this in the literature especially in field measurements of diffusion (Blake and Page, 1948; Millington, 1957). Aslyng (1957) suggests that in tilling soil an aim should be to maintain ε_g at 0.15 or more but without making the soil so open that undue evaporation will occur.

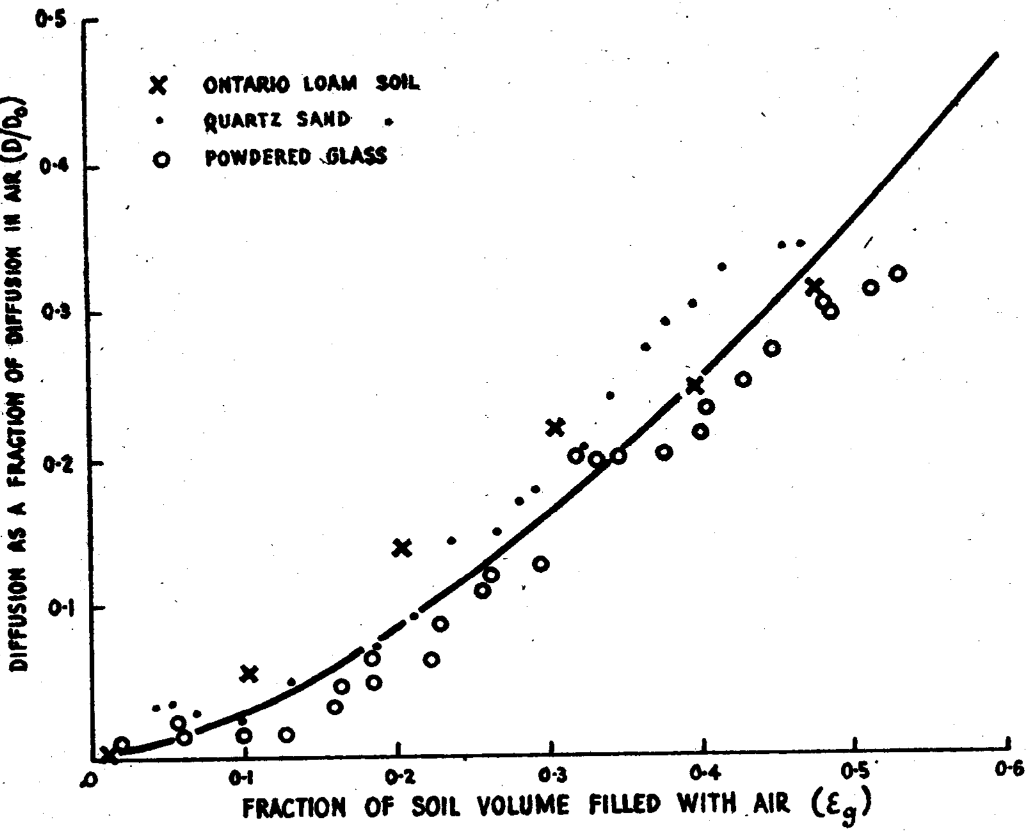

FIG. 3. *The effect of air-filled pore space on gaseous diffusion in three materials at various water contents* (Taylor, 1949). *The curve for Equation* (27) *in Section* 7(*II*) *is also shown.*

2. RETENTION OF WATER BY SOIL

I. Wetness of Soil

To find out how much water there is in a soil, a weighed sample is dried at some chosen temperature (usually 105°C) and the mass of water per unit mass of dry soil determined. This gives the water content, c_w in grams per gram, on a weight basis. For many purposes water content is better expressed on a volume basis. If the apparent (or bulk) density of the soil is ρ_a in g/cm^3, then the volume of water per unit volume of soil is given by $c = c_w \rho_a/\rho$ cm^3/cm^3 and ρ, the density of water, may be taken as unity. Here the water content, c, represents also the equivalent depth of water in unit depth of soil. This is the quantity that is required when dealing with storage of water in soil and the gains or losses as by rain, irrigation, evaporation, transpiration or drainage.

These measurements of the quantity of water in soil do not give all the information needed for knowing how wet it is. A soil of high clay content can feel dry to the touch while a sandy soil at the same water content is quite moist. The first soil will not support plant growth while the second is wet enough to do so. Similarly water will tend to move from the sandy soil to the clay soil if they are in close contact although they are at the same water content.

This difficulty can be met in a rough way by expressing the water content as a ratio to some other value which is characteristic of the retentiveness of the soil for water. For example, if water content is expressed as a ratio to moisture equivalent (the water retained after centrifuging in a specific way) then the relative wetness of a soil is obtained. Other reference values which are characteristic of the colloidal properties of soil such as lower plastic limit, sticky point, or clay content have also been used instead of moisture equivalent in the same way.

A sounder and more direct way of getting this information is to find how strongly the water is held in the soil. This can be done by means of a tensiometer—an instrument for measuring the suction exerted by soil on the water enclosed in a porous ceramic cup to which a vacuum gauge or manometer is attached. The drier the soil the greater is the suction.

The wetness of a soil can therefore be specified in two ways—by the amount of water it contains and by the suction. The first specification is needed when working on the balance of gains and losses of water and the second is needed for an understanding of movement of water and availability of water to plants. The curve connecting amount with suction helps also to give information about the porous structure of a soil because water is withdrawn more easily from large pores than from small.

II. Suction of Soil

In Fig. 4, a method is illustrated for measuring suction. Porous cups attached to glass or plastic tubing containing water are inserted in the soil and water flows into or out of the soil through the cups until equilibrium is reached between the soil water and the unbalanced length, h, of the water column in the manometer.

The hydrostatic pressure of water, P, at any point in a body of water at rest (as in the manometer) is given by

$$P = P_o - \rho g h \text{ dynes/cm}^2$$

where ρ is the density of water, g is the acceleration due to gravity, and h is the vertical distance of the point from a reference level at which the pressure is P_o. If the reference level is the free surface of the water at atmospheric pressure where the reference pressure P_o is taken as 0, then

$$P = -\rho g h \text{ dynes/cm}^2$$

The negative sign indicates that pressure decreases with increasing height in a column of water, *h* having positive values when measured upward and negative when measured downward from the reference level according to convention. It can be seen that the pressure of the water in the porous cup of Fig. 4B is less than atmospheric pressure. The corresponding deficiency in pressure of water in the soil (taking this to be a sand for the time being) is given by the curvature

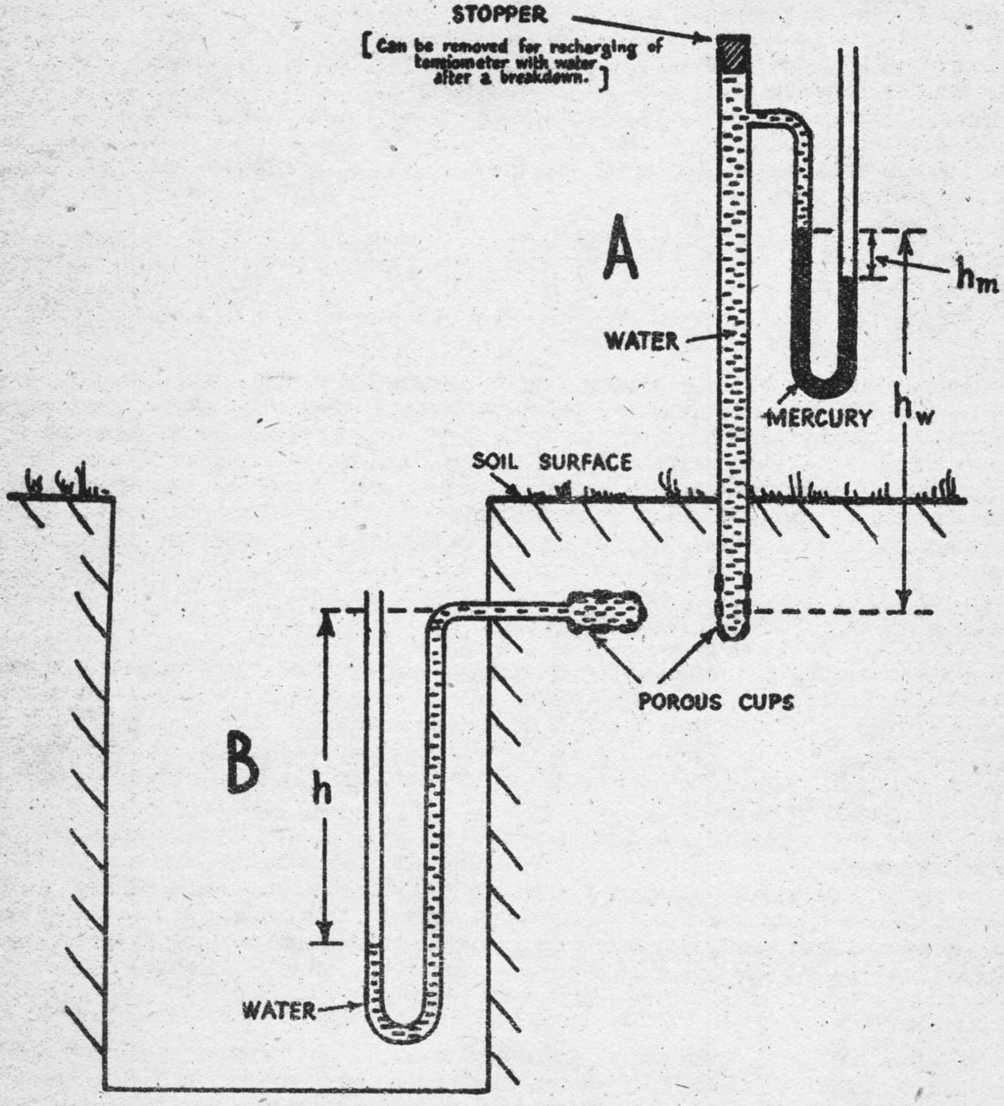

FIG. 4. *A.—Tensiometer for use in the field with a mercury manometer. B.—A simple tensiometer in which the suction is shown as the length h of a column of water. This type of system is used in the laboratory for small suctions but is not ordinarily suitable for the field*

of air-water interfaces which exist within the unsaturated soil. When the air in the soil is at atmospheric pressure, the pressure, P, in the water on the other side of the interface is given * by

$$P = -2\sigma/r = -\rho g h \text{ dynes/cm}^2 \quad (1)$$

where σ is the surface tension of water and r is the radius of curvature of a simple hemispherical interface which would be in equilibrium with the more complex air-water interfaces of the porous system. For a non-circular pore, $1/r_1 + 1/r_2$ takes the place of $2/r$ where r_1 and r_2 are the principal radii of curvature of the interface.

To avoid the use of the negative sign in dealing with unsaturated soils, the water is said to be at a negative pressure, pressure deficiency, tension, or suction of $\rho g h$ dynes/cm². The dyne/cm² is not convenient as a working unit for suction which is consequently either expressed as cm of water (h) or as atmospheres ($h/1035$) for soils of low or high suction respectively. The bar ($=10^6$ dynes/cm²) has also come into use as an alternative unit for suction (Richards, Gardner, and Ogata, 1956). It is close to 1 atmosphere (1 bar = 0.99 atmosphere) and the millibar ($=10^3$ dynes/cm²) is also close to 1 cm of water (1 mb = $h/1.022$). The bar and millibar are in general use as pressure units in other fields, especially meteorology. They are convenient for expressing both high or low suction in a consistent way. Inter-relations between these and other units for expressing water retention by soils are set out in Table 1.

Pressure deficiency constitutes a force capable of sucking water (at atmospheric pressure in bulk) into unsaturated soil. This is not however the only mechanism responsible for suction. Water can be drawn into a two-phase system of moist clay although there is no air-water interface within the soil mass. Here water is attracted to the solid surface and to the exchangeable cations associated with that surface. The range of operation of the attractive forces is limited and they are therefore of most consequence in the thinnest water films. In soils with very small particles (soils of high clay content) these thin films may together constitute a considerable amount of water because of the large total surface area of the particles and the ability of the soil to swell. Water is probably under a positive pressure near the solid surface (the pressure which can be developed by a swelling clay is evidence of this). Hence it may not be valid to speak of a negative pressure or pressure deficiency in soil water and for this reason the word "suction" is commonly used instead to cover the general case. Suction can be due to either mechanism and it is represented by the pressure deficiency of water in the porous cup of the tensiometer at equilibrium. In soils of low clay content, water retention can be treated as a capillary phenomenon (involving pressure deficiency) over the range of suction of main interest in agriculture. In soils of high clay content there is usually some filling and emptying of pores as well as change in volume upon wetting and drying and both capillary and attractive forces may be involved.

A number of different methods are used for measuring soil suction. The tensiometer is suitable for use when the suction does not exceed about 850 cm. As it increases beyond this, entrapped or dissolved air causes breakdown. Fig. 4A shows the general features of a tensiometer for measuring suction in the field using mercury as the manometer liquid. If ρ_m is the density of mercury, then suction is given by $s = \rho_m g h_m - \rho g h_w$ dynes/cm² $= h_m \rho_m/\rho - h_w$ cm water. Alternatively Bourdon vacuum gauges may be used. Details of tensiometer systems and similar laboratory devices (suction plates and tables) for measuring the relation between water content and suction have been reviewed by Richards (1949) who has played a leading part in the development of these instruments. The tensiometer cups are constructed with pores small enough not to let air be drawn through when the water in them is under a suction of about one atmosphere. Modifications to the usual type of tensiometer to enable suction to be measured without serious exchange of water between soil and tensiometer have been introduced by Miller (1951) and Croney (1952).

Richards (1941) has developed an instrument known as the pressure membrane apparatus by which the pressure difference across the interface can be measured for soil water at much greater suctions than are covered by the tensiometer. It consists of a closed chamber the floor

*—Assuming the contact angle between water and soil to be zero. The derivations and assumptions for equations used in this section are to be found in standard works on the properties of matter or in Edlefsen and Anderson (1943).

TABLE 1

Relation between the various units used for expressing retention of water (illustrated by approximate values at four levels of soil moisture)

Soil moisture condition	Suction		Capillary potential or free energy	pF	Equivalent radius of largest pores which could be full of water	Instruments suitable for measuring the suction
	length, *h* in cm, of vertical column of water or millibars	atmospheres or bars	ergs/g or ergs/cc	log *h*	10^{-4}cm or µ	
At suction of 1 cm (soil saturated or nearly so)	1	0.001	-9.8×10^{2}	0	1,500	tensiometer (or suction or pressure plate)
At suction of 100 cm (corresponding uncritically to field capacity)	100	0.1	-9.8×10^{4}	2.0	15	tensiometer (or suction or pressure plate)
At suction of 15 atmospheres (corresponding to permanent wilting point)	15,000	15	-1.5×10^{7}	4.2	0.1	pressure membrane apparatus
At relative vapour pressure of 0.85 (soil feels dry)	220,000	220	-2.2×10^{8}	5.4	0.007	vapour adsorption methods
Conversion from suction in cm (at 20°C when appropriate)	*h* cm or *h*/1.022 mb	*h*/1035 atm or *h*/1022 bars	−980 *h*	log *h*	0.15/*h*	

of which is a membrane of cellophane or sausage casing suitably supported to withstand high pressures from inside. Water and dissolved salts can pass through this membrane (Reitemeyer and Richards, 1944) but it will hold back air when wet. Wet soil is placed on the membrane, compressed air or nitrogen is introduced into the chamber and brought to a chosen pressure. Water passes out of the soil through the membrane and continues to do so until the forces holding the water in the soil just balance the gas pressure tending to force water out of it. When flow ceases the soil water (under the influence of the gas pressure in the chamber) is in equilibrium with water outside the membrane at atmospheric pressure. If the gas in the chamber is then returned to atmospheric pressure, a suction of the same magnitude as the original gas pressure would need to be applied to the water outside the membrane to prevent it reentering the soil. Thus the pressure to which the gas was raised in the chamber is equivalent to the suction of the soil at the equilibrium water content. Pressures ranging from 0.1 to 170 atmospheres have been applied in this way although the working range for routine use does not commonly exceed 15 atmospheres. The water content of soil at this pressure ("fifteen atmosphere percentage" or "fifteen bar percentage" of Richards) corresponds rather closely to the permanent wilting point of soils.

Richards (1947) has published full details and drawings of the pressure membrane apparatus. A modification introduced later by Tanner and Hanks (1952) enables data to be obtained for the wetting (intake) curve as well as the drying (release) curve. This is accomplished by running water continuously below the membrane. The only serious criticism of the pressure membrane apparatus is that raised by Collis-George (1952) who found a progressive decline in water content of soil held under a constant gas pressure for several weeks. The decline was considered to be due to diffusion of gas through the membrane and the consequent necessity to introduce dry gas periodically into the chamber in order to maintain the pressure. However, according to Quirk (1953) this is probably not a major factor affecting the routine use of the apparatus.

The tensiometer (and similar suction devices) together with the pressure membrane apparatus (and the similar pressure plate apparatus of S. J. Richards (1938) and L. A. Richards and Fireman, 1943), enable the relation between water content and suction to be determined for a soil sample from saturation to permanent wilting point. For drier conditions than this, the vapour pressure of soil water is used as a measure of water retention (Bodman and Edlefsen, 1934; Schofield, 1938). It can be shown by means of the Kelvin equation that the suction in cm, h, is related to the relative vapour pressure, p/p_o, by the expression

$$h = -(RT/g)\ln(p/p_o) \qquad (2)$$

where R is the gas constant per gram, T is the absolute temperature, g is the acceleration due to gravity, p is the vapour pressure of the water in the soil and p_o is the vapour pressure of water in bulk. Since p will be affected by solutes in the soil solution as well as by the suction due to the solid matrix, Equation (2) will represent suction of the matrix only in the absence of solutes. It will be seen by reference to Table 1 that suction can reach very high values in the range covered by vapour pressure methods. For convenience suction is often expressed as $\log_{10}h$ for which the term pF was introduced by Schofield (1935).

In one of the many methods available for determining the relation between water content and vapour pressure, the soil is placed in a shallow container in an evacuated desiccator containing a saturated salt solution of known vapour pressure. The water content of the soil at equilibrium is determined for any chosen vapour pressure. Tables of vapour pressure for various saturated solutions have been published by O'Brien (1948). The vapour adsorption methods cannot at present be applied successfully to wet soil because there is very little difference in the vapour pressure of soil water from permanent wilting point to saturation. The relative vapour pressure changes only from 0.99 to 1 within this range. Vapour adsorption is used principally for conditions drier than the permanent wilting point but with refinement of methods (Steiger, 1951; Wylie, 1957) the range can be extended. There is therefore some promise of increasing usefulness of vapour pressure methods in soil physics.

Curves such as those in Fig. 11 and Fig. 6 which relate water content to suction are much used in soil water investigations. They have been given special names by some workers such as retention curves or moisture characteristics. An indication of the order of magnitude of the suction under different moisture conditions and the relation between different methods for expressing water retention are given in Table 1. The measuring methods appropriate to each moisture condition are also given.

III. Suction and Pore Size

Curves relating water content and suction can also be used to help define the structure of soil in terms of the size of the pores which make up its pore space.
Equation (1) can be rewritten in the form

$$r = 2\sigma/\rho g h \qquad \text{- - - - - - - - - - (3)}$$

Here r is the upper limiting radius of pores which can remain full of water when a suction of h cm is applied to the water in wet soil. At 20°C, r is equal to $0.15/h$. The volume of water withdrawn in changing from one suction to a greater one in a soil which does not shrink, represents the volume occupied by pores of sizes lying between the corresponding limiting radii assuming the pores to be of circular section. The pore size distribution can therefore be determined directly from the water content—suction curve for a porous material as in Fig. 11. In this diagram, the curve represents the cumulative volume of pores smaller than a given size in a manner similar to that for representing particle size analysis.

The size distribution of the pores in a soil provides a specification of its structure which has been used in studying water and air movement. For example, permeability of saturated soil is related to the amount of larger pores and, in unsaturated soil, permeability is similarly related to the size distribution of those pores which are small enough to be full of water at the prevailing suction. Sometimes instead of using a complete curve the amount of pore space larger than one chosen size is determined ("non-capillary porosity" or "macroporosity"). A radius of 1.5×10^{-2} mm corresponding to 100 cm suction is frequently chosen arbitrarily for separating "large" from "small" pores.

IV. Some Limitations in the Use of Suction Data

There is one important difficulty involved in using a water content—suction curve. The curve exhibits hysteresis—it differs according to whether the soil is being wetted or dried. If two samples of a soil are brought to equilibrium with a given suction, a sample which was dry to start with will contain less water than another which was wet. Because soil is exposed most of the time to drying conditions when crops are being grown on it, the drying curve alone is commonly used. The question of which curve to select for measuring size distribution of pores is a more difficult one.

This hysteresis phenomenon in soils was early studied by Haines (1930). A number of different explanations have been advanced for it based on (1) possible differences of contact angle of water to soil as between wetting (advancing) and drying (receding), (2) possible effects of thickening of films before a hemispherical meniscus forms at the opening of the pore, and (3) the so-called "blocked pore" or "ink-bottle" effect. Hysteresis in soils is usually attributed to this last effect which is presumed to arise because many pores are larger than their openings. On wetting, these pores will not fill with water until the suction has fallen to that appropriate to the wide dimension of the pore proper. On the other hand they will not empty on drying until a higher suction has been reached appropriate to the narrow dimension of the neck. Hysteresis occurs in saturated clays for a rather different reason that will be discussed in Section 3 (II).

Carman (1953) prefers the drying curve for pore size measurements on porous materials because he considers that one or more connecting channels will usually be wide enough to allow a meniscus to enter easily into the pore. He attributes hysteresis more to delay in filling pores than to delay in the emptying of "blocked pores" during drying. This is the course usually followed by soil workers. Using drying curves (progressively increasing suction), Swanson and Peterson (1942) compared their results with size distributions measured microscopically. Although there was great irregularity in the shape of the pores, they found a close relation between results obtained by the two methods. Further comparisons of this sort are required.