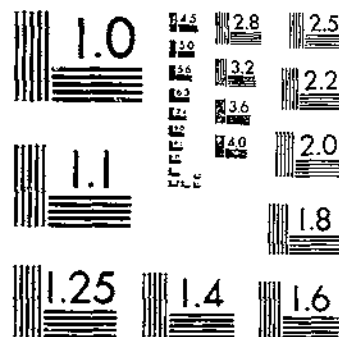# START



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

# RATE OF FLOW OF CAPILLARY MOISTURE [1,2]

### By M. R. Lewis

*Irrigation engineer, Division of Irrigation, Bureau of Agricultural Engineering, and Soils Department, Oregon Agricultural Experiment Station*

## CONTENTS

## INTRODUCTION

The rate of flow of moisture through unsaturated soils is a problem that has attracted a great deal of interest among soil investigators. It is of direct importance in farm operations for many reasons and is of great technical interest because of its indirect bearing on other problems.

Perhaps the question that has been most generally considered is the loss by direct evaporation from the surface of the soil and the effect of cultivation in preventing that loss. This problem has been attacked by both field and laboratory methods and somewhat contradictory results have been obtained.

A second important problem is that of supply of soil moisture to plant roots. The relative importance of the movement of moisture through the soil to the absorbing roots and the movement of roots through the soil to the moisture supply has been debated at considerable length in technical literature.

It is generally recognized that water is held in the soil above the upper surface of the zone of saturation (the water table) by capillary force. The soil zone so moistened is known as the capillary fringe. Some of the earlier investigators considered the movement of moisture

from the zone of saturation into or through the capillary fringe to the root zone to be of very great importance and thought that it might take place through distances of many feet. More recently its importance has been denied and some workers have held that the roots must always go to moisture rather than that moisture may move to the roots. Conclusive evidence as to the real importance of the movement of capillary moisture has not been available.

In irrigation practice capillary movement is important in at least three ways. In furrow and corrugation irrigation the lateral movement of moisture through the space between the furrows is essential to the moistening of the root zone. In many cases the rate of this movement is the governing factor determining the length of time during which water must be applied. The downward movement of moisture under the combined influences of gravity and capillary forces is also of primary importance. The possibility of producing maximum crops under irrigation without permitting the loss of water by deep percolation is bound up with this question of the rate of flow of capillary moisture. The third phase of importance in irrigation farming is the upward movement of moisture carrying dissolved salts. This movement accounts for the accumulation of alkali at the surface of irrigated lands.

If, as seems entirely possible, the rate of movement of moisture through the soil to the roots is at times the limiting factor in plant growth, it is probable that a knowledge of the ability of soils to transmit water will furnish another criterion of the agricultural value of different soils.

The foregoing may be considered the more immediately practical phases of the problem. There are, in addition, some fundamental questions that need further study. These are particularly concerned with studies of the capillary potential and the capillary conductivity of different soils.

In the range between the field capacity and the wilting point, methods heretofore used have not yielded satisfactory data as to the value of the capillary potential. The vapor-pressure method is useful with moisture contents below the wilting point. Above that point moderate increases in moisture content result in extremely small decreases in vapor pressure. This fact raises considerable doubt regarding the shape and position of the moisture-content versus capillary-potential curves as they may be determined by the vapor-pressure method in the moister soils. The porous cup method is useful with very moist soils, but it has been found incapable of obtaining values with soils much drier than the field capacity. It is obvious that the intermediate zone (between the wilting point and the field capacity) is of primary importance in studies of plant-soil-water relations.

The capillary potential is an expression for the force with which moisture is held at a given time and at a particular point in the soil by capillary action. As used in this bulletin it may be defined as the work performed by the capillary force in moving a unit mass of water from a free water surface to the point in question. Since no values are given it is not necessary to fix the units or determine whether the potential is positive or negative. The capillary-potential gradient is the rate of change from point to point of the capillary potential.

The capillary conductivity of the soil is a measure of its ability to transmit water when in an unsaturated condition. The capillary-

conductivity factor as used in this bulletin may be defined as the ratio of the rate of flow of moisture in an unsaturated soil to the capillary-potential gradient. Here again no values are given and the units need not be specified.

Certain theoretical studies of the ability of soil to transmit moisture in capillary form have been made and a few values for the conductivity factor have been secured.

Heretofore, most studies of capillary movement have been based on the movement of moisture from a free water supply or a moist soil into air-dry soil. Obviously plants do not grow in air-dry soil, and the movement of moisture into such soil is of comparatively little importance in actual farm operations. A smaller number of studies have been made of the movement into soil containing some moisture, but seldom have soils moist enough to support rapidly growing crops been used. Moreover, most of the experiments concerned the maximum distance through which moisture would advance into the dry soil and the rate at which that advance would take place. In most instances no attempt has been made to evaluate the actual quantity of water flowing through soil of any particular moisture content.

The ability of a soil to transmit water to the absorbing roots may be compared to the ability of an aquifer to yield water to a well. In either case the total quantity of water held may be very great, as may be also the available capacity in the one case and the specific yield in the other, but unless the ability of the soil or the aquifer to transmit water to the point of use is reasonably high, neither the plant roots nor the well will be satisfactorily supplied.

In this investigation, the actual rate of flow of moisture, under the influence of capillary forces acting in soil columns of different and varying moisture contents (chiefly between the wilting point and the field capacity), has been measured. This range is obviously of paramount importance in agriculture but has been generally neglected in other studies. Measurements have been made on several soil types and on soils taken from different depths. The effect of gravitation on capillary flow has been measured and will be used in determining the capillary potential and transmission factor.

## OTHER STUDIES

The importance of a knowledge of the rate of the capillary flow was recognized early in the modern period of soil research in the United States. Briggs and Lapham (9)[3] say:

Further, in order to distinguish in the field between the effect of extensive root systems and capillary action, it is necessary to know the maximum limit of capillary action in a given moist soil together with the rate at which water can be supplied under given conditions.

They carried on some experiments with a fine sand in which 1.09 cc of water per square centimeter per day was lifted 85 cm from a free water surface and evaporated at the surface. The sand transmitted 0.15 cc per square centimeter per day through a column 165 cm high, but did not move any water through a height of 180 cm.

Livingston and Koketsu (32) were also impressed with the importance of the water-supplying power of the soil. They devised the soil-point method of measuring this value. The fact that they defined the length of time during which the soil point should be kept in contact

with the moist soil indicates that they recognized the dynamic character of the problem.

Recently, Magness (*37*) has reiterated the importance of this problem. He says:

We need much more evidence on the rate of capillary movement of moisture in soils of different textures. It seems probable that the rate at which water is supplied to roots by the soil depends in considerable part upon the rate of this capillary movement. Thus, a heavy soil will apparently supply water more slowly but for a longer period, while a light soil may supply water much more rapidly with the available supply being rather quickly used up by the trees.

The distance through which water may be expected to move by capillary action has been the subject of study by many investigators. King (*29, 30*) devoted several pages to the subject (*30*). He reported an extreme case where quartz sand raised 44.09 surface inches of water through a distance of 6.75 inches in 24 hours. There was some loss from a depth of 10 feet, and rates of rise from free water of 1 or 2 pounds of water per square foot per day through 1 to 4 feet of a fine sand and a clay loam. From shallow depths the rise was at a greater rate through the sand but almost the same through both soils from a depth of 4 feet. No data were reported as to the moisture content of the soil. King concluded that capillary rise through a few feet is of importance but not sufficient to meet the needs of crops.

McGee (*34*) concluded that the ground water at an average depth of about 30 feet in the plains section of Kansas supplies 5 to 10 inches annually of water to crops. He believed that this water rises to the root zone by capillary action. In another publication (*33*) he concluded that " * * * moisture will move under capillarity with sufficient freedom to affect the growth of crops from a depth of 3 to 4 feet."

More recently, thought along this line has gone to the other extreme and many investigators have concluded that capillary movement is of little importance in crop growth. Shull (*45, 46*) holds the view that wilting of plants at a rather definite moisture content was due to the slowness of movement of moisture from soil particle to soil particle and again (*46*) points out that "the whole relation of the root and soil to the soil water is a dynamic one." On the other hand, he describes a case where a buckwheat root had grown through the soil and had apparently removed all the available moisture from a cylinder of the same diameter as the root with its root hairs, the inference being that the root moved to the moisture rather than the moisture to the root.

McLaughlin (*35*), Shaw (*43*), and Conrad and Veihmeyer (*11*) all conclude that the movement of moisture by capillarity is of little if any importance in supplying plant roots. The last say: "It appears very probable that capillarity cannot be counted on to move moisture appreciable distances from moist soil into soil that has been dried by root extraction."

The importance of the movement of capillary moisture through short distances within the root zone is not definitely established. Some investigators believe that the rate of movement is so small as to be of no practical importance, while others hold that observed plant responses to differences in soil moisture may be explained only on the ground of capillary movement of soil moisture.

Veihmeyer (*52, 53*), Hendrickson and Veihmeyer (*24, 25*), Veihmeyer and Hendrickson (*54, 55, 56*), Beckett, Blaney, and Taylor (*6*), and Taylor, Blaney, and McLaughlin (*47*) are of the opinion that

plants do not suffer for moisture until the soil in some portion of the root zone is reduced to about the wilting point. They believe that when the moisture content in the soil adjoining the roots is reduced to the permanent wilting percentage and soil with a higher moisture content is available, the roots will grow into the moister soil.

On the other hand, Aldrich and Work (1, 2), Aldrich, Work, and Lewis (3), Lewis, Work, and Aldrich (31), and Work and Lewis (57) are of the opinion that the moisture must move through the soil to the roots and that it is this condition which causes plants to slow up in their growth when the average moisture content in all parts of the root zone is well above the wilting point. This condition has been noted by Furr and Degman (14), Furr and Magness (15), and Bartholomew (5). Shantz (42, p. 711) says: "Plants, as a rule, require more water during drought periods than during periods of abundant supply, and may be greatly damaged by extreme conditions even if the soil is still well supplied with water."

As pointed out by Vasquez (51), Magness (37), Aldrich and Work (1), and Work and Lewis (57), the explanation of the suffering of plants often noticed when available moisture is still shown by ordinary soil sampling lies in the slow movement of capillary water through the soil.

Shantz (42) pointed out the fact that there is little definite information as to the movement of soil moisture in the field under conditions where the subsoil is permanently moist. This is an important observation and may serve to point the way to a reconciliation of some of the contradictory opinions on the importance of capillary movement of water.

Harris and Turpin (23) carried on many experiments showing the extent of movement of moisture from a moist soil into a dry soil. Many others have carried on experiments with the rate and extent of movement of moisture from free water into a dry soil.

Alway and McDole (4) and Karraker (28) studied the flow of moisture from a moist soil into drier soils of different moisture contents. The former used soils with moisture contents between 0.5 and 1.5 times the hygroscopic coefficient. The moister soils were thus approximately at the wilting point. The latter used soils slightly more moist but little, if any, above the wilting point. Except under rather extreme conditions such as occur in dry farming, irrigation with very limited water supplies, or during serious droughts, field soils below the surface few inches are seldom dried to the wilting point and almost never below that point. These experiments do not cover the zone of moisture contents which is most usually met with in the field and which is of most importance.

Shaw and Smith (44) carried on an experiment with soils which had been saturated and allowed to drain. Tubes 4, 6, 8, and 10 feet long were used and moisture was allowed to rise from a free water surface and to evaporate at the top of the tubes. With Yolo loam, evaporation was 3.60, 1.92, 1.00, and 0.16 surface inches monthly from 4-, 6-, 8-, and 10-foot tubes respectively in 321 to 324 days. From Yolo sandy loam 1.84, 0.62, −1.3 and −0.8 surface inches respectively were lost monthly in 87 to 96 days from tubes of the lengths mentioned. The minus values are due to the fact that the experiment was started before all of the excess water had drained out of the tubes. At the end of the experiment the moisture content of the soil at different

distances from the ends was determined. The resulting curves are not dissimilar to those secured in the experiments reported herein. These results and those which Briggs and Lapham (9) and King (29, 30) quoted are in accord with field experience and numerous experiments in showing that considerable quantities of water may be raised by capillarity through moist soils from a free water surface.

The question of the quantity of water that moves through the soil in the vapor phase is also raised by some investigators. Scofield and Wright (41) in reporting field studies of moisture conditions draw the conclusion that moisture was lost from certain of their field plots by evaporation well down in the soil and diffusion of the vapor through the soil and into the atmosphere at the surface. They go on to say that evidence, both in the field and in the laboratory, indicates that movement "takes place quite as much by alternate vaporization and condensation as by the capillary movement of liquid water." Other workers had been led to the conclusion that movement of water in vapor form is of considerable importance.

Buckingham (10) studied this question and came to the conclusion that loss of moisture by vaporization below the surface and diffusion through moist soil is very small. He found rates of loss of 1.4 surface inches per year into still air and 4.3 surface inches per year into a 3-mile-per-hour breeze through 2 inches of coarse dry sand. Through 1 inch of loam he found a loss of 2.71 surface inches per year and through fine sandy loam 2.52 inches per year. Through 12 inches of sandy loam the loss was less than 0.2 surface inch per year. All of these tests were from a saturated atmosphere below the column of soil and into a current of air from a fan. The soils all appear to have held less moisture than the wilting point at the time these rates were determined.

Bouyoucos (8) gives data showing that the movement of water vapor from a warm moist soil into a cold dry soil is very small even with temperature differences of 20° and 40° C.

A number of investigators have applied the general laws of hydrodynamics to the soil-moisture problem. Buckingham (10) defined the capillary potential and carried on experiments to determine the relation between the capillary potential and the moisture content of the soil. He set up tubes filled with different soils which he allowed to stand for periods ranging from 2 to 10½ months with the tops protected from evaporation and the bottoms in free water. On the assumption that static equilibrium had been reached, he then determined the moisture content at different heights above the water table, and thus arrived at the relation between the two quantities. His experimental data indicated a wide variation in different soils.

Gardner and others of the Utah Agricultural Experiment Station also have studied this problem from the point of view of the physicist. In this work they have (16, 17, 18, 19, 20, 21, 26, 38, 48, 49, 50) always stressed the dynamic nature of the problem. In the early work Gardner (18) defined a transmission constant as a single-valued function for each soil. This transmission constant has the physical dimensions of $\frac{M^{\frac{1}{2}}L}{T}$. Later Gardner (19), Gardner and Widtsoe (21), Gardner, Israelsen, Edlefsen, and Clyde (20), Israelsen (26, 27), and Richards (38) have stressed the use of the capillary potential in problems of capillary movement. A great deal of study has been given to

the relation between the moisture content of the soil and the capillary potential.

E. A. Fisher (12) R. A. Fisher (13) and Haines (22) have made applications of mathematical and physical methods to capillary flow problems.

Thomas (48, 49) found that the vapor pressure lowering at the wilting point with three different soils ranged from 0.2 to 0.46 mm of mercury. He found that the vapor pressure was approximately proportional to the reciprocal of the moisture content and states that the vapor pressure lowering was about 0.02 mm at the moisture equivalent, but that it cannot be accurately determined.

Israelsen (26) concluded from a theoretical study that the moisture content in a deep uniform soil at equilibrium between capillarity and gravity would decrease from the water table upward. He gave the following equation for the relation between the moisture content and capillary potential:

$$(\rho' - a) \ (\psi + b) = C$$

where $\rho'$ equals the moisture content, $\psi$ equals the capillary potential, and $a$, $b$, and $C$ are constants.

Richards (38) described the porous-plate method of measuring the capillary potential and gave curves showing the relation between the moisture content and the capillary potential. He pointed out that this method cannot be used for capillary potentials in excess of about one atmosphere. He (39, 40) carried the work further and determined the relation of both the capillary potential and the capillary conductivity to the moisture content. He also developed formulas for the application of these factors to specific problems of capillary flow. His measurements of the capillary potential were made by the porous-plate method and, therefore, are limited to values of less than one atmosphere.

Bodman and Edlefsen (7) discussed the soil-moisture system and pointed out that measurements of the capillary potential above the wilting point and below about the field capacity have not been very successful.

Harris and Turpin (23) and McLaughlin (35, 36) found that water moved downward from a moist soil into a dry soil, and from a supply of free water into a dry soil, more rapidly than it moved upward under the same conditions, but did not attempt to interpret their data in terms of the gravitational potential.

The studies heretofore made of capillary movement of soil moisture may be somewhat arbitrarily divided into two groups. In the first group the approach has been through laboratory and field studies of soil-moisture movement, with the principal emphasis on the physical results obtained. These results have been used to explain other field observations. In the second group the experiments have aimed to apply the fundamental laws of physics to soil-moisture movement. The studies reviewed have not furnished satisfactory data on the movement of soil moisture in the range between the wilting point and the field capacity. They have, however, shown the need for such data and an evolution of ideas leading toward a clearer conception of the relations between soil and water. The experiments herein described were undertaken for the purpose of adding to the accumulation of data obtained by other investigators.

## EXPERIMENTAL PROCEDURE

In the main the attempt has been to use soils with their natural field structure. In a few instances soils have been used that have been broken up, sifted, and mixed in the laboratory. It is hoped that a conductivity factor and the relation between the moisture content and the capillary potential may be found for different soils. For the second part of the study different rates of flow vertically, both up and down, and different lengths of soil columns have been used with samples of a single soil type taken at the same depth and as near together as possible in the field, or samples uniformly prepared in the laboratory.

For the first objective a few replications only were used, often with only one rate of flow and in one direction only. The number of replications used in the second type of study ranged from 5 to 20. In most instances it was found that four or five replications gave reasonably consistent results.

This bulletin presents the data obtained up to the present on the first phase of the problem. Much of the data herein reported will be analyzed in a study of the more fundamental aspects of the problem.

The experience of other investigators has shown that long periods of time are necessary if approximately static equilibrium is to be secured with long soil columns. For this reason short columns 2, 4, and 6 inches in length were used. The differences in field soil make it necessary to replicate the tests, and it was desired to make tests on a large number of soil types. Moreover, part of the incentive for undertaking this experiment was the peculiar fluctuations in soil moisture found in the soil at depths of several feet in certain orchards in western Oregon. The cost of securing large numbers of undisturbed field samples of large diameter at depths of several feet was prohibitive. Moreover, the equipment available precluded the possibility of using much space for samples. For these reasons soil columns of small diameter were used.

It appears possible to secure a state of steady flow much more quickly than to secure static equilibrium in soil columns of moderate length and moisture content. These experiments were conducted on the basis of steady rates of flow.

By working with different rates of flow both upward and downward the gravitational potential can be used to evaluate the capillary potential. Where flow takes place in an upward direction the two potential gradients are in opposition, whereas with downward flow they work together. This fact gives a basis for using the known gravitational potential in determining the value of the unknown capillary potential.

From the data it is possible to plot curves between the rate of flow of moisture and the moisture-content gradient (i. e., the rate of change with distance of the moisture content) at different moisture contents. By extrapolating these curves to zero flow, conditions at static equilibrium can be estimated. Theoretically the curves for upward flow and for downward flow should coincide at zero flow.

The experiment consisted essentially in setting up a series of soil columns exposed at one end to a current of air at constant temperature and humidity and adding water at different predetermined rates at the other end of the columns. In the earliest trial it was felt necessary to add the water in small quantities at very short intervals. It was

soon discovered, however, that water could be added at intervals of 12 hours without creating too great irregularity in the results. The columns were left in the evaporation chamber until the rate of loss by evaporation from the exposed ends became approximately constant and equal to the rate of addition. This rate of loss, ordinarily averaged over the final 24-hour period, has been used as representing the rate of flow through the tubes.

In the earlier trials water was added from the burette directly on the surface of the soil at the closed end of the soil column. It was found however, that this tended to puddle the soil, and thereafter small pieces of cotton felt were placed between the soil and the stopper. These served to hold the moisture in contact with the soil column and also to protect the soil from the puddling action of the dropping water. In the early trials, as noted above, 2-, 4-, and 6-inch soil columns were used. However, even with the heavier soils, the 2-inch columns were of little use, and the later trials were made with 4-, and 6-inch samples only.

In certain cases where the rate of addition of water was great enough to cause a portion of the soil in the tubes to become saturated, the replacement of the rubber stoppers after adding water developed pressure in the tubes. This pressure forced water through the soil column in some instances. During the latter part of the experiment small holes were bored in the side of the tube opposite the felt pads and closed by rubber bands so arranged as to prevent the building up of pressure in the tubes.

After approximate dynamic equilibrium had been attained, the soil was removed from the tubes in small transverse sections and the moisture content determined. Approximately half of the tubes were placed so that the movement of moisture was vertically upward and in the remainder downward. In most instances duplicate sets were used for upward and downward flow. In some cases where data were required for some particular soil depth or soil type a single set of tubes with flow either upward or downward was used.

### SAMPLING APPARATUS

The use of the King soil tube is practically standard in soil-moisture work by the Division of Irrigation, and this method of sampling has been used in the present experiment. A special point for the King tube was prepared by adding stellite to the cutting edge of a standard point and grinding out as shown in figure 1. Samples of transparent tubes made of a transparent plastic with an inside diameter of 0.840 inch were obtained, and in the figure are shown the washer and rivet through the body of the steel tube for holding the small sample tubes in the King tube. Unfortunately when it came time to order a supply of the tubes the manufacturers were out of the size required, and white celluloid tubing was substituted. It is believed that transparent tubing would have made it possible to detect breaks in the soil columns and might have permitted the sorting out of samples which gave erratic results.

Considerable difficulty was encountered in securing samples in the field, when the soil was very wet. This was particularly true with the Medford clay adobe and the Willamette silt loam. When the moisture content was slightly below the field capacity no difficulty was encountered. The small difference in inside diameter between the

point and the celluloid tube is necessary in order that the sample may slip inside the tube without too much compacting.  With wet and sticky soils it was found helpful to thoroughly wet the inside of the tubes just before taking a sample.  Even when this was done it was sometimes necessary to make several attempts before the sample in
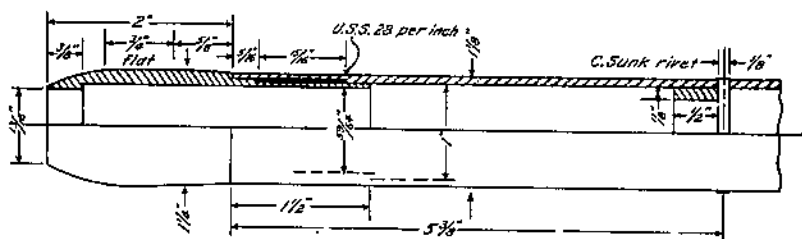


FIGURE 1.—Modified soil-tube point.

the tube proved to be approximately as long as the distance the tube had been driven.  After the samples were secured one end of the tube was covered with a piece of cheesecloth and the other end closed with a rubber stopper.

### EVAPORATION CHAMBER

Figure 2 shows the evaporation chamber used in the experiment. A plywood box 16 by 20 by 39 inches was fitted with galvanized-iron transitions on both ends.  At one end the box was connected to
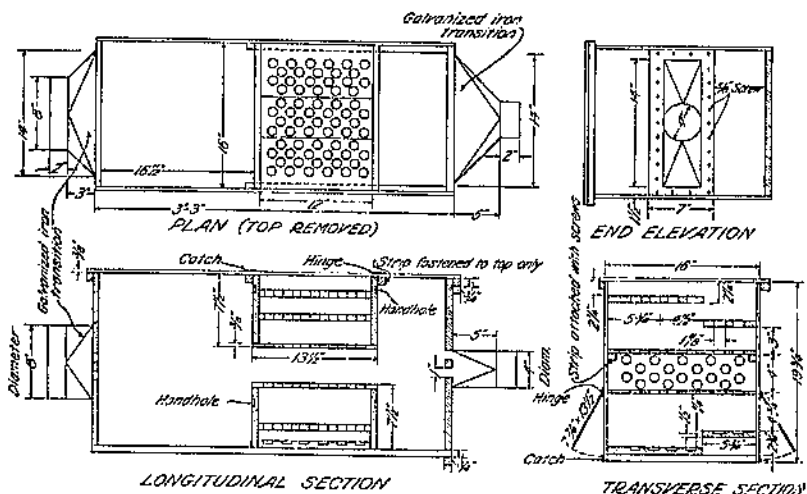


FIGURE 2.—Evaporation chamber in which tubes were exposed to secure steady flow.

another galvanized-iron box used as an air-conditioning chamber, while at the other end a fan was installed in the opening to draw air through the chamber.  Inside the main box were racks arranged to hold the sample tubes in a vertical position.  The racks, which were 13 inches long were supported by means of solid boards at each end. These boards forced the air to pass through a 4-inch space between the two racks.  The upward-flow tubes were held in the lower of the

two boxlike racks with their cloth-covered ends flush with the top of the rack.   Similarly the cloth-covered ends of the downward-flow tubes were flush with the bottom of the upper racks.   Thus all the tubes were exposed to the current of air in the 4-inch restricted space. Air entered and left the box through a series of holes at each end.   It was expected that the air currents would thus be made uniform. Extra space in the chamber was utilized for a thermohygrograph and thermostat.

The current of air drawn through the chamber was heated in a second box by lamp banks or Nichrome resistance wire.   The apparatus was set up in the basement where the fluctuations in temperature ordinarily were not very great. There were, however, steam pipes in the room, and the steam in these pipes was cut off over the week ends.   Occasionally the resulting drop in temperature was greater than the heating elements in use at the time could overcome. In a few instances, also, the contact on the thermostat stuck, and the temperature in the evaporation chamber ran high.   Some cases were noticed when the rate of loss from all tubes would be somewhat low or high depending on whether the temperature was below or above the normal.   In the main, however, it was impossible to detect any correlation between these accidental variations in temperature and the rates of loss.   In fact, it was not unusual for part of the tubes to show marked increases in rates of loss at the same time others showed a constant or even lower rate.

### STEADY FLOW

In order to determine when the flow had reached an approximately steady state, the tubes were weighed before and after each addition of water.   In some cases



FIGURE 3.—Rate of loss of water from 6-inch cores of beach sand to which water was added at different rates.

all the tubes of a group were weighed, while in other cases only one or two of a group were weighed as indices of the rate of loss.   After the index tubes had reached an approximately
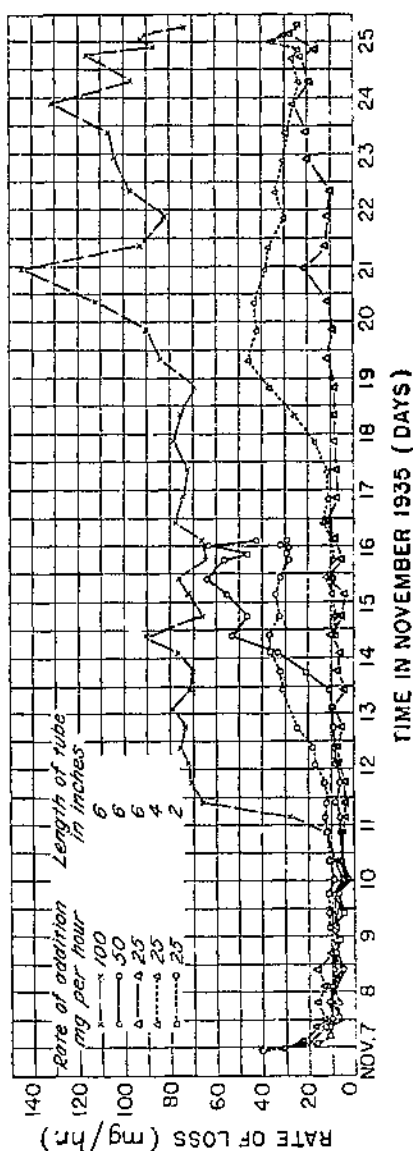
steady state of flow, all of the tubes of the group were weighed before and after adding water at intervals during the last 24 hours before 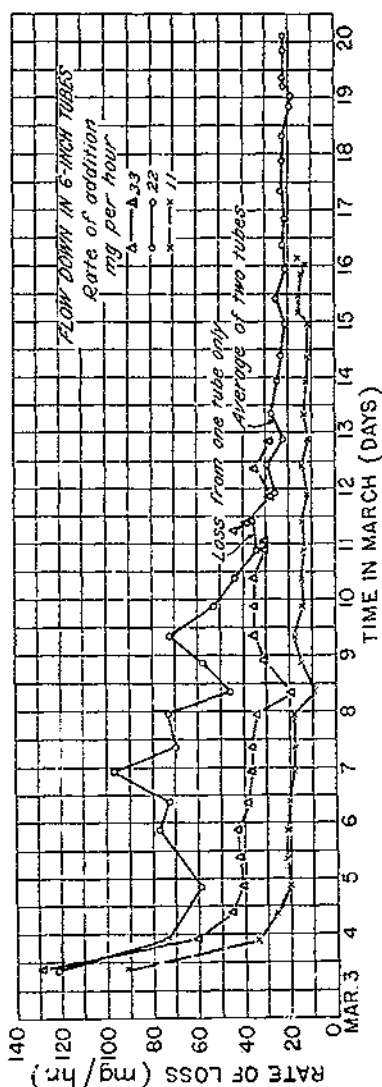breaking down the soil columns. As was to be expected, moist soil samples lost water rapidly at first. The rate of loss dropped off rapidly as the portion of the soil column near the open end dried out. Thereafter, if the rate at which water was added was high the rate of loss increased, sometimes temporarily becoming considerably higher than the rate of addition. In planning the experiment, it was feared that wave motion might be set up in the water flowing through the tubes. It was thought that the soil at the open end of the tubes might dry out more rapidly than the moisture could move up, and that as a result the dry zone would gradually extend back toward the closed end of the tube until soil, moist to the field capacity or above, was encountered. Then the moisture might move forward into the dry soil until the open end was reached, and the drying-out process would then start over again.

Careful consideration led to the conclusion, however, that a condition of dynamic equilibrium would be reached, with the soil at the open end of the tubes just moist enough to cause evaporation to take place as rapidly as moisture was supplied. The moisture-content gradient back of the open end would then be sufficient to move the moisture at the rate of supply, and the moisture content at the closed end would depend on the rate of supply and the length of the tube. This conclusion has been confirmed by the experimental work. Figure 3 shows the rate of loss of water from several tubes filled with a rather coarse beach sand. Each curve shows the average of four tubes. The curve for the 6-inch tubes with the highest rate of flow seems to indicate a tendency toward the wave motion which was feared. In some other cases with the beach sand a similar tendency was observed. However, in most cases with the sand, and in practically every case with undisturbed soils, the conditions illustrated by figure 4 were found.

The data for groups of tubes filled with Willamette silt loam are shown in figure 4. The portion of each curve for the last few hours,



FIGURE 4.—Rate of loss of water from 6-inch cores of Willamette silt loam to which water was added at three different rates.

which is separated from the rest of the curve, represents average values for all five tubes in each group instead of the values for the index tubes alone. It will be noted that in each instance the rate of loss approached the rate of addition and became nearly constant at a value close to that at which water was added. This indicates that the rate of flow had become approximately steady before the tubes were broken down. The curves of figure 4 are typical of the curves obtained in these experiments.

## SUPPLEMENTARY EXPERIMENTS

### MOVEMENT AS VAPOR

In order to determine whether an important part of the movement through the tubes was in the vapor phase, a special group of tubes was set up. In these tubes a break in the soil column was provided by placing two pieces of 30-mesh screen about 1 mm apart at a predetermined point in the column. Breaks were placed at 1 cm from the open end in one group of eight tubes, at 2 cm in a second group, at 4 cm in a third, at 7 cm in a fourth, and a control group was provided without any break. Each group of eight was divided into two subgroups of four. One set of subgroups was supplied with water at the rate of 11 mg per hour and the other set at the rate of 44 mg per hour. All were set with the flow upward because it was feared that the soil on the wet side of the break might become saturated and allow free water to drip across.

The rates of loss from the set receiving 11 mg per hour are shown in figure 5. The data as shown are the averages for the four tubes of each subgroup. The first weighing was made about 12 hours after the tubes were set up and the effect of the breaks was already apparent.



FIGURE 5.—Rate of loss of water from 6-inch cores of Willamette silt loam having breaks at different distances from the end when water was added at the rate of 11 mg per hour.

The tubes without a break showed the greatest rate of loss, the tube with 7 cm of soil between the break and the open end lost the second

highest rate, and so on in regular order.    The difference between the groups having breaks 1 and 2 cm from the open end is very small.

As the experiment progressed the curves representing the rate of loss from the broken soil columns crossed each other in regular sequence.    Before the second weighing the rate of loss from the tubes with the break 2 cm from the open end became less than that from the tubes with the break 1 cm from the end.    By the end of the third day the curve of the 4-cm tube had crossed both the 2-cm and the 1-cm curves.    These curves indicate that a rather definite quantity, approximately 16 mg per hour, of moisture diffused across the break and through 1 cm of soil.    Smaller quantities were able to pass through the longer soil columns.    An explanation of the fact that the movement of moisture through 7 cm of soil appeared to be almost as rapid as through 4 cm appeared when the columns were broken down, as will be shown later.

During the first 145 hours the different groups in the set receiving 44 mg per hour acted exactly as did those receiving 11 mg per hour, as may be seen in figure 6.    However, at the end of that time (Apr.1) the subgroup broken at 7 cm, followed a day or so later, by the 4-cm group, suddenly began to lose water at an increasing rate.    The explanation appeared to be that water or moist soil was being forced through the screens by the pressure set up when the rubber stoppers were seated in the tubes.    Upon breaking down the tubes this explanation was found to be correct.

The average moisture contents of the soil at different distances from the open end for each subgroup of the 11-mg set are shown in figure 7.    The sharp changes in moisture content at the breaks in the soil columns are obvious.    If the moisture were moving through the soil in the vapor phase there should be no breaks in the curves, since the movement of vapor through the open space between the screens would be fully as rapid and should be more rapid than through the soil.    The moisture content just below the screens in every instance was well above the field capacity, while just above the screen it was much lower in every case.    In the columns broken at 1 and 2 cm the moisture content just above the screens was well below the wilting point.
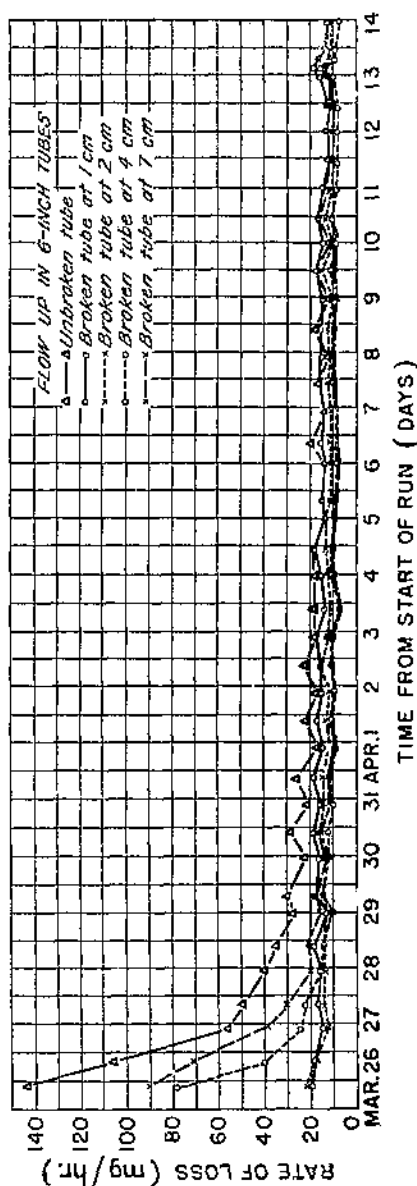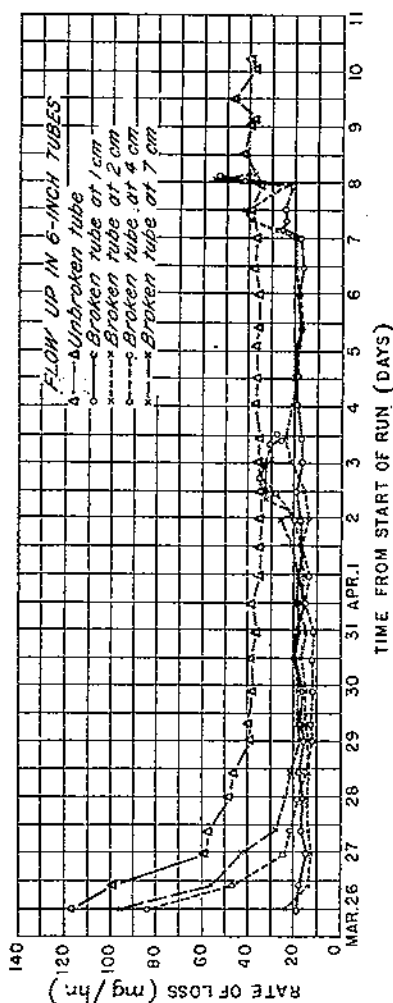


FIGURE 6.—Rate of loss of water from 6-inch cores of Willamette silt loam having breaks at different distances from the end when water was added at the rate of 44 mg per hour.

It is interesting to note that the portions of all of the curves either to the left or to the right of the break are approximately parallel to each other and to the lower and upper portions respectively of the curve for the unbroken column. These data seem to indicate that moisture distilled across the break in the column and built up a moisture content, or capillary, gradient above that point. It appears to have required a difference of moisture content of 12 to 17 percent to force 8.5 to 12 mg per hour of water in the vapor phase across an open space of about 1 mm. These rates are equivalent to 2.4 and 3.4 mg per square centimeter per hour or 0.69 and 0.97 inch in depth (surface inches) per month. If this is true the movement through the soil pores must be negligible and the conclusion seems justified that the movement of moisture observed in these experiments was predominately, if not exclusively, in liquid form.

The observations on the soil columns receiving water at the rate of 44 mg per hour were not satisfactory because of the forcing of wet soil through the screens. The subgroup broken at 1 cm did not show any of this effect, and its moisture-content-v.-
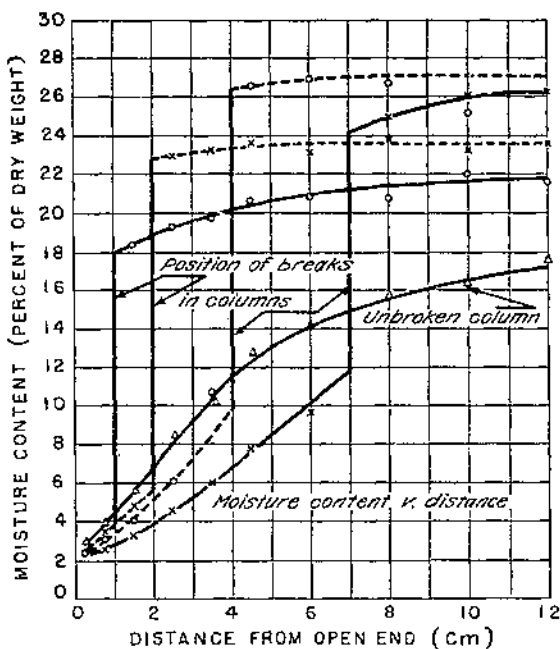


FIGURE 7.—Average moisture content throughout length of five groups of four 6-inch cores of Willamette silt loam having 1-mm breaks at different distances from the open end. Water was added to all tubes at a rate of approximately 11 mg per hour. It was lost from the unbroken cores at an average rate of 10.3 mg per hour and at rates of 12.0, 10.2, 8.5, and 9.0 mg per hour from cores having breaks 1, 2, 4, and 7 cm, respectively, from the open ends.

distance curve is very similar to the corresponding curve on figure 7. However, the data of figure 6 indicate that so long as water was compelled to cross the breaks in the vapor phase, the movement corresponded closely with that shown by the set of tubes receiving 11 mg per hour.

### EFFECT OF INTERMITTENT ADDITION

The method adopted in this experiment required that water be added in batches rather than continuously. At first it was thought that satisfactory results could be secured only if the additions were small and made at very frequent intervals. Since this procedure added greatly to the difficulty of carrying on the work, a special test was made to determine the effect of adding a comparatively large volume of water at one time. A set of 20 tubes containing Newberg clay loam was used. All these samples were taken within a few feet of the same point and at the same depth. Water was added at 12-hour intervals until the rate of loss as indicated by two index tubes became steady and approximately equal to the rate of addition. At

the beginning and end of the last 12-hour period all tubes were weighed and the rate of loss was found to be about equal to the rate of addition.

When the tubes were ready 12 drops, approximately 400 mg, of water was added to every tube at as nearly the same time as possible. The first tube was broken down immediately; the next three at 5-minute intervals; the next three at 10-minute intervals; and the others at increasing time intervals, the last tube being broken down 8 hours and 45 minutes after the water was added. It was expected that the added water could be traced through the series of tubes as a sort of wave. However, analysis of the data, both by individual tubes and by groups of four, failed to show any regular progression of a wave of high moisture content through the tubes. In fact, it was impossible, even in the tubes broken down almost immediately after adding the water, to detect the position of the slug of water. In breaking down the tubes the section of soil next the open end was removed first and that at the end where water was added last. It took about 10 minutes to complete one tube, so even in the first tube broken down the water had several minutes to distribute itself through a portion of the soil.

These results together with the fact that the rate of loss appears to be only slightly affected by differences of several hours in the length of time between additions of water appear to indicate that adding the water in batches at intervals of 12 hours or less gives practically the same result as would be secured by continuous addition. This is a point that needs more study, however.

## RESULTS

### RATE OF WATER MOVEMENT

The primary purpose of the experiment was to determine the distance through which water in appreciable quantities can be moved by capillary forces in the range of moisture content between the field capacity and the permanent wilting percentage. It appears possible that eventually a single-valued conductivity factor may be determined for any given soil that can be used to determine the rate of movement for any given set of conditions of temperature, moisture content, direction of flow, etc. Until such a factor and its relation to other conditions has been found we must be content with experimental determinations of the rate of movement under a variety of conditions. The results are shown in table 1. The distance given in column 9 is the distance through which the moisture content fell from the upper to the lower limits shown in columns 6 and 7 while steady capillary flow was taking place at the rate shown in column 8. For example the data of no. 7–a are from the experiment shown in the curve for the unbroken column in figure 7. The moisture content at a point 11.2 cm from the open end after a state of steady flow had become established was 17 percent of the dry weight, while at a point 2.9 cm from the open end the moisture content was 9 percent, the permanent wilting percentage for this soil. The rate of flow was 2.9 mg per square centimeter per hour. This rate of flow, therefore, took place through a distance of 8.3 cm upward under the influence of a drop in moisture content from 17 percent to 9 percent.

TABLE 1.—*Distance through which different quantities of water moved in various soil types under the influence of moisture-content differences approximately between the wilting point and the field capacity*

| No. | Soil type | Depth of sample | Moisture content — Wilting point | Moisture content — Field capacity | Limits of experiments — Lower | Limits of experiments — Upper | Rate of flow | Distance between moisture-content limits | Direction of flow | Tubes | Average temperature | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *Inches* | *Percent* | *Percent* | *Percent* | *Percent* | *mg/cm²/hr.* | *Cm* | | *Number* | *° F.* | |
| 1-a | Dune sand | ...... | ¹3 | ¹10 | 14 | 22 | 28.4 | 10.2 | Up | 4 | 90.5 | 6-inch tubes only; all of moisture-content curves above field capacity. |
| 1-b | | | | | 3 | 10 | 15.6 | 8.3 | ...do..... | 12 | 82.4 | |
| 1-c | | | | | 3 | 10 | 7.4 | 8.6 | ...do..... | 12 | 88.2 | |
| 2-a | Chehalis loam | 6–12 | ²10.6 | ²27 | 10.6 | 25 | 6.1 | 9.3 | ...do..... | 12 | 81.0 | 2-inch and 4-inch samples from 6–10 inch depth. 6-inch samples from 6–12 inch depth. Large portion of moisture-content curve above field capacity. |
| 2-b | | 6–12 | | | 10.6 | 27 | 13.1 | 2.9 | ...do..... | 12 | 81.0 | |
| 2-c | | 6–12 | | | 10.6 | 24 | 6.5 | 9.5 | Down | 11 | 81.0 | |
| 2-d | | 6–12 | | | 10.6 | 27 | 13.4 | 6.4 | ...do..... | 10 | 81.0 | |
| 2-e | | 24–28 | ²10.6 | ²27 | 10.6 | 27 | 7.4 | 4.2 | Up | 6 | 83.8 | |
| 2-f | | | | | 12.0 | 27 | 15.1 | 1.6 | ...do..... | 7 | 83.8 | |
| 2-g | | | | | 10.6 | 27 | 7.3 | 4.8 | Down | 6 | 83.8 | |
| 2-h | | | | | 10.6 | 27 | 14.9 | 5.3 | ...do..... | 5 | 83.8 | |
| 3-a | Newberg clay loam | 12–14 | ²14.8 | ²34 | 14.8 | 32 | 7.8 | 2.7 | Up | 15 | 82.4 | Large numbers of tubes used in an attempt to smooth out curves and secure data on effect of gravity. |
| 3-b | | | | | 14.8 | 32 | 9.5 | 2.5 | Down | 15 | 82.4 | |
| 3-c | | 14–18 | | | 14.8 | 34 | 9.3 | 4.2 | Up | 15 | 83.5 | |
| 3-d | | | | | 14.8 | 31 | 8.6 | 5.4 | Down | 14 | 83.5 | |
| 3-e | | 18–24 | | | 14.8 | 33 | 8.6 | 7.5 | ...do..... | 19 | 82.1 | |
| 4-a | Meyer clay adobe | 16–22 | 18.8 | 33.7 | 18.8 | 32 | 3.5 | 6.8 | Up | 12 | 81.7 | Each group included four 2-inch, four 4-inch and eight 6-inch samples. 2-inch and 4-inch samples only. |
| 4-b | | | | | 18.8 | 30 | 3.6 | 6.4 | Down | 12 | 81.7 | |
| 4-c | | | | | 18.8 | 33.7 | 5.8 | 7.0 | Up | 16 | 79.7 | |
| 4-d | | | | | 18.8 | 33.7 | 6.3 | 4.8 | Down | 16 | 79.7 | |
| 4-e | | 12–14 | | | 18.8 | 29 | 6.5 | 1.6 | Up | 8 | ...... | |
| 4-f | | 28–30 | | | 18.8 | 27 | 5.6 | 1.2 | Down | 4 | ...... | |
| 4-g | | 34–36 | | | 18.8 | 28 | 5.0 | 1.4 | ...do..... | 4 | ...... | |
| 4-h | | 14–18 | | | 18.8 | 33.7 | 5.9 | 4.5 | Up | 1 | 80.0 | |
| 4-i | | 24–28 | | | 18.8 | 33.7 | 5.6 | 4.4 | Down | 4 | 80.0 | |
| 4-j | | 32–36 | | | 18.8 | 32.0 | 5.0 | 5.3 | ...do..... | 4 | 80.0 | |
| 4-k | | 18–24 | 18.8 | 33.7 | 18.8 | 33.7 | 5.2 | 4.0 | ...do..... | 3 | 79.3 | |
| 4-l | | 30–36 | 18.8 | 33.7 | 18.8 | 27.0 | 5.9 | 5.3 | Up | 4 | 80.8 | |
| 5-a | Loamy sand (Hermiston) | ...... | 4.0 | 14.0 | 6.0 | 14.0 | 15.4 | 11.4 | Down | 7 | 77.6 | All 6-inch samples mixed in laboratory. Much of moisture-content curves above field capacity. |
| 5-b | | | | | 4.0 | 14.0 | 9.6 | 11.5 | ...do..... | 7 | 78.7 | |
| 5-c | | | | | 4.0 | 11.0 | 4.5 | 10.0 | ...do..... | 7 | 77.8 | |
| 5-d | | | | | 6.0 | 14.0 | 14.4 | 1.1 | Up | 7 | 77.8 | |
| 5-e | | | | | 4.0 | 14.0 | 7.5 | 3.0 | ...do..... | 7 | 77.4 | |
| 5-f | | | | | 4.0 | 14.0 | 5.5 | 6.0 | ...do..... | 7 | 75.9 | |

¹ These values are only approximate.
² These values were determined by C. S. Schuster on soil samples taken at points very close to the places where the samples used in these experiments were taken.

TABLE 1.—*Distance through which different quantities of water moved in various soil types under the influence of moisture-content differences approximately between the wilting point and the field capacity*—Continued

| No. | Soil type | Depth of sample | Moisture content | | | | Rate of flow | Distance between moisture-content limits | Direction of flow | Tubes | Average temperature | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Wilting point [2] | Field capacity [2] | Limits of experiments | | | | | | | |
| | | | | | Lower | Upper | | | | | | |
| | | Inches | Percent | Percent | Percent | Percent | mg/cm²/hr. | Cm | | Number | °F. | |
| 6-a | | 24-28 | 9.0 | 24.0 | 9.0 | 19.0 | 5.6 | 5.3 | ...do | 5 | 78.6 | |
| 6-b | | 24-28 | | | 9.0 | 17.0 | 6.3 | 4.5 | Down | 5 | 78.6 | |
| 6-c | | 36-40 | | | 9.0 | 24.0 | 6.3 | 4.2 | Up | 5 | 75.8 | |
| 6-d | | 36-40 | | | 9.0 | 24.0 | 6.8 | 4.2 | Down | 5 | 78.2 | |
| 6-e | | 48-52 | | | 9.0 | 24.0 | 6.3 | 7.0 | Up | 5 | 77.2 | |
| 6-f | | 48-52 | | | 9.0 | 24.0 | 6.8 | 4.5 | Down | 5 | 79.2 | |
| 6-g | Willamette silt loam | 60-64 | | | 9.0 | 24.0 | 6.3 | 5.4 | Up | 5 | 79.5 | |
| 6-h | | 60-64 | | | 9.0 | 24.0 | 6.3 | 4.5 | Down | 5 | 82.8 | |
| 6-i | | 12-18 | | | 9.0 | 18.0 | 3.9 | 8.9 | Up | 5 | 75.8 | |
| 6-j | | | | | 9.0 | 16.0 | 3.9 | 6.9 | Down | 5 | 79.5 | |
| 6-k | | | | | 9.0 | 22.0 | 5.2 | 9.2 | Up | 5 | 77.4 | |
| 6-l | | | | | 9.0 | 19.0 | 6.1 | 9.0 | Down | 5 | 77.2 | |
| 6-m | | | | | 9.0 | 20.0 | 8.7 | 8.8 | Up | 5 | 78.6 | |
| 6-n | | | | | 9.0 | 23.0 | 8.5 | 9.1 | Down | 5 | 78.6 | |
| 7-a | Willamette silt loam | 12-18 | 9.0 | 24.0 | 9.0 | 17.0 | 2.9 | 8.3 | Up | 4 | 80.2 | |
| 7-b | | | | | 9.0 | 24.0 | 11.9 | 5.8 | ...do | 4 | 82.8 | |
| 8-a | | 6-10 | 9.43 | 24.66 | 9.4 | 23.0 | 5.5 | 6.5 | ...do | 4 | 75.7 | |
| 8-b | | 24-28 | 18.08 | 30.06 | 18.1 | 28.0 | 4.6 | 3.8 | ...do | 4 | 75.7 | |
| 8-c | | 36-40 | 16.12 | 28.27 | 16.1 | 25.0 | 4.8 | 5.1 | ...do | 4 | 75.7 | |
| 8-d | | 48-52 | 15.07 | 25.87 | 15.1 | 22.0 | 7.0 | 4.4 | ...do | 4 | | |
| 8-e | | 60-64 | 15.94 | 24.14 | 15.9 | 19.0 | 6.7 | 2.3 | ...do | 4 | 75.8 | |
| 8-f | | 72-76 | 15.94 | 24.14 | 10.0 | 15.0 | 6.4 | 3.9 | Down | 4 | 75.8 | |
| 8-g | | 6-10 | 9.43 | 24.66 | 9.5 | 21.0 | 6.7 | 5.5 | ...do | 4 | | |
| 8-h | Carlton silty clay loam | 12-16 | 9.70 | 29.37 | 9.7 | 18.0 | 6.7 | 5.2 | ...do | 4 | | |
| 8-i | | 24-28 | 18.98 | 30.06 | 18.1 | 28.0 | 8.1 | 3.7 | ...do | 4 | 75.8 | |
| 8-j | | 12-18 | 9.7 | 29.37 | 9.7 | 18.0 | 4.7 | 8.1 | Up | 10 | 77.0 | |
| 8-k | | | | | 9.7 | 22.0 | 6.3 | 8.4 | ...do | 10 | | |
| 8-l | | | | | 9.7 | 25.0 | 8.8 | 7.7 | ...do | 10 | | |
| 8-m | | | | | 9.7 | 26.0 | 10.7 | 8.3 | ...do | 10 | | |
| 8-n | | | | | 9.7 | 14.0 | 4.0 | 5.8 | Down | 5 | | |
| 8-o | | | | | 9.7 | 20.0 | 5.4 | 10.8 | ...do | 5 | 74.1 | |
| 8-p | | | | | 9.7 | 24.0 | 7.2 | 10.8 | ...do | 5 | 74.1 | |
| 8-q | | | | | 9.7 | 24.0 | 9.1 | 8.9 | ...do | 5 | | |

[2] These values are determined by C. S. Schuster on soil samples taken at points very close to the places where the samples used in these experiments were taken.

The other data in the table may be interpreted in the same way. Where possible the field capacity and the permanent wilting percentage have been used as the upper and lower limits respectively because this is the range of moisture content of primary importance in plant growth, and it is believed that the data are more trustworthy within this range.

### EFFECT OF SOIL TYPE ON RATE OF FLOW

The data of table 1 are intended primarily to show the rate of flow of capillary moisture in different soils. So many factors are involved, however, that it is very difficult to determine directly from the table the effect of individual factors on the rate of flow. Figures 8 and 9 clearly indicate the effect of soil type. The curves on these figures are similar to those of figure 7 in that they show the average moisture content of the soil at different distances from the open end in groups of tubes under similar conditions. These curves show that for any given rate of flow of water the moisture-content gradient is steepest at the lowest moisture contents, and becomes less steep as the moisture content increases. There is a decided difference in the moisture-content gradient at any given moisture content for the different soil types represented by the curves in these two figures.
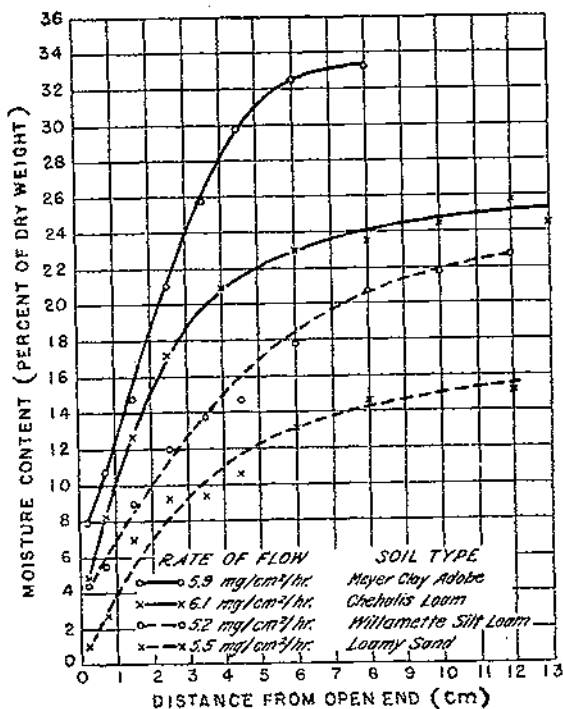


Figure 8.—Moisture content throughout length of groups of cores of different soil types with approximately the same rates of flow upward, against gravity.

Mechanical analyses of these soils are not available and the soils are classified as mapped in the soil-survey reports. On this basis there are two cases in these two groups where a soil of a finer texture transmits water more readily than one of coarser texture. The Willamette silt loam shows a lower moisture content and flatter moisture-content gradient than does the Chehalis loam with practically the same rate of flow. The Carlton silty clay loam also shows a lower moisture content and flatter gradient than the Newberg clay loam with the same rate of flow. It may be, but probably is not, significant that both the Chehalis and Newberg soils are recent river bottom soils.

Perhaps the most interesting point brought out by this comparison of the rate of movement through different soil types is the very small differences in the rate of capillary flow under similar conditions as compared to the very great differences in rate of flow through satu-

rated soils of the same classes. Figure 10 shows that with practically the same moisture-content gradient between 10 and 22 percent the flow through Meyer clay adobe, Chehalis loam, and Carlton silty clay loam was 3.5, 6.1, and 8.8 mg per square centimeter per hour, respectively.

For two of the soils, the clay adobe and the loam, data are available on the rate of infiltration of water applied at the surface. During the third consecutive hour during which water stood on the surface, the clay adobe absorbed 0.4 inch of water, while the loam absorbed four times as much, or 1.6 inches. Moreover, the rate of infiltration into the clay adobe was rapidly decreasing, and in fact became negligible within a few hours, whereas the movement in the loam appeared to have reached a constant rate.

The ratio of flow under saturated conditions was then 4 to 1 (and eventually much more) in the Chehalis loam as compared to the Meyer clay adobe while under nonsaturated conditions the ratio for the same soils was less than 2 to 1. Specific water-conductivity measurements as defined by Israelsen (26) are not available
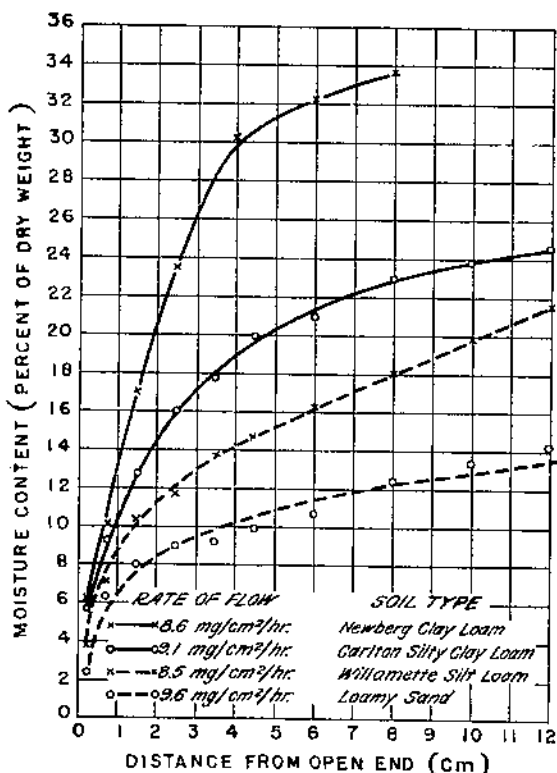


FIGURE 9.—Moisture content throughout length of groups of cores of different soil types with approximately the same rates of flow downward, with gravity.

for these soils. It will be noted on this figure that the rate of flow of the Chehalis loam is less than that of the Carlton silty clay loam, a condition similar to that noted in figures 8 and 9.

### EFFECT OF GRAVITY ON RATE OF FLOW

Pairs of curves are shown in figure 11 illustrating the difference in the moisture-content gradient for flow upward as compared with flow downward. With each of the three soils illustrated it required 2 percent more difference in the moisture content between the two ends of a soil column 12 cm long to force the water to move upward against the gravitational potential gradient and the frictional resistance than it did to force water downward with gravity but against the same frictional resistance at the same rate. It is hoped that use can be made of this effect of gravity on the rate of flow to evaluate the capillary potential and a conductivity factor in terms of ordinary units of

mass, force, and distance. As has already been stated these data make it possible to plot curves showing the relation between the moisture-content gradient and the rate of flow, both when the capillary-potential gradient and the gravitational potential gradient are opposite and when they work in conjunction.

### MOISTURE-CONTENT GRADIENT FOR DIFFERENT RATES OF FLOW

The curves of figures 12 and 13 show the differences in the moisture-content gradients at given moisture contents required to force different quantities of water through the soil either upward or downward. The slope of the curves at any given moisture content represents the rate of change, or gradient, of the moisture content at the given moisture content and for the conditions represented by the curve. Thus, if a tangent be drawn to one of the curves at a given moisture content, the difference between the moisture contents indicated by the intersections of this tangent with any two vertical lines representing a distance apart of 1 centimeter will be the rate of change, or gradient, of moisture content in percent per centimeter.

Figure 12 shows that at a moisture content of 18 percent a gradient of 3.2 percent per centimeter is required to force water upward at the rate of 10.7 milligrams per square centimeter per hour, 2.8 percent per centimeter



FIGURE 10.—Moisture content throughout length of groups of cores of different soil types showing differences in rates of flow (upward, against gravity) with approximately uniform moisture-content gradients.

for 8.8 milligrams per square centimeter per hour, 1.7 percent per centimeter for 6.3 milligrams per square centimeter per hour, and only 0.6 percent per centimeter to force water upward at the rate of 4.7 milligrams per square centimeter per hour. Figure 13 shows at the same moisture content a gradient of 1.8 percent per centimeter will force water downward at the rate of 9.1 milligrams per square centimeter per hour, 1.4 percent per centimeter for 7.2 milligrams per square centimeter per hour, and 0.6 percent per centimeter will force water downward the rate of 5.4 milligrams per square centimeter per hour. The 6-inch tubes used were not long enough to build up a moisture content of 18 percent with a flow of 4.0 milligrams per square centimeter per hour.

From another point of view it may be noted that a moisture-content gradient of 2 percent per centimeter will force 4.0 milligrams per
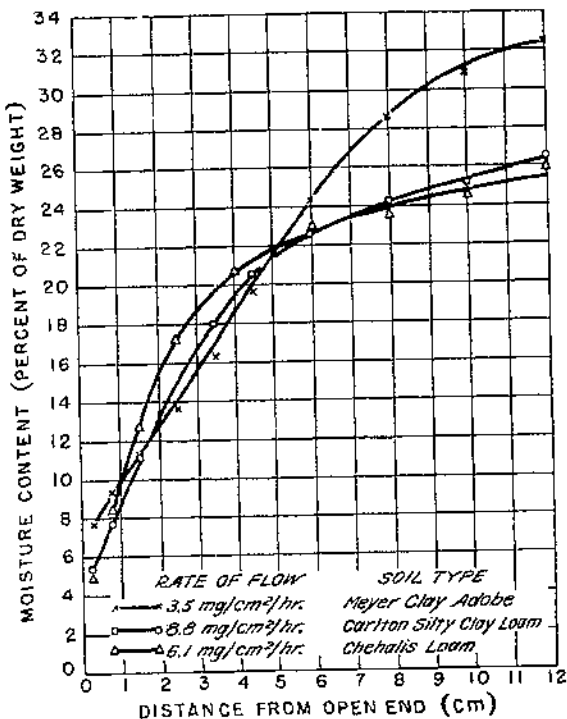
square centimeter per hour downward through Carlton silty clay loam at a moisture content of 5 percent, 5.4 milligrams per square centimeter per hour at 12 percent, 7.2 milligrams per square centimeter per hour at 16 percent, and 9.1 milligrams per square centimeter per hour at a moisture content of 17 percent.

### CONVERSION OF UNITS

The equipment used in these experiments gave data in terms of milligrams per hour through a soil column 0.84 inch in diameter. In table 1 and the moisture-content versus distance curves these data have been converted into terms of milligrams per square centimeter per hour. In considering the field application of the data it may be remembered that 1 milligram per square centimeter per hour is approximately equivalent to 0.00945 inch in depth of water (sometimes called surface inches) per day, or 1 inch in 106 days.

### DISCUSSION

These data serve to give some idea of the rate at which water may move through the soil under the influence of differences in moisture content. Table 2 shows the number of days required for 1 inch of water to move from soil at the field capacity through different distances either up or down to soil at the wilting point in several soil types. Movement laterally may reasonably be assumed to be intermediate between the rates in these directions. It will be observed that in the case of the Meyer clay adobe the flow upward appears to be more ready than the flow downward in that only a slightly longer time was required to move an inch of water 2.8 inches upward than to move the same quantity 1.9 inches downward. This case is almost unique in these experiments and probably serves to show the differences in soil samples rather than to prove that the Meyer clay adobe has some strange power to counteract the gravitational field. The results are harder to explain in that the lower part of each of the corresponding curves represents the data from 16 tubes and the upper part from 8 tubes.
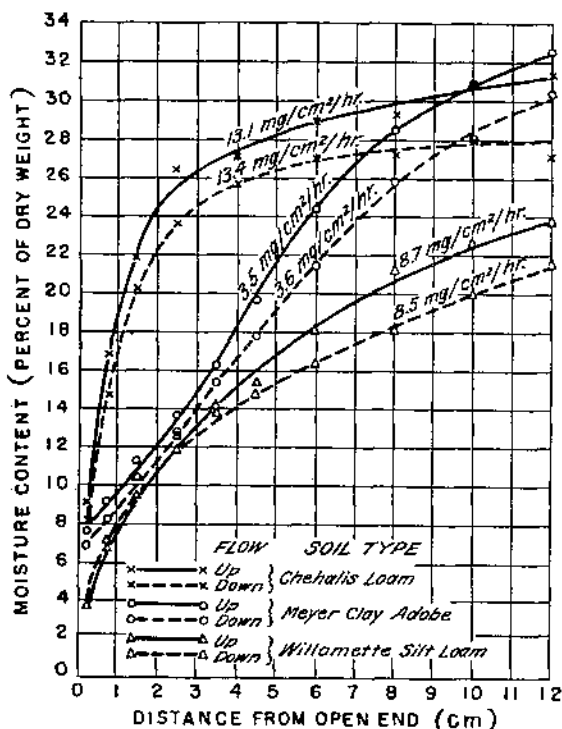


FIGURE 11.—Moisture content throughout length of pairs of groups of cores of different soils when flow at the same rate is taking place upward or downward.

TABLE 2.—*Distance through which 1 inch of water will move in a given time through soils of different types from zones at field capacity to zones at the wilting point*

| Soil type | Time | Distance | Direction of flow | Soil type | Time | Distance | Direction of flow |
|---|---|---|---|---|---|---|---|
| | *Days* | *Inches* | | | *Days* | *Inches* | |
| Chehalis loam | 17 | 3.7 | Up. | Loamy sand | 14 | 1.2 | Up. |
| | 8 | 1.1 | Do. | | 11 | 4.5 | Down. |
| | 16 | 3.7 | Down. | Willamette silt loam | 21 | 3.6 | Up. |
| | 8 | 2.5 | Do. | | 12 | 3.6 | Down. |
| Newberg clay loam | 11 | 1.7 | Up. | Carlton silty clay loam | 12 | 3.6 | Up. |
| | 12 | 2.1 | Down. | | 12 | 3.5 | Down. |
| Meyer clay adobe | 18 | 2.8 | Up. | | | | |
| | 17 | 1.9 | Down. | | | | |

If it be assumed that the moisture content at the ground surface is at the wilting point and that a few inches below it is at the field capacity the loss by evaporation might become appreciable. For instance with the Willamette silt loam if the soil 3.6 inches below the surface were maintained at the field capacity an inch of water might be lost every 21 days. If the soil 3.3 inches below the surface were maintained halfway between the wilting point and the field capacity it would take 37 days for 1 inch of water to be lost.[4] The conditions of the experiment do not afford direct measurements of the losses through greater distances but from the above data it may be inferred that it would take about 3 months for 1 inch to



FIGURE 12.—Moisture content throughout length of groups of cores of Carlton silty clay loam when upward flow is taking place at different rates.

be lost from Willamette silt loam if the soil a foot below the surface were maintained at the field capacity. Where crops are growing they will, of course, reduce the moisture content well below that point within a week or two after rain or irrigation. These data, then, confirm the general opinion that where field crops are growing and the water table is deep, losses by evaporation of moisture brought to the surface by capillary action are not great.

There appear to be no data available as to the length of roots or root hairs, that are effective in absorbing moisture, in the soil at any one time. Schuster[5] has found that a soil-tube sample 0.75 inch in

[4] From no. 7-a in table 1 and line 15 on p. 22, 2.9 mg per square centimeter per hour equals 0.027 inch per day.
[5] Unpublished data.

diameter by 12 inches long which contains 80 to 100 cm of fine roots represents a good root distribution. If all of this root length absorbs water it indicates that, on the average, there is about 1 cm of absorbing root per cubic centimeter of soil. (Root hairs appear to be absent or nearly so on both walnut and pear roots in this area and if present are so short that in effect they only increase the diameter of the absorbing root a millimeter or less. Their influence, therefore, is not considered in the present discussion.)

If it be assumed that only 10 percent of the length of fine roots is water absorbing, that the root zone is 4 feet deep, and that the diameter of the water-absorbing roots is 1 mm the area of water-absorbing root surface per square centimeter of ground surface will be 3.7 square centimeters. On these assumptions and the further assumption that the root distribution is uniform, the maximum distance water would have to move through the soil to the roots would be about 4.5 cm. On the further assumption that the water requirement of a mature tree is 2 acre-inches per acre per week or 0.03 cubic centimeter per square centimeter of ground surface per hour, the flow through the soil adjacent to the absorbing roots would need to be at the rate of 0.008 cubic centimeters, or 8 mg per square centimeter, per hour.
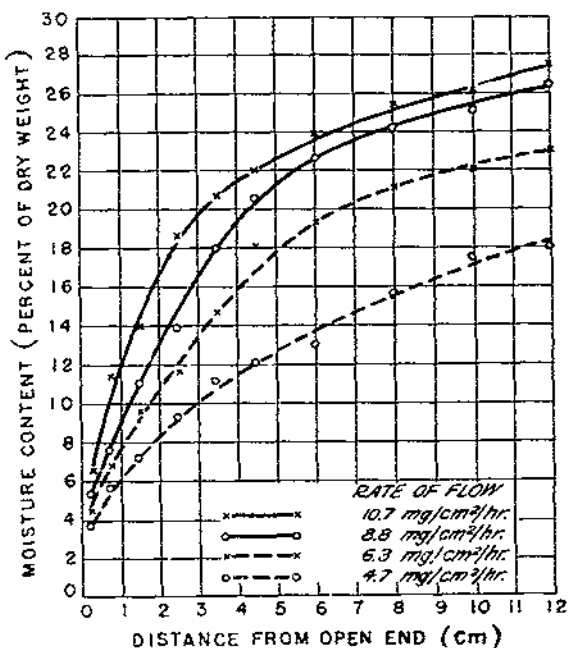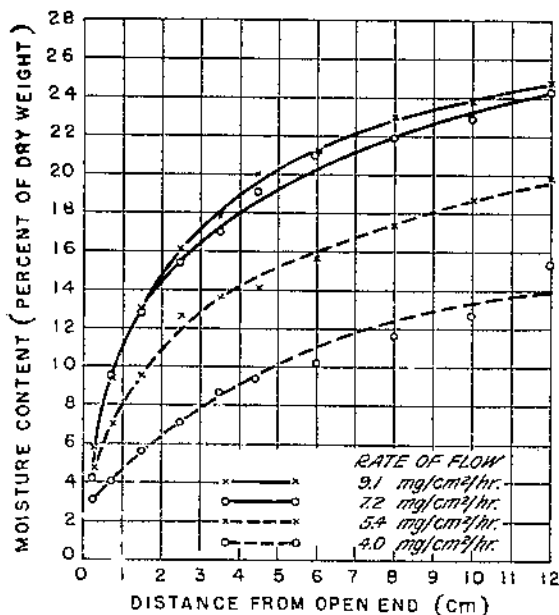


FIGURE 13.— Moisture content throughout length of groups of cores of Carlton silty clay loam when downward flow is taking place at different rates.

The data of table 1 indicate that with most of the soils tested flow at this rate through distances of a few centimeters will take place under the influence of soil-moisture differences roughly between the field capacity and the wilting point.

The flow of moisture toward a root is somewhat analogous to the flow of water toward a well. After a rain or an irrigation the soil mass may be assumed to be wet to the field capacity. Immediately the roots begin to abstract water. At first the water comes from the soil adjacent to the root but very soon a moisture-content, or capillary-potential, gradient is set up and flow toward the root through the soil takes place. As the loss of water continues the sphere of influence about each root expands and in time interferes with the sphere of influence about adjoining roots. The flow toward any root crosses concentric cylindrical surfaces and, therefore, the maximum rate, in volume per unit area per unit of time, occurs adjacent to the root. Assuming a root diameter of 1 mm, the rate of flow 1 cm from the root would be only one-twentieth as great as that at the root. More-

over, part of the supply is always being drawn from the soil near the root and does not need to be forced toward the root from the outer region of the sphere of influence. Taking these factors into account, together with the foregoing assumptions, it seems that the moisture content midway between roots might be well below the field capacity before the rate of flow through the soil toward the roots would become the limiting factor of tree growth. Whether the assumption that 10 percent of the fine roots is water absorbing is even approximately true is unknown so far as the writer can learn.

Admittedly this discussion is based on a number of assumptions and is somewhat speculative. However, it is believed that it throws some light on plant-soil-moisture relations. It is hoped that as the investigation progresses it will be possible to work out this phase more definitely.

## SUMMARY AND CONCLUSIONS

The experiments reported herein were designed to furnish data on the rate at which capillary water will move through various soil types under the influence of gradients in the moisture content.

The importance of these data for the solution of many field and orchard problems is discussed.

Most of the recent pertinent literature in English on the subject is briefly reviewed.

The study was inaugurated with the intent of securing both experimental data on the rate of flow in many soil types and fundamental information on (1) the relation between the moisture content of the soil and the capillary potential, (2) the relation between the capillary-potential gradient and the rate of flow of capillary moisture, and (3) the specific conductivity of the soil for moisture.

Only the first part of the study is reported here, but enough comparisons are shown to give some idea of the principal factors which affect the rate of flow.

For several reasons short, small-diameter soil columns of undisturbed structure were used. A steady state of flow can be secured much more quickly in short than in long tubes. Several duplications of small samples were considered more trustworthy than one or two larger samples. Detailed data for different depths in the soil profile were desired. The ease of securing samples at considerable depth with the King soil tube was an important consideration.

The experiment consisted of setting up series of soil columns exposed to the evaporating influence of an air current at one end and adding water at predetermined rates at the other end. When a state of steady flow was secured the soil columns were broken down and moisture content of each short transverse section was determined.

That approximately steady flow had been attained was determined by weighing the tubes before and after adding water each time and plotting up the rate of loss. When the rate of loss became and continued approximately uniform and equal to the rate of addition it was evident that dynamic equilibrium had been reached.

It was found that a very small portion of the water could be moving through the moist soil in the vapor phase. Only 8 to 12 mg per hour of water crossed a screened space of about 1 mm in these tubes. If no more than that quantity of water will cross a practically open space it seems impossible that any appreciable quantity would pass through the pores of the soil.

Ideally, the water should be added to the soil column in this experiment continuously rather than intermittently. A series of tests indicate that the addition of comparatively large quantities of water at 12-hour intervals did not seriously distort the data.

The distances through which water flowed at different rates under the influence of certain differences in moisture content at the two ends of the soil columns in a number of soil types and at different depths are tabulated.

Because of the large number of factors involved it is difficult to make direct comparisons from the tabulated values and a number of comparisons are presented graphically.

Curves showing the moisture content throughout the length of soil columns of different soil types when moisture was flowing through them at the same rate are shown. These curves show that, in general, the finer textured soils will not transmit capillary water as readily as will coarser textured soils. They show that for steady flow in any particular case the moisture-content gradient is always steeper as the moisture content becomes less.

The difference in the ability of different fine-textured soils to transmit capillary moisture as compared with coarse-textured soils is much less than the corresponding difference in the ability of similar soils to transmit moisture under saturated conditions.

The effect of the gravitational field on the moisture-content gradient required to force capillary water through the soil is shown graphically. With each of three soils represented it required about 2 percent more difference in moisture content at the ends of 12-cm columns to drive water upward than downward.

For one soil, moisture-content-versus-distance curves are shown for four different rates of flow both upward and downward. These curves show graphically the different moisture-content gradients required at various moisture contents to force different quantities of capillary water through the soil.

These data show that between approximately the field capacity and the wilting point the several soil types will transmit 1 inch of water through 1 to 4 inches in 8 to 20 days.

From these data it is obvious that with differences in moisture content between the field capacity and the wilting point water in sufficient quantities to support crops could be raised a few inches from a moist subsoil, but only a few inches. Examination of the curves shows that most of the movement takes place at moisture contents well above the wilting point.

Losses by evaporation at the soil surface of water moved upward by capillary action are not great.

The portion of the soil mass midway between absorbing roots might be well below the field capacity but still well above the wilting point before the movement of moisture through the soil would become the limiting factor in tree or fruit growth.

At moisture contents below the wilting point the moisture-content gradient is extremely steep for the rates of flow used in this experiment.

The different opinions noted earlier in the bulletin on the importance of capillary flow are reconciled. At high relative moisture contents and with low rates of flow water may move through considerable distances. At low relative moisture contents the distance through which moisture will move is very small.

## LITERATURE CITED

(1) ALDRICH, W. W. and WORK, R. A.
    1933. PRELIMINARY REPORT OF PEAR TREE RESPONSES TO VARIATIONS IN
        AVAILABLE SOIL MOISTURE IN CLAY ADOBE SOIL. Amer. Soc.
        Hort. Sci. Proc. (1932) 29: 181–187, illus.
(2) ———— and WORK, R. A.
    1935. EVAPORATING POWER OF THE AIR AND TOP-ROOT RATIO IN RELATION
        TO RATE OF PEAR FRUIT ENLARGEMENT. Amer. Soc. Hort. Sci.
        Proc. (1934) 32: 115–123.
(3) ———— WORK, R. A., and LEWIS, M. R.
    1935. PEAR ROOT CONCENTRATION IN RELATION TO SOIL-MOISTURE EX-
        TRACTION IN HEAVY CLAY SOIL. Jour. Agr. Research 50: 975–987.
(4) ALWAY, F. V., and McDOLE, G. R.
    1917. RELATION OF MOVEMENT OF WATER IN A SOIL TO ITS HYGROSCOPICITY
        AND INITIAL MOISTNESS. Jour. Agr. Research 10: 391–428, illus.
(5) BARTHOLOMEW, E. T.
    1926. INTERNAL DECLINE OF LEMONS. III. WATER DEFICIT IN LEMON
        FRUITS CAUSED BY EXCESSIVE LEAF EVAPORATION. Amer. Jour.
        Bot. 13: 102–117, illus.
(6) BECKETT, S. H., BLANEY, H. F., and TAYLOR, C. A.
    1930. IRRIGATION WATER REQUIREMENT STUDIES OF CITRUS AND AVOCADO
        TREES IN SAN DIEGO COUNTY, CALIFORNIA, 1926 AND 1927. Calif.
        Agr. Expt. Sta. Bull. 489, 51 pp., illus.
(7) BODMAN, G. B., and EDLEFSEN, N. E.
    1934. THE SOIL-MOISTURE SYSTEM. Soil Sci. 38: 425–444, illus.
(8) BOUYOUCOS, G. J.
    1915. EFFECT OF TEMPERATURE ON SOME OF THE MOST IMPORTANT PHYSICAL
        PROCESSES IN SOILS. Mich. Agr. Expt. Sta. Tech. Bull. 22,
        63 pp., illus.
(9) BRIGGS, L. J., and LAPHAM, M. H.
    1902. CAPILLARY STUDIES AND FILTRATION OF CLAY FROM SOIL SOLUTIONS.
        U. S. Dept. Agr., Bur. Soils Bull. 19, 40 pp., illus.
(10) BUCKINGHAM, E.
    1907. STUDIES OF THE MOVEMENT OF SOIL MOISTURE. U. S. Dept. Agr.,
        Bur. Soils Bull. 38, 61 pp., illus.
(11) CONRAD, J. P., and VEIHMEYER, F. J.
    1929. ROOT DEVELOPMENT AND SOIL MOISTURE. Hilgardia 4: [113]–134,
        illus.
(12) FISHER, E. A.
    1923. SOME FACTORS AFFECTING THE EVAPORATION OF WATER FROM SOIL.
        Jour. Agr. Sci. [England.] 13: [121]–143, illus.
(13) FISHER, R. A.
    1926. ON THE CAPILLARY FORCES IN AN IDEAL SOIL: CORRECTION OF
        FORMULAE GIVEN BY W. B. HAINES. Jour. Agr. Sci. [England]
        16: [492]–505.
(14) FURR, J. R., and DEGMAN, E. S.
    1932. RELATION OF MOISTURE SUPPLY TO STOMATAL BEHAVIOR OF THE
        APPLE. Amer. Soc. Hort. Sci. Proc. (1931) 28: 547–551,
        illus.
(15) ———— and MAGNESS, J. R.
    1931. PRELIMINARY REPORT ON RELATION OF SOIL MOISTURE TO STOMATAL
        ACTIVITY AND FRUIT GROWTH OF APPLES. Amer. Soc. Hort. Sci.
        Proc. (1930) 27: 212–218, illus.
(16) GARDNER, W.
    1919. THE MOVEMENT OF MOISTURE IN SOIL BY CAPILLARITY. Soil Sci.
        7: 313–317, illus.
(17) ————
    1919. CAPILLARY MOISTURE-HOLDING CAPACITY. Soil Sci. 7: 319–324,
        illus.
(18) ————
    1920. A CAPILLARY TRANSMISSION CONSTANT AND METHODS OF DETER-
        MINING IT EXPERIMENTALLY. Soil Sci. 10: 103–126, illus.
(19) ————
    1920. THE CAPILLARY POTENTIAL AND ITS RELATION TO SOIL-MOISTURE
        CONSTANTS. Soil Sci. 10: 357–359, illus.
(20) ———— ISRAELSEN, O. W., EDLEFSEN, N. E., and CLYDE, H. S.
    1922. THE CAPILLARY POTENTIAL FUNCTION AND ITS RELATION TO IRRIGA-
        TION PRACTICE. Phys. Rev. (2) 20: 196–197.

(21) GARDNER, W., and WIDTSOE, J. A.
    1921. THE MOVEMENT OF SOIL MOISTURE.   Soil Sci. 11: 215–232, illus.
(22) HAINES, B. W.
    1927. STUDIES IN THE PHYSICAL PROPERTIES OF SOILS.   IV. A FURTHER CON-
        TRIBUTION TO THE THEORY OF CAPILLARY PHENOMENA IN SOIL.
        Jour. Agr. Sci. [England] 17: [264]–290, illus.
(23) HARRIS, F. S., and TURPIN, H. W.
    1917. MOVEMENT AND DISTRIBUTION OF MOISTURE IN THE SOIL.   Jour.
        Agr. Research 10: 113–155, illus.
(24) HENDRICKSON, A. H., and VEIHMEYER, F. J.
    1929. IRRIGATION EXPERIMENTS WITH PEACHES IN CALIFORNIA.   Calif.
        Agr. Expt. Sta. Bull. 479: 1–56, illus.
(25) ———— and VEIHMEYER, F. J.
    1934. IRRIGATION EXPERIMENTS WITH PRUNES.   Calif. Agr. Expt. Sta.
        Bull. 573, 44 pp., illus.
(26) ISRAELSEN, O. W.
    1927. THE APPLICATION OF HYDRODYNAMICS TO IRRIGATION AND DRAINAGE
        PROBLEMS.   Hilgardia 2: [479]–528, illus.
(27) ————
    1932. IRRIGATION PRINCIPLES AND PRACTICES.   422 pp., illus.   New York
        and London.
(28) KARRAKER, P. E.
    1920. THE EFFECT OF THE INITIAL MOISTURE IN A SOIL ON MOISTURE
        MOVEMENT.   Soil Sci. 10: 143–152, illus.
(29) KING, F. H.
    1889. SOIL PHYSICS.   Wis. Agr. Expt. Sta. Ann. Rept. 6: 189–206, illus.
(30) ————
    1904. TEXT BOOK OF THE PHYSICS OF AGRICULTURE.   Ed. 3, 604 pp.,
        illus.   Madison, Wis.
(31) LEWIS, M. R., WORK, R. A., and ALDRICH, W. W.
    1935. INFLUENCE OF DIFFERENT QUANTITIES OF MOISTURE IN A HEAVY
        SOIL ON RATE OF GROWTH OF PEARS.   Plant Physiol. 10: 309–323.
(32) LIVINGSTON, B. E. and KOKETSU, R.
    1920. THE WATER-SUPPLYING POWER OF THE SOIL AS RELATED TO THE
        WILTING OF PLANTS.   Soil Sci. 9: 469–485.
(33) McGEE, W. J.
    1913. FIELD RECORDS RELATING TO SUBSOIL WATER.   U. S. Dept. Agr.,
        Bur. Soils Bull. 93, 40 pp.
(34) ————
    1913. WELLS AND SUBSOIL WATER.   U. S. Dept. Agr., Bur. Soils Bull. 92,
        185 pp.
(35) McLAUGHLIN, W. W.
    1920. CAPILLARY MOVEMENT OF SOIL MOISTURE.   U. S. Dept. Agr. Bull.
        835, 70 pp., illus.
(36) ————
    1924. THE CAPILLARY DISTRIBUTION OF MOISTURE IN SOIL COLUMNS OF
        SMALL CROSS SECTION.   U. S. Dept. Agr. Bull. 1221, 23 pp., illus.
(37) MAGNESS, J. R.
    1935. STATUS OF ORCHARD SOIL MOISTURE RESEARCH.   Amer. Soc. Hort.
        Sci. Proc. (1934) 32: 651–661.
(38) RICHARDS, L. A.
    1928. THE USEFULNESS OF CAPILLARY POTENTIAL TO SOIL-MOISTURE AND
        PLANT INVESTIGATORS.   Jour. Agr. Research 37: 719–742, illus.
(39) ————
    1931. CAPILLARY CONDUCTION OF LIQUIDS THROUGH POROUS MEDIUMS.
        Physics 1: 318–333, illus.
(40) ————
    1936. CAPILLARY CONDUCTIVITY DATA FOR THREE SOILS.   Jour. Amer.
        Soc. Agron. 28: 297–300, illus.
(41) SCOFIELD, C. S., and WRIGHT, C. C.
    1928. THE WATER RELATIONS OF YAKIMA VALLEY SOILS.   Jour. Agr.
        Research 37: 65–85.
(42) SHANTZ, H. L.
    1925. SOIL MOISTURE IN RELATION TO THE GROWTH OF CROP PLANTS.
        Jour. Amer. Soc. Agron. 17: 705–711.

(43) Shaw, C. F.
         1927. the normal moisture capacity of soils.  Soil Sci. 23: 303-317,
           illus.
(44) —— and Smith, A.
         1927. maximum height of capillary rise starting with soil at
           capillary saturation.  Hilgardia 2: 399-409, illus.
(45) Shull, C. A.
         1916. measurement of the surface forces in soils.  Bot. Gaz.
           62: 1-31, illus.
(46) ——
         1930. absorption of water by plants and the forces involved.
           Jour. Amer. Soc. Agron. 22: 459-471.
(47) Taylor, C. A., Blaney, H. F., and McLaughlin, W. W.
         1934. the wilting-range in certain soils and the ultimate wilting-
           point.  Amer. Geophys. Union Ann. Meeting 15: 436-444, illus.
(48) Thomas, M.D.
         1921. aqueous vapor pressure of soils.  Soil Sci. 11: 409-434, illus.
(49) ——
         1924. aqueous vapor pressure of soils. ii. studies in dry soils.
           Soil Sci. 17: 1-18, illus.
(50) —— and Harris, K.
         1926. the moisture equivalent of soils.  Soil Sci. 21: 411-424, illus.
(51) Vasquez, N. F.
         1933. el agua del suelo en relación con la planta.  Min. Fomento,
           Dir. Agr. y Ganadería [Peru] Circ. 20: 21-30.
(52) Veihmeyer, F. J.
         1927. some factors affecting the irrigation requirements of de-
           ciduous orchards.  Hilgardia 2: [125]-284, illus.
(53) ——
         1932. the disposal of moisture from the aerated portion of soils.
           Amer. Geophys. Union Trans. Ann. Meeting 13: 330-331.
(54) —— and Hendrickson, A. H.
         1927. soil-moisture conditions in relation to plant growth.  Plant
           Physiol. 2: 71-82, illus.
(55) —— and Hendrickson, A. H.
         1930. essentials of irrigation and cultivation of orchards.  Calif.
           Agr. Ext. Serv. Circ. 50, 24 pp.  (Revised, 1936).
(56) —— and Hendrickson, A. H.
         1934. some plant and soil-moisture relations.  Amer. Soil Survey
           Assoc. Bull. 15: 76-80, illus.
(57) Work, R. A., and Lewis, M. R.
         1936. the relation of soil moisture to pear tree wilting in a heavy
           clay soil.  Jour. Amer. Soc. Agron. 28: 124-134, illus.

## ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

| | |
|---|---|
| *Secretary of Agriculture* | HENRY A. WALLACE. |
| *Under Secretary* | M. L. WILSON. |
| *Assistant Secretary* | HARRY L. BROWN. |
| *Director of Extension Work* | C. W. WARBURTON. |
| *Director of Finance* | W. A. JUMP. |
| *Director of Information* | M. S. EISENHOWER. |
| *Director of Personnel* | W. W. STOCKBERGER. |
| *Director of Research* | JAMES T. JARDINE. |
| *Solicitor* | MASTIN G. WHITE. |
| *Agricultural Adjustment Administration* | H. R. TOLLEY, *Administrator.* |
| *Bureau of Agricultural Economics* | A. G. BLACK, *Chief.* |
| *Bureau of Agricultural Engineering* | S. H. MCCRORY, *Chief.* |
| *Bureau of Animal Industry* | JOHN R. MOHLER, *Chief.* |
| *Bureau of Biological Survey* | IRA N. GABRIELSON, *Chief.* |
| *Bureau of Chemistry and Soils* | HENRY G. KNIGHT, *Chief.* |
| *Commodity Exchange Administration* | J. W. T. DUVEL, *Chief.* |
| *Bureau of Dairy Industry* | O. E. REED, *Chief.* |
| *Bureau of Entomology and Plant Quarantine* | LEE A. STRONG, *Chief.* |
| *Office of Experiment Stations* | JAMES T. JARDINE, *Chief.* |
| *Farm Security Administration* | W. W. ALEXANDER, *Administrator.* |
| *Food and Drug Administration* | WALTER G. CAMPBELL, *Chief.* |
| *Forest Service* | FERDINAND A. SILCOX, *Chief.* |
| *Bureau of Home Economics* | LOUISE STANLEY, *Chief.* |
| *Library* | CLARIBEL R. BARNETT, *Librarian.* |
| *Bureau of Plant Industry* | FREDERICK D. RICHEY, *Chief.* |
| *Bureau of Public Roads* | THOMAS H. MACDONALD, *Chief.* |
| *Soil Conservation Service* | H. H. BENNETT, *Chief.* |
| *Weather Bureau* | WILLIS R. GREGG, *Chief.* |

This bulletin is a contribution from

| | |
|---|---|
| *Bureau of Agricultural Engineering* | S. H. MCCRORY, *Chief.* |
| *Division of Irrigation* | W. W. MCLAUGHLIN, *Chief.* |

30

# END