WATER AVAILABILITY AND ITS UNSATURATED PERMEABILITY IN SOME SOILS OF LEBANON

By

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SOIL WATER AVAILABILITY

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AN ABSTRACT OF THE THESIS OF

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Title: Water availability and its unsaturated permeability in some soils of Lebanon.

The available soil moisture capacity of a typical calcareous clay soil of Lebanon and the relation of capillary conductivity to moisture levels was studied. The available moisture ranged from 80 to 103 mm. per meter depth. Since almost half of the available moisture was held at tensions greater than 2 bars, and since plants are unable to extract water easily even at considerably lesser moisture tension levels when transpiration rates are high; a rather low range of readily available water is indicated. A plot of capillary conductivity against moisture tension on a log-log scale produced an "S" shaped curve. The relation of capillary conductivity with moisture content by volume was linear only up to about 1.5 bars moisture tension. The water conductivity rates of this soil do not differ from those of other soils of clay texture. As such, the inability of the soil to maintain full leaf turgor, after 2 or 3 days of irrigation, is probably due to a small soil reservoir of water at low enough tensions to meet the relatively high evapotranspiration rates of the area.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

Figure

I. INTRODUCTION

The concept of available water is very important in arid and semi-arid regions, where artificial irrigation is needed for successful agriculture. The frequency of irrigation needed is based upon both the consumptive use of the plants as well as on the available soil moisture.

The rate of water transmission through the soil to the plant roots may limit absorption of water by plants whenever the transpiration rate is potentially greater than movement of water into the roots. A combination of high consumptive use of water accompanied by low soil water capillary conductivity may result in inadequate water supply even under conditions of relatively low soil moisture tension. Inadequate rates of moisture absorption in plants result in loss of turgor pressure and closure of plant stomata and this reduces photosynthesis and plant growth. Therefore, maximum plant growth calls for frequency of irrigations great enough to maintain full plant turgor at all times. Adequate frequency of irrigation depends on consumptive use of water and rate of movement of soil water to plant roots, as well as on the actual amount and tension of soil water.

The problem of frequency of irrigation is being faced in the Beqa'a Plain, Lebanon. Plants may start showing signs of water shortage, indicated by partial closure of stomata, as early as two or three days after irrigation (Fuehring, et al., 1966). The study reported here was undertaken to investigate the relationship, in a typical soil of the Beqa'a, between the available water of the soil and soil capillary conductivity.

II. REVIEW OF LITERATURE

Moisture Constants

The soil is a reservoir in which water is stored for plant use between irrigations. The storage and the movement of this soil water are important concepts in irrigation planning.

The upper and the lower limits of water storage in the soil reservoir are fixed by two soil moisture conditions, which might be called soil moisture constants. Veihmeyer and Hendrickson (1950) believe that they are the only ones of any practical value for consideration in connection with plant growth.

Field capacity: Field capacity of a soil represents the practical upper limit of field soil-moisture under conditions of unobstructed drainage. It is generally understood (Veihmeyer and Hendrickson, 1931) to be the moisture content of soil, following wetting by rainfall or irrigation, when downward water movement has almost ceased. Shaw (1927) has defined a similar value, "the normal moisture capacity", more functionally as the moisture content attained during soil drainage when the water films on the soil particles have become so thin that reduced permeability permits negligible further moisture decrease in the liquid state. However, in practice the terms are essentially synonymous.

Colman (1944) stated that field capacity represents merely a point on the moisture-drainage-time curve at which the drainage rate has become so slow that in comparison with early rates, it is insignificant. In well drained soils of at least moderate permeability, the field capacity is considered to have been reached two or three days after an irrigation or rainfall.

Some soils which show the phenomenon of delayed drainage strongly, such as some deep uniform moderately silty soils, can't be said to possess a field capacity. The drainage continues to remove appreciable quantities of water from them over periods of several months (Russell, 1961, pp. 381-382). This is attributed to pore space distribution. Soils possessing definite field capacity have two fairly distinct pore space systems - a continuous system of coarse pores extending round the main structural units through which water can move rapidly, and another continuous system of fine pores extending throughout the interior of these units through which water movement is practically inhibited by the viscous resistance to flow in such thin sheets. But soils with no definite field capacity don't possess these two distinct pore space systems and as such, continue draining.

There is little information concerning the tension at which water is held at field capacity (Baver, 1956, pp. 285-286). Richards and Weaver (1944) found that the soil water tension at the moisture equivalent was about 340 cm. of water, or one-third atmosphere, for a number of soils in which the moisture equivalent value varied from 8 percent to 22 percent. In the light of close correlation between the moisture equivalent and field capacity these tensions approximate the field capacity as well (Baver, 1956, pp. 285-288).

Colman (1947) found, with a group of forest soils, that the 1/3-atmosphere percentage, (like the moisture equivalent) is appreciably lower than the field capacity in coarse-textured soils; is equal to the field capacity at moisture values around 20; and is somewhat higher than field capacity in finer textured soils. Richards (1949) reported that the 1/3-atmosphere percentage correlated roughly with the moisture equivalent which is also considered as an index of field capacity.

Permanent wilting point or wilting percentage: The lower limit of the soil water reservoir or the soil moisture at which it may be considered to be emptied, since it no longer maintains normal growth and vigor of the plants, is taken as the permanent wilting point (Veihmeyer and Hendrickson, 1950). It was also pointed out (Veihmeyer and Hendrickson, 1948) that this moisture content is so important that special consideration should be given to it. Veihmeyer and Hendrickson (1949) indicated that Briggs and Shantz (1912) were the pioneers in concluding that on a given soil all plants reduce the moisture content to about the same extent when permanent wilting is attained. This contention was confirmed by Veihmeyer and Hendrickson (1945, 1948). They asserted that the permanent wilting percentage is a constant and is characteristic of a soil irrespective of environmental conditions under which plants wilt in the field. They suggested that it is a "satisfactory reference point" from which the amount of readily available water may be calculated. Furr and Reeve (1945) reported similar results.

Richards and Weaver (1943, 1944) found that the wilting percentage for a number of Western United States soils is near or slightly higher than the 15-atmosphere percentage. Peele _et_ _al_. (1948) found a similar relation for a group of South Carolina soils.

Since soils normally drain to the moisture content of the field capacity, and since plants permanently wilt at the wilting point, it may be seen that the amount of water available to plants is represented by the difference between these two equilibrium values (Baver, 1956, p. 286). Consequently, the nature of the tension moisture curve for a given soil will give a fairly good measure of the availability of soil water. If the curve is steep between these two points, there will be little available water, and it will be difficult to grow plants satisfactorily. Water will be held too tenaceously to be removed by plant roots at a rate rapid enough for growth. On the other hand, if the curve is gently sloping between field capacity and the permanent wilting point, water will be more available.

Soil moisture content near the wilting point is not readily available to the plant. Hence, the term "readily available moisture" is used to refer to that portion of the available moisture that is most easily extracted by plants. This amounts to approximately 75 percent of the available moisture according to Israelsen and Hansen (1962, p. 166).

Evaluation of Methods Used for Determining Soil Moisture Constants

Field capacity: Field capacity, as measured by making moisture determination 2 or 3 days after thorough wetting of the soil by irrigation or rainfall, is a valuable method in understanding and properly interpreting the field capacity characteristics of soil (Israelsen and Hansen, 1962, pp. 163-164). But the soil must be well drained before reliable field determinations can be made in this manner. Restricting layers of silt and clay as well as a high water table will impede drainage and give erroneous indications of field capacity.

Richards and Weaver (1944) concluded that there is no completely satisfactory laboratory method for estimating field capacity. However, the moisture equivalent is the most commonly used laboratory characterization of soil moisture and measure of field capacity (Veihmeyer and Hendrickson, 1949). Previously it was also shown (Veihmeyer and Hendrickson, 1931) that the moisture equivalent is a fairly reliable measure of field capacity for fine textured soils, but that for sands with moisture equivalent values less than 14 percent, the estimated values are usually lower than field capacity. The results of Browning (1941) also show a fair agreement between these two soil moisture constants for soils of medium to high water holding capacities. With soils having moisture equivalent values less than 10, however, the field capacity greatly exceeds the moisture equivalent and there appears to be no generally satisfactory laboratory method for determining the field capacity of such soils. Veihmeyer and Hendrickson (1931) quoted the work of Mathews (1923) who concluded that field capacity is a little lower than moisture equivalent, but bears a linear relation to it.

Use of porous plate apparatus at one-third atmosphere pressure, is a good laboratory method for estimating field capacity (Richards and Weaver, 1944). Since equipment costs and determination labor per sample are less with the porous plate method than with moisture equivalent determinations, it is probable that this determination will replace the moisture equivalent determinations for routine laboratory analyses.

<u>Permanent wilting point (PWP)</u>: Sunflowers are used most commonly in standardized laboratory methods for determining PWP. These plants give a clear indication of the onset of wilting and results are reproducible (Marshall, 1959, p. 55). Determination of soil moisture tension is a resonably reliable physical method for estimating the lower limit for available moisture in soils (Richards 1949). It has been found by Richards and Weaver (1943) and later by Veihmeyer and Hendrickson (1949) that the determination of water content at a pressure of 15-atmospheres is a reliable method of estimating the lower limit of the soil water reservoir. This can be more rapidly measured and has greater significance than other methods as a soil characteristic. Moreover, it is not affected very greatly by alteration of structure (Elrick and Tanner, 1955), and requires no special precautions to be taken during sampling of the soil

in the field. Since the 15-atmospheres tension method is very satisfactory, it is used very frequently.

Pertinent Factors Governing the Availability of Soil Moisture to Plants

The supply and availability of soil moisture to plants is attributed to (a) plant factors (b) climatic factors and (c) soil properties (Jamison, 1956).

Plant factors: Plants vary considerably in rooting habit with regard to both depth and ramification (Kelley, 1954, and Harrold, 1954). The quantities of water that different crop plants will extract from the same soil profile will vary with stage of growth (Robins and Domingo, 1953) and kind of plant. Although the root extraction pattern of maturing plants depends largely on the kind of plant (Hagan and Peterson, 1953), it can be modified by such variables as thickness of stand, soil aeration, soil fertility, dense soil layers and high water table (Corey and Blake, 1953; Hagan, 1950; Kelley, 1954; Painter and Leamer, 1953; and Wadleigh and Fireman, 1948). Any factor that will affect the vigor or condition of a plant may be expected to influence the extraction of moisture from the soil. Kramer (1950) found that wilting of sunflower plants reduced the rate of intake when water was again made available. Injury to plant roots through flooding may reduce water absorption due to plugging of conductive tissues (Kramer, 1951) or reduction of absorptive surfaces.

Crop management practices will affect soil moisture availability to the crop to be harvested. Rock and Lowe (1950) found that available water stored during the summer for fall planted wheat may be conserved for the production of grain by judicious winter pasturing.

Plants vary widely in drought resistance. Guayule and sorghum can be subjected to considerable moisture stress, whereas crops like celery, potatoes and lettuce are very sensitive to drought (Kelley, 1954).

Climatic factors: Gains or losses of available moisture, due to evaporation and condensation, are considered important under certain climatic conditions (Gurr et al., 1952).

Under conditions of high humidity or fog, plants may absorb considerable moisture through leaf surfaces (Breazeale et al., 1950, 1951), and continue to grow though the available moisture supply of the soil is limited. On the other hand, plants wilt on hot, dry windy days, even though some available soil moisture is still present (Bybordi, 1964). This is due to the fact that the moisture flow rate to the root is not sufficient to satisfy the evapo-transpiration rate during such hot days. Likewise, plants often wilt during freezing weather. This has been attributed by Kramer (1949) to damage to plant tissues and by Bethlahmy (1952, quoted by Jamison, 1956) to high moisture stress due to freezing of soil.

The effect of climate on the soil moisture supply is further indicated by the fact that the moisture storage needed to produce a good crop increases with increasing average daily summer temperatures

(Jamison, 1956). Because of increases in the transpiration rate of the plant with increases in air temperature, and hence lowered relative humidity, the water requirements of plants increase. However, some soil moisture tension and conductivity factors will modify this effect.

Soil properties: As water is withdrawn from the soil and the moisture content progressively decreases from field capacity to permanent wilting point, there is a progressive increase in the forces resisting withdrawal. This is referred to as soil moisture suction (Wadleigh, 1946). With the increase in soil moisture suction availability of water is decreased.

The rate of water transmission through the soil to the plant roots limits the water availability (Gardner and Ehlig, 1962). This, in turn, depends upon the hydraulic gradient and the unsaturated conductivity (Staple and Lehane, 1954). A higher conductivity is required for clay than for other types of soils under the same climatic conditions (Gardner and Ehlig, 1962).

The field capacity condition depends upon the depth of wetting. With a greater depth of wetting, the field capacity may be relatively high somewhat behind the wetting front, because the hydraulic gradient is small (Jamison, 1956). On the other hand, if the amount of rainfall or irrigation is small, the depth wetted will be limited. The moisture soon spreads into the dry soil, and the wetting front feathers out. Here, slow drainage conditions of field capacity will be reached, since the moisture conductivity is low at the moisture content in the limited depth zone behind the wetting front.

The observed field capacity will be at a relatively low moisture content.

Colman (1944) showed that soils must be wetted 12 to 30 inches deep, depending upon the soil being studied, before the surface layers have attained a moisture content as high as its field capacity.

Field capacity and permanent wilting point tend to increase as the soil particles become finer (Wilcox, 1940). There is a strong correlation between available moisture and texture of the soil, but very heavy soils contain no higher content of available moisture than do moderately heavy soils with clay contents of about 35 percent.

Wide variations in available water are found to occur with depth, depending upon the texture of the soil (Corey and Blake, 1953). Colman (1944) found that field capacity of a sidehill residual clay loam soil decreased from 25 percent at the surface to 17 percent at a depth of 18 inches and to 15 percent at 60 inches. He attributed this to high organic matter and clay contents in the surface layers which continued decreasing with depth.

Hard pans or areas of high bulk density, relatively close to the surface, may interfere with root penetration and thus affect availability of water in lower depths (Kelley, 1954). Marshall (1959, p. 60) quoted the work of Heinonen (1954) who reported that the amount of available water varied inversely with bulk density in clay soils. Since Veihmeyer and Hendrickson (1946) showed that density increased gradually with depth from 1.38 in the surface soil to 1.83 in the fifth foot depth, available water should decrease accordingly with an increase in the bulk density. The permanent wilting point will increase with an increase in the salt content of the soil (Wadleigh, 1946). Thus, the range of available moisture decreases as the salt content of the soil increases.

Very fine textured soil, or very compact or frozen soil layers will impede moisture movement and affect the available moisture supply in the soil (Diebold, 1954). The moisture conductivity in sandy soils is high at low moisture tensions, but very low at intermediate and high tensions (Gardner and Gardner, 1950). Water will move moderately fast in a medium textured soil at medium tensions, especially if the hydraulic gradient is large. Likewise, the conductivity of very loose soil at high tensions is less than that of moderately compact soil.

The kind of ions present in the soil solution and absorbed on the soil colloids may affect moisture movement and tension relationship by causing dispersion and swelling of the soil colloids, thereby affecting the water availability (Jamison, 1956).

Soil temperature is of consequence because it will affect both the growth vigor of the plant and the soil moisture tension relationships. Richards and Weaver (1944) found that as the temperature was lowered, soils generally retained more water both at 1/3-atmosphere and 15-atmosphere tensions. The difference or the approximate available moisture quantity did not consistently increase or decrease with temperature for the soils studied.

Jamison (1956) concluded that the available moisture supply is not equally available to plants over the range from field capacity to permanent wilting point. The moisture availability and plant growth decreases progressively as the wilting point is approached.

Unsaturated Flow of Soil Water

Saturated soils transmit water primarily through the large pores under the influence of gravity, while in unsaturated soils, capillary forces dominate and the movement is confined to the smaller pores (Linsley _et al_., 1949, p. 289). Since a portion of the voids in unsaturated soils are filled with air, the transport of water takes place in both liquid and the vapor phase. Moreover, gravity is not necessarily the controlling force and the movement of water may take place in any direction.

Gardner and Gardner (1950) pointed out that Darcy's law, in its simple form, "$V = - k \nabla O$ can't be used to describe the movement of water in unsaturated soils. They suggested that the above flow equation needs the addition of an undetermined function, f, which is not a function of the moisture alone. They postulated the possibility of a gradient due to dynamic process. Thus $V = - k f \nabla O$

Where:

k = proportionality having the dimension of time and representing capillary conductivity for unsaturated flows.

∇O = symbol representing force per unit mass that drives the water through soil.

Thus the rate of movement of moisture in an unsaturated soil depends upon two variables, the driving force (the hydraulic gradient) and the unsaturated conductivity or capillary conductivity at the particular soil moisture contents involved (Gardner and Gardner, 1950 and Staple and Lehane, 1954). The conductivity is strongly dependent upon the soil water content and the soil moisture suction, and may decrease by a factor of 10^6 as the soil dries out from saturation to wilting point (Gardner, 1956). Gardner (1965) established an empirical expression to approximate reasonably well the relation between the unsaturated conductivity of many soils and the soil moisture tension:

$$k = \frac{K}{(T/a)^n + 1}$$

where:

k = unsaturated conductivity.

K = saturated or hydraulic conductivity of soil.

T = soil moisture tension.

a = a constant of the order of 10 to 100 millibars.

n = a dimensionless constant which varies from about 2 for a clay soil to as high as 10 or more for a sand.

A rapid rate of flow takes place as long as the conductivity and the potential gradient are large. A slow movement of water results if either or both of these factors are small (Baver, 1956, p. 253).

Movement of water in the soil and from the soil to the plant root continues as long as there exists suction or potential difference, and the movement is from lower to higher suction (Gardner, 1960, Gardner and Ehlig, 1962, and Gardner, 1965). Thus, if the soil water is to be taken up by a plant root it must be in contact with the root at a suction lower than that in the root.

The capillary conductivity depends upon the kind of soil, its state of packing and the moisture content. Moore (1939) showed that the capillary conductivity is a maximum at or near saturation. It then decreases rapidly with moisture content to about the moisture equivalent, where the conductivity is approximately zero, and any further moisture distribution must take place through movement in the vapor phase. Bodman and Colman (1943) confirmed the observations of Moore, except that they found that with certain soils capillary movement does take place at a moisture content below the moisture equivalent. Gardner (1956) found that the capillary conductivity of the Chino soil decreased from 3.0×10^{-3} cm. per day to 6.8×10^{-10} cm. per day with an increase in suction from 0.3 bars to 0.5 bars. He, thus, concluded that capillary conductivity decreases extremely rapidly with increasing suction and the rate of decrease was approximately inversely proportional to from the square to the cube of the suction.

The texture and structure of the soil affects capillary conductivity by influencing the number, size and continuity of the pores. Moore (1939) gave the following increasing order to different textured soils with regard to capillary conductivity at a 0.1 atmosphere tension:

Sand $<$ fine sandy loam $<$ light clay $<$ clay. He explained, on the basis of these results, that water films in sands become discontinuous at much lower tension or moisture content than in clays, since clays possess a large number of small pores in contrast with a smaller number of large pores in sands.

Gardner (1920) showed the effect of packing on conductivity with the Greenville soil. Both loosely and extremely closely packed samples exhibited the lowest conductivity, i.e. 1.8×10^{-3} cm. per day and 5.4×10^{-3} cm. per day, respectively. Field soil in natural structure showed capillary conductivity of 8.7×10^{-3}. He explained that in the case of loosely packed soil, the pores are apparently too large to permit establishment of a continuous moisture film. In closely packed soil, the pores are so small that there is considerable resistance to flow. So these two factors result in low capillary conductivities.

The rate of water transmittance through the soil to the plant root plays a major role in determining the water availability range. The concept of available water and movement can't be completely separated. There is an obvious association between the availability of water and maintenance of flux (Penman, 1956). Soil moisture flow rate affects both the upper and the lower limits of water extraction by plants (Jamison, 1956). The transpiration data at various suctions was found consistent with conductivity values by Gardner and Ehlig (1962). Thus, they supported the idea that the rate of water transmission through the soil to plant roots limits the water availability. Therefore, the concept of water availability must be used upon an understanding of water movement in the soil and in the plant.

Techniques Used for Unsaturated Permeability Determination

Considering its importance to agriculture, it is perhaps surprising that comparatively few experimental data are available on moisture movement in unsaturated soils.

Gardner and co-workers (1920, 1921, 1950) were the pioneers in this field, both experimentally and theoretically. They showed how conductivity coefficients could be obtained, and found that conductivity increased with soil packing up to a maximum, then it decreased.

The conductivity of unsaturated soil may be measured by two types of techniques, steady-state and unsteady-state (Klute, 1965). The steady-state method involves the establishment of a flow system in which the water content, tension, and flux remain unchanged with time. In the unsteady-state method, the quantities vary with time.

Marshall (1959, p. 31) quoted the work of Richards (1931) who measured conductivity by applying known suctions at the ends of the small test column through suction plates, and measuring potential gradient by means of tensiometers. Richards and Moore (1952) used gas pressure instead of suction to control the unsaturation of the column.

Using a different method, Moore (1939) measured potential gradient in large soil columns through which water was passing and evaporating at one end. Childs and Collis-George (1950) measured the permeability of unsaturated materials packed in a column three meters long and of adjustible inclination. This column was long enough to provide a zone of uniform water content and suction in which potential gradient was known from the inclination of the column. Thus, they developed a method whereby conductivities could be calculated from the moisture characteristics or release curves of porous media.

In all these methods the attempt was made to reach steady-state conditions in which the inflow rate was equal to the outflow rate. It was possible to measure unsaturated permeability while the soil was in the process of wetting and drying, provided that data for potential gradient and flow velocity could be obtained with sufficient reliability under these conditions. Richards and Weeks (1953) adopted this approach using a column of wet soil, from which water was continuously withdrawn under suction. Similarly, Richards et al. (1956) measured the suction and water content at various depths and times while water was evaporating from a deeply irrigated soil. Thus, they determined unsaturated permeability in the field. Ogata and Richards (1957) were able to reproduce these results when the same soil was protected against evaporation and water moved downward after irrigation instead of upward. The two sets of results were also found to agree rather well with those obtained on the same soil by Richards and Moore (1952) in the laboratory under steady state conditions. However, this particular comparison was not as critical as the other because a packed column of fragmented soil was used in the laboratory and this may had been of different structure from soil in the field.

Staple and Lehane (1954) worked on the permeability of soil by following the movement of water from moist to dry soil. They inferred the suction from the measured water content at different times and depths in their columns using a drying curve for the relation between water content and suction. Since wetting conditions were also represented in their experiment, their results were not free from the effect of hysteresis. Moreover, vapor transfer to dry soil could be appreciable in their short columns. These effects limited the accuracy of their permeability data, especially at the dry end of their range of values. But despite these limitations, the authors (Staple and Lehane, 1954) believe that the data presented and the methods used are applicable to many problems of moisture movement in cultivated soils.

Gardner (1956) also measured permeability in relatively dry soil. He did this in the pressure plate and pressure membrane apparatus from data obtained on the progressive loss of water from the soil under each of a number of small increments of gas pressure.

Klute (1952) demonstrated a numerical method for calculating the change in soil moisture profiles from conductivity data. Later, he (1965, pp. 255-258) developed an apparatus and technique, making use of the ideas of many other scientists who had been working in this line, which could be used to determine unsaturated conductivity.

This special apparatus consisted of two porous plates in between which the soil sample was placed. Water was maintained at constant hydraulic heads at the top of the upper and below the lower porous plate. The soil sample was subjected to a controlled gas-phase pressure. Since hydrualic head on the top porous plate was greater than one below the lower porous plate, the flow was maintained in a downward direction.

Soil Water Availability to Plants and Meteorological Conditions

The potential transpiration rate or the water use by crops is primarily determined by weather factors (Denmead and Shaw, 1962). As previously pointed out, (Gardner and Ehlig, 1962) water moves through the soil to the plant root and from the root to transpiring leaves along pressure gradients, gradient of suction (negative pressure) in the soil and gradient of diffusion pressure deficit (DPD) in the plant. Since water moves from lower to higher suction, the DPD in the plant must always be higher than the soil suction in order for soil water to be taken up by a plant root. Gardner (1960) showed that the suction gradient between root and soil necessary to maintain a given rate of uptake by the root, is proportional to the potential transpiration rate and inversely proportional to the capillary conductivity of the soil.

Penman (1963, pp. 46-50) showed that the potential transpiration rate must not exceed the rate of water absorption by the plants from the soil if full leaf turgor and maximum growth rate are to be maintained. Otherwise, wilting occurs accompanied by a reduction in the rate of photosynthesis and closing of stomata.

Under high potential tranpiration conditions the actual transpiration rate decreases with decreasing soil moisture content. The particular soil moisture content at which this decline in transpiration occurs also depends upon the soil properties (Denmead and Shaw, 1962). In soils, in which most of the water is held at low suction, the decline is not evident until most of the available soil water has been extracted. In soils, on the other hand, in which suction increases rapidly as soil moisture content decreases, the decline in transpiration is noticeable at comparatively high soil moisture contents. Consequently, plant under high potential transpiration conditions may show signs of water shortage by closing of stomata, even at low soil moisture tensions. This is due to an inadequate soil moisture flow to the roots. In such areas of high potential transpiration rate and low capillary conductivity more frequent irrigations may be necessary for maximum crop growth, depending upon the economic costs of the crops grown (Fuehring et al., 1966).

From the foregoing it was concluded that the growth of plants depends on the quantity of water in the soil, the tension with which it is held, the potential rate of evapo-transpiration and the rate of movement of soil water to plant root surfaces. Therefore any investigation of the water supplying relationships of soils must take all of these factors into consideration.

III. MATERIALS AND METHODS

In order to study the available moisture of soil in the Beqa'a Plain, four sites were selected at the Agricultural research and Education Center of the American University of Beirut. The plots were irrigated and covered with a layer of wheat straw to prevent evaporation loss from their surface. Two days after irrigation, a pit was dug to expose the whole profile up to 100 cm. depth. Soil samples were taken from 12.5, 25, 50, 75 and 100 cm. depth. Percent moisture was determined in these samples to estimate the upper limit of available water (Colman, 1947; Peters, 1965, pp. 281-282).

Moisture equivalent and permanent wilting point were estimated in the laboratory by the methods described by Richards and Weaver (1943).

Soil clods were collected from each depth in order to determine the volume weight of each layer (Russell and Balcerek, 1944). Texture analysis of the various depths was run by the Bouyoucos hydrometer method (Bouyoucos, 1936).

Capillary conductivity measurements were made, following the technique of Staple and Lehane (1954), on soil taken from profile No. 2. This soil had moisture contents of 29.6 percent and 19.3 percent at one-third and 15-atmosphere tension respectively, and volume weight of 1.38. The air dry soil samples were packed into 18.5 cm. tall metallic cylinders. These cylinders were built up of rings, 8.26 cm. in diameter and 1.5 cm. high, fixed together rigidly in place, by means of masking tape during the initial filling. Then for sampling, these rings were readily separated by means of a diaphragm to cut the soil into 1.5 cm. sections. Eight cylinders were prepared in order to have duplicate results for four sampling intervals.

The cylinders were filled as uniformly as possible, as described by Fireman (1944), and the final bulk density in each cylinder was approximately 1.22. After adding 19 mm. of water, the top of each cylinder was sealed to prevent evaporation. The cylinders were kept in a basement room at a temperature of about 23.9°C.

Typical moisture profiles, obtained by sampling the soil at intervals of 1 hour, 24 hours, 4 days and 12 days are shown in Figure 5. The area bounded by any pair of curves above a chosen level represents the amount of moisture that passed through that level in the time interval represented by the bounding curves. Thus, by considering the area above successive levels throughout the profile, and knowing the bulk density of the soil, the moisture movement at different moisture contents was calculated. This movement was converted to capillary conductivity by dividing the moisture moving past each level, by the pressure gradient at that depth.

In order to convert moisture gradients to pressure gradients, the capillary tensions of the soils at different moisture contents were obtained by using Richard's pressure membrane method (1949).

The saturated conductivity of the soil was determined by a constant head permeameter (Fireman, 1944).

IV. RESULTS AND DISCUSSION

Available Soil Moisture

Soil moisture constants were determined by various methods to calculate the available moisture capacity of the four soil profiles. The bulk density of each layer was determined in order to express the available water as millimeters of water per meter depth of soil.

In general, the surface layers contained, comparatively, more available water than the subsurface layers (Table 1). In contrast, the bulk density was low at the top, but increased with depth. The soil of profile 4 had low bulk density values associated with high amounts of available water as compared to the bulk densities of the soil of profile 1 which were high and accompanied by lesser amounts of available water (Table 1). This indicated that available water varied inversely with the bulk density (Figure 1). These results agree with those obtained by Heinonen (1954, quoted by Marshall, 1959, p. 60). He found that when the bulk density was 0.73 grams per cm^3., the available water was 23.3 percent by volume, but as the bulk density increased to 1.26 grams per cm^3., the available water was decreased to 14.9 percent by volume.

The bulk density of cultivated surface soils tends to be less than for the accompanying subsoils because cultivating and cropping practices tend to increase porosity (Dawson, 1961, p. 30).

Table 1. Available moisture per unit depth of soil.

Depth	Field capacity dry weight basis	Permanent wilting dry weight basis	Bulk density	Available moisture
cm.	percent	percent	gm. per cm^3	mm. per meter
Profile 1				
12.5	26.05	17.74	1.29	94.16
25.0	26.33	18.92	1.27	82.50
50.0	24.45	18.58	1.52	78.33
75.0	23.59	18.22	1.55	73.33
100.0	22.90	17.71	1.56	70.83
Mean	24.66	18.23	1.44	79.83
Profile 2				
12.5	26.81	17.52	1.23	98.33
25.0	27.00	18.84	1.43	99.16
50.0	24.36	18.05	1.48	80.83
75.0	24.01	17.99	1.54	79.16
100.0	23.53	17.10	1.56	80.00
Mean	25.14	17.90	1.46	87.50
Profile 3				
12.5	29.41	19.61	1.31	115.00
25.0	28.83	19.77	1.34	108.33
50.0	26.56	19.53	1.43	90.00
75.0	25.07	19.65	1.45	70.00
100.0	---	---	---	---
Mean	27.47	19.64	1.38	95.83
Profile 4				
12.5	32.25	20.46	1.14	120.83
25.0	29.80	20.93	1.30	103.33
50.0	29.10	20.65	1.40	105.83
75.0	29.50	22.01	1.41	95.00
100.0	30.50	23.40	1.43	90.00
Mean	30.23	21.49	1.33	103.16

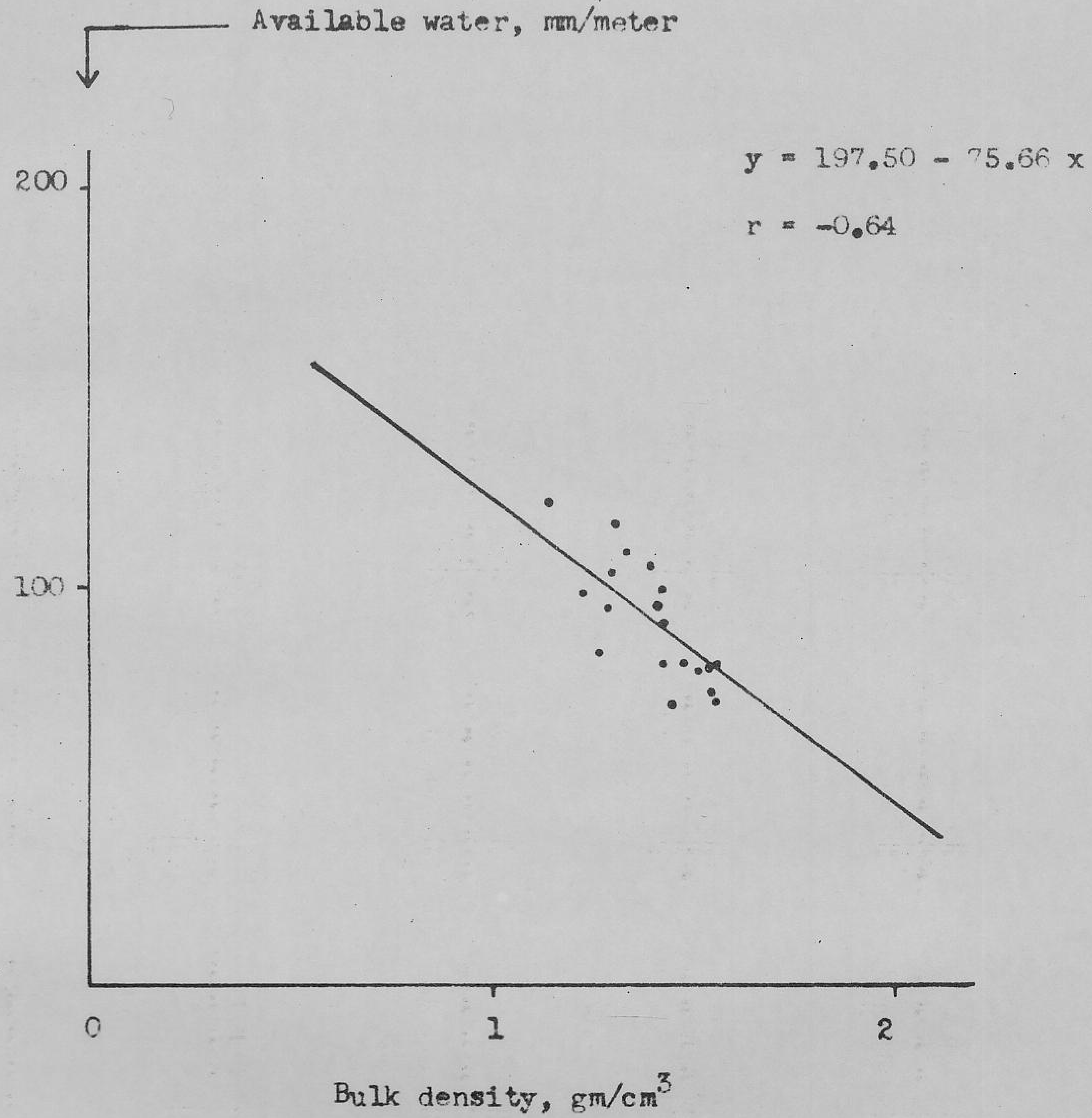

Figure 1. Relation between bulk density and available water for various depths of four soil profiles.

Also, the surface soils tend to be higher in organic matter content which may tend to result in lesser bulk densities. Very compact subsoils, regardless of the texture, may have high bulk densities. The soils under study also showed lower bulk densities in the surface layers. The increased bulk densities with depth, were supposedly due to compaction of the soil. These results agreed with Nelson and Muckenhirn (1941), who found that the bulk densities were low in the plow layer in four soils and increased with depth.

There was a close correlation (r = + 0.91) between the PWP and the 15-bar percentage for various depths in the four soil profiles (Figure 2). The equation for the relationship (Figure 2) showed the 15-bar about the same at the lower end of scale (18 percent), but tended to overestimate PWP by about 0.5 percent (22.5 instead of 22) at the upper end. The correlation between field capacity and moisture equivalent (r = + 0.89) was close (Figure 3), but the moisture equivalent was higher (2 to 15 percent) in all cases than the field capacity. Moisture equivalent overestimated field capacity by about 3.4 percent (26.3 instead of 22.9) at the lower end and by about 2 percent (33 instead of 31) at the higher end. The results of moisture equivalent determination were much more variable at the higher end of the scale, so were less reliable as an indication of field capacity. These results (Figures 2 and 3) are in good agreement with those obtained by Richards and Weaver (1943, 1944) and Mathews (1923, quoted by Veihmeyer and Hendrickson, 1931). Richards and Weaver

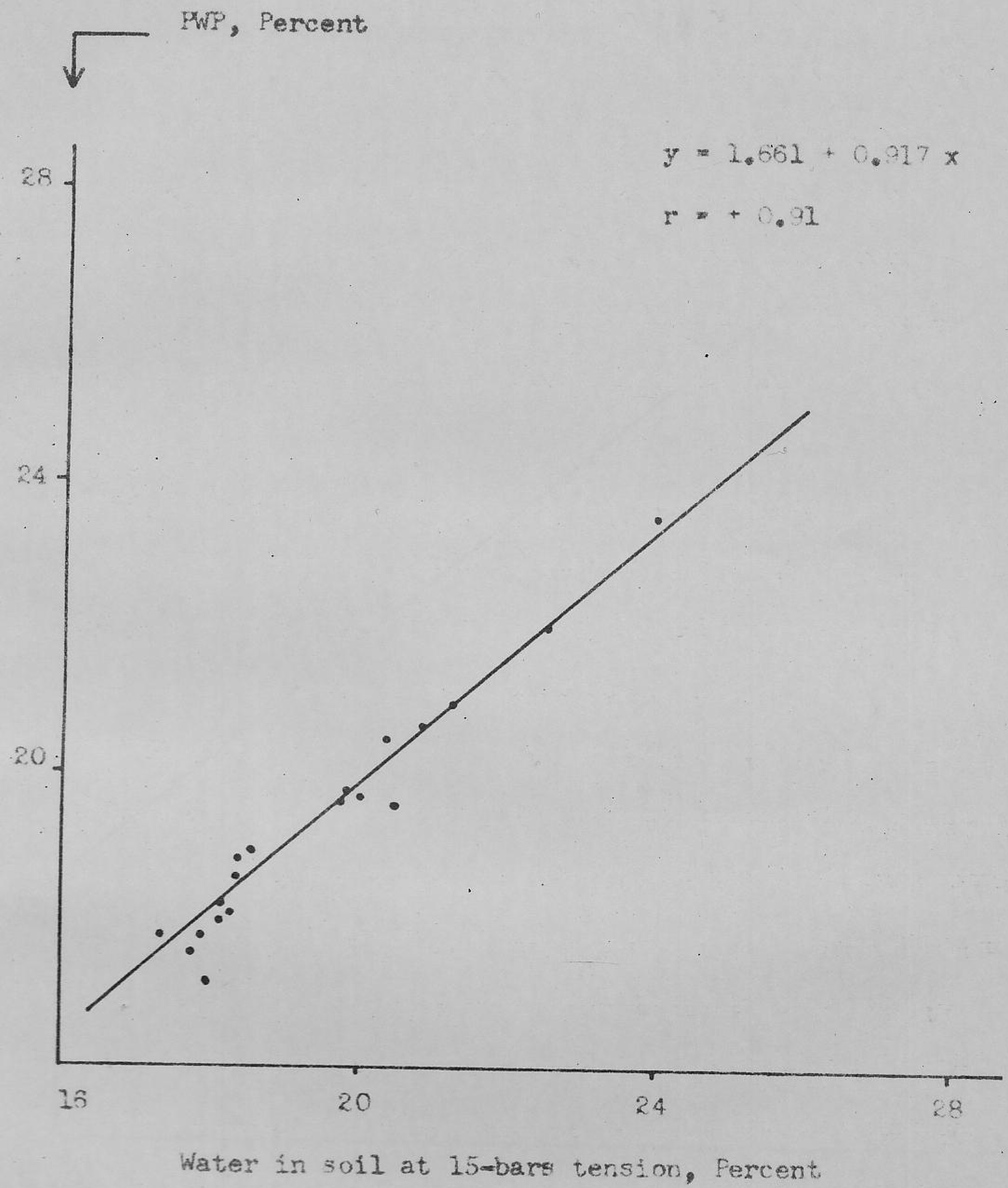

Figure 2. Relation between PWP and 15-bars percentage for various depths of four soil profiles.

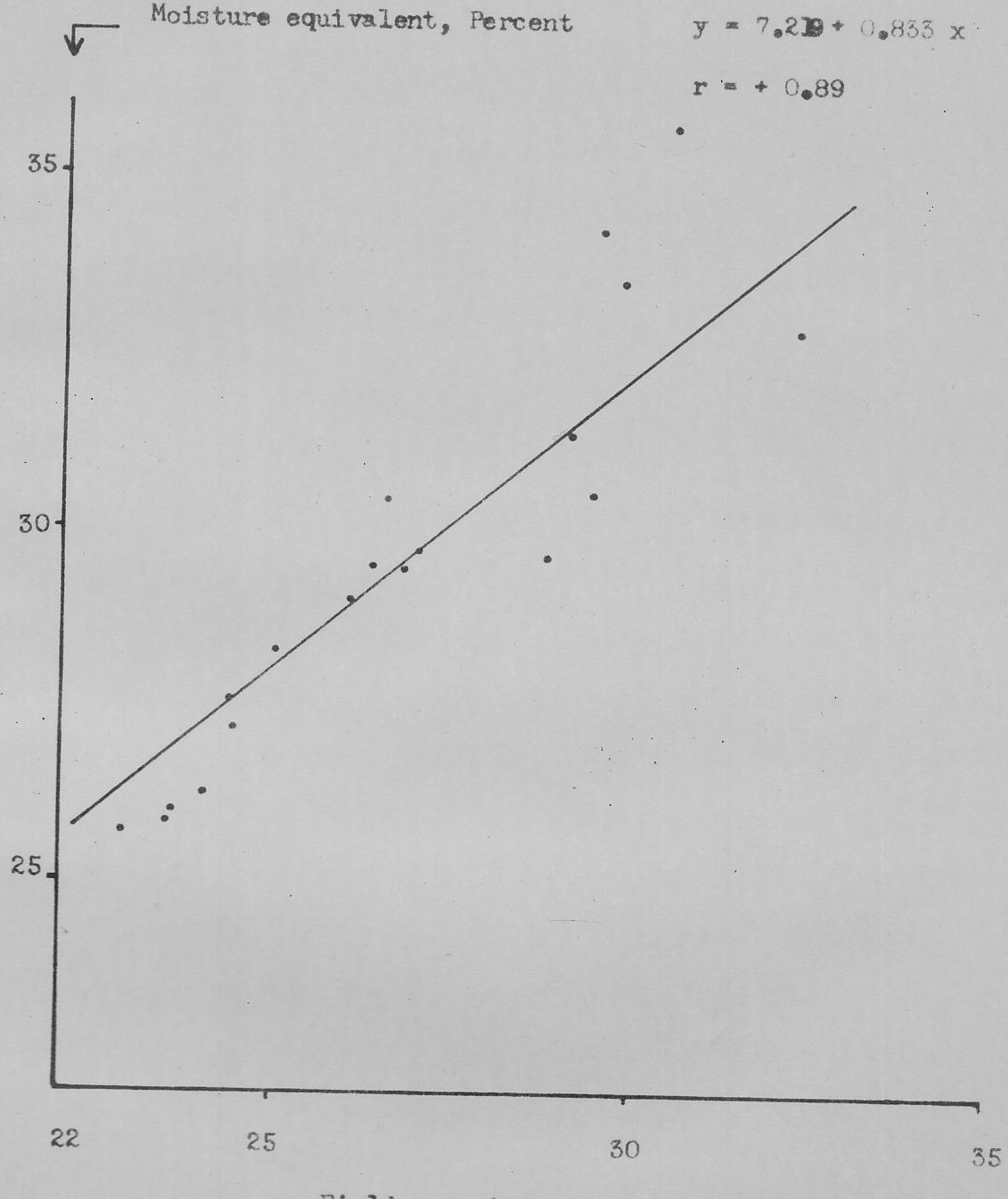

Figure 3. Relation between the field capacity and the moisture equivalent for various depths of four soil profiles.

(1943, 1944) found that the wilting percentage for a number of Western United States soils was near or slightly higher than the 15-bar percentage. Mathews (1923) concluded that field capacity was a little lower than moisture equivalent, but bore a linear relation to it.

The comparison of the data (Tables 2 and 3) showed the effect of texture on both the field capacity and PWP. Soil profile 4 had the highest clay contents in the surface as well as in the lower layers, so the field capacity and PWP values were comparatively higher than those of the other soil profiles. However, available water did not increase appreciably with the increase in clay content, since both field capacity and PWP increased with clay content. This confirmed the findings of Wilcox (1949) who found field capacity and PWP to increase with clay content, and as such no appreciable increase in the available water.

Marshall (1959, p. 60) quoted the data of Heinonen (1954) who found that as the bulk density of the soil increased from 1.01 to 1.26, the field capacity decreased from 41.5 percent to 25.9 percent by volume. Also, in this study, the bulk density increased with depth in the four soil profiles (Table 1) and the field capacity decreased. Thus, these results showed a very good agreement with those of Heinonen (1954, quoted by Marshall, 1959, p. 60).

The available soil moisture ranged from about 80 to 103, with an average of 91.5 mm. per meter. The average potential evapotranspiration, for July and August as calculated from a modified Penman equation, was found to be 6 to 7 mm. per day (Fuehring *et al.*,

Table 2. Soil separates as determined by the Bouyoucos Hydrometer method[+].

Depth	Clay	Silt	Sand
cm.	percent	percent	percent
Profile 1			
12.5	54.2	36.9	8.9
25.0	62.2	27.7	10.6
50.0	60.6	28.9	10.5
75.0	58.6	31.4	10.0
100.0	55.6	31.4	13.0
Profile 2			
12.5	54.2	35.8	10.0
25.0	62.2	28.0	9.0
50.0	61.6	28.4	10.0
75.0	59.6	29.4	11.0
100.0	57.6	29.4	13.0
Profile 3			
12.5	58.0	23.0	19.0
25.0	60.0	19.0	21.0
50.0	62.0	20.0	18.0
75.0	60.0	23.0	17.0
100.0	---	---	---
Profile 4			
12.5	60.4	28.4	11.2
25.0	62.6	28.2	9.2
50.0	61.8	25.0	13.2
75.0	67.4	24.4	8.7
100.0	69.2	23.6	7.2

[+] Texture of all the soil profiles was clay.

Table 3. Comparison of the soil moisture constants (dry weight basis) for the four soil profiles.

Depth	Field capacity	Moisture equivalent	PWP	15-bars
cm.	percent	percent	percent	percent
Profile 1				
12.5	26.05	29.01	17.74	17.95
25.0	26.33	29.45	18.92	18.55
50.0	24.45	27.13	18.58	18.34
75.0	23.59	26.00	18.22	18.15
100.0	22.90	25.72	17.71	17.36
Profile 2				
12.5	26.81	29.44	17.52	17.73
25.0	27.00	29.70	18.84	18.39
50.0	24.36	27.56	18.05	18.26
75.0	24.01	26.24	17.99	18.16
100.0	23.53	25.86	17.10	17.97
Profile 3				
12.5	29.41	30.53	19.61	19.70
25.0	28.83	29.62	19.77	19.82
50.0	26.56	30.40	19.53	20.46
75.0	25.07	28.33	19.65	20.01
100.0	---	---	---	---
Profile 4				
12.5	32.25	32.80	20.46	20.33
25.0	29.80	33.50	20.93	21.24
50.0	29.10	31.35	20.65	20.82
75.0	29.50	34.24	22.01	22.50
100.0	30.50	35.71	23.40	23.91

1966). According to the data of this experiment, the actual readily available water at less than 2 bar tension in the upper 3 feet of soil was only about 40 mm. which was enough only for about 6 days at an evapo-transpiration rate of 7 mm. per day. From this work and the work of Fuehring et al. (1966) it was concluded that weekly irrigation was about the maximum interval and, for high value crops, the interval should be even less, because of some reduction in growth below the 2-bar soil moisture tension level.

Soil Capillary Conductivity

The soil for capillary conductivity determination was taken from profile 2 to a depth of 50 cm. A soil moisture sorption curve was obtained for this soil (Figure 4). A straight line fitted very closely when the soil moisture content was plotted versus the logarithm of soil moisture tension. This curve depicted that almost half of the available moisture was held at tensions greater than 2 bars. Assuming water extraction by the plants beyond 2 bars becomes difficult at higher rates of transpiration (Fuehring et al, 1966), this indicated a rather low range of readily available water.

Typical moisture profiles (Figure 5), obtained by adding 19 mm. of water and sampling the soil at 4 intervals of time, were used to calculate the soil capillary conductivity. Moisture profile "D" (Figure 5) showed that the surface soil was far below the assumed field capacity 12 days after the addition of water. It is

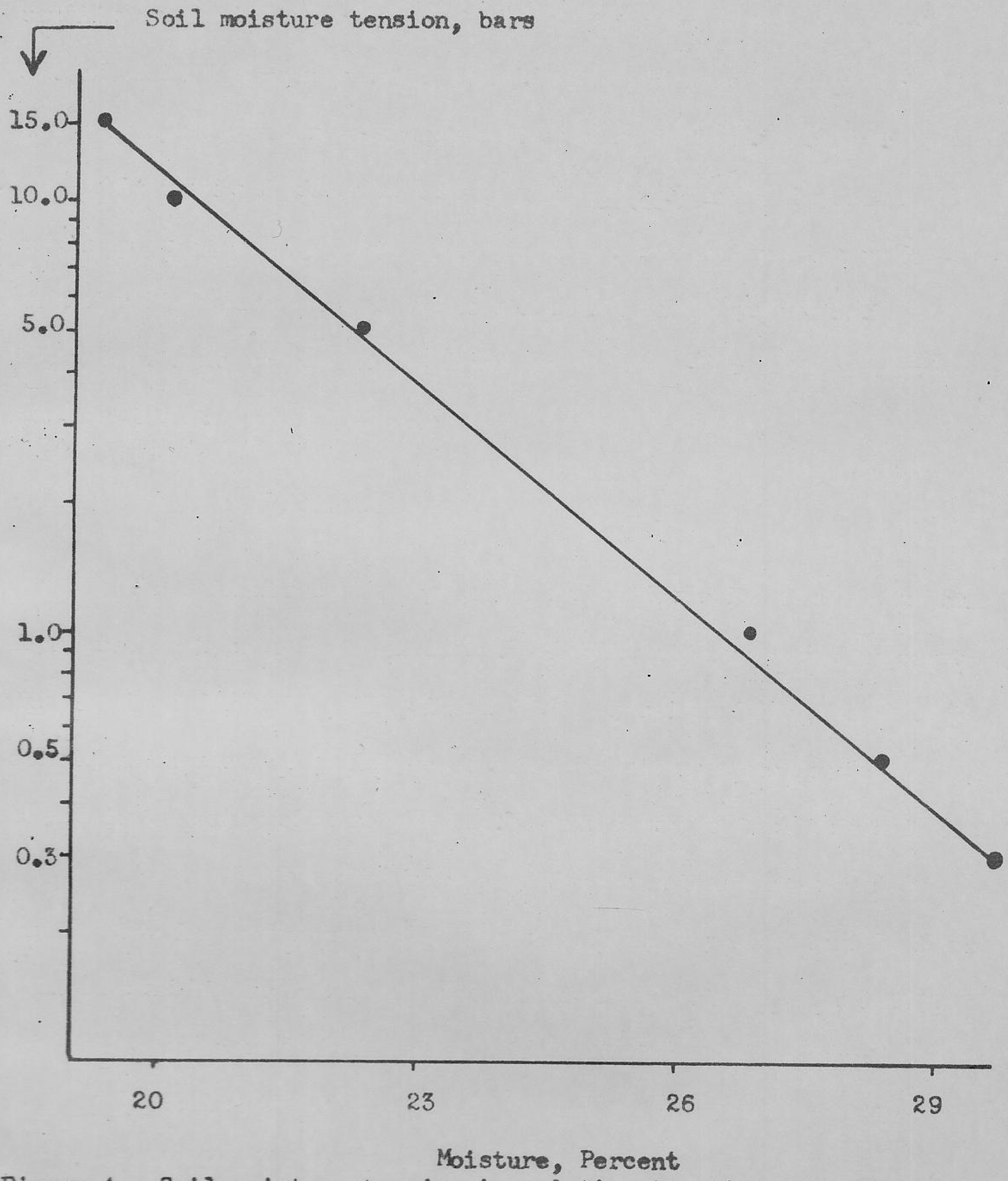

Figure 4. Soil moisture tension in relation to moisture content.

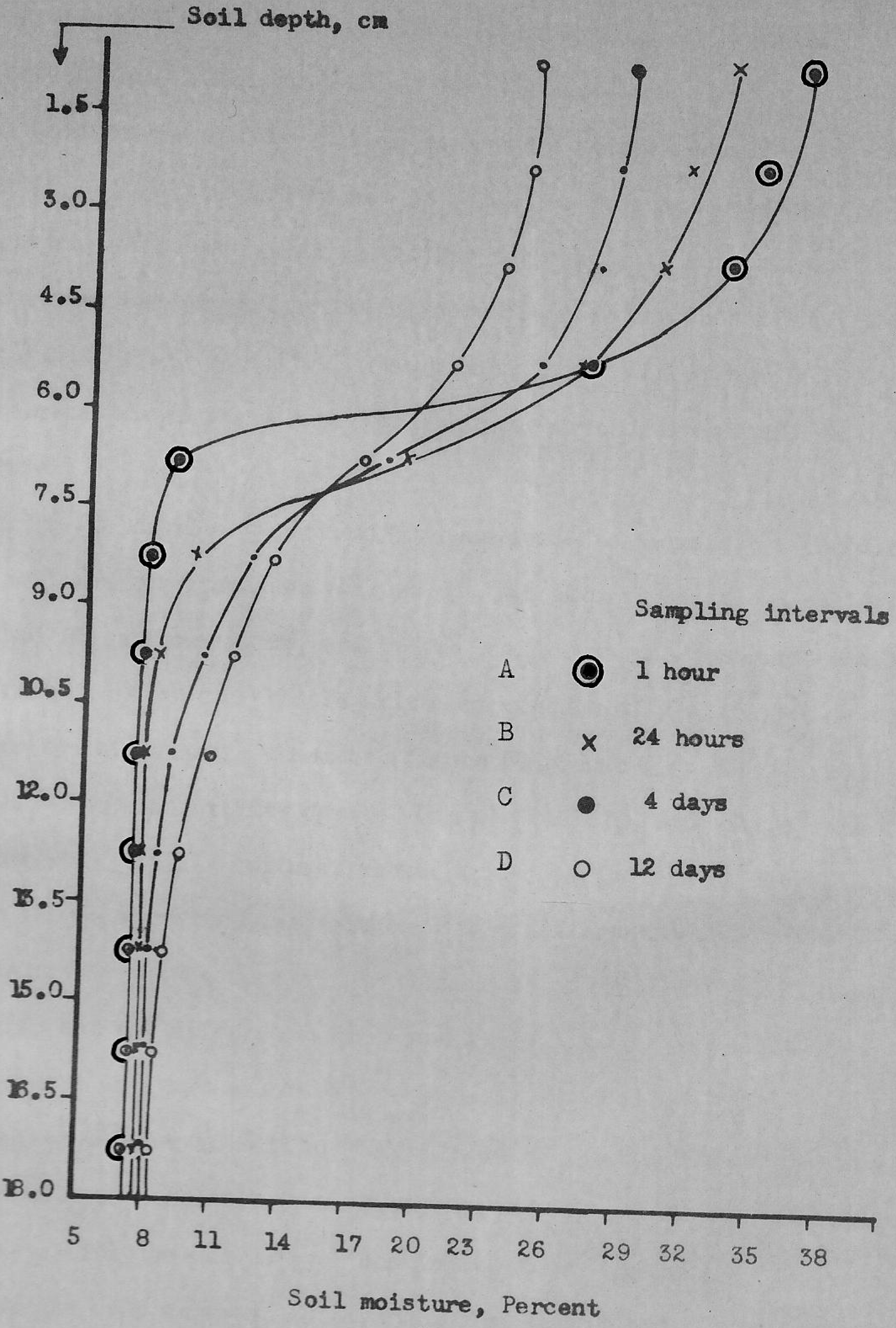

Figure 5. Moisture profiles at various sampling intervals.

probable that the soil had not obtained a true equilibrium condition. This might be attributed to insufficient depth of water (19 mm.) added, as well as the short columns (18.5 cm.) used in the experiment. The surface soil can attain an equilibrium condition when the soil is wetted to 0.3 to 0.75 meters depth according to Colman (1944). Further work needs to be done with longer columns of soil to determine whether or not these soils have a definite field capacity. Also, longer intervals of time for determination of field capacity under field conditions would be helpful.

The capillary conductivity was found to be mainly a function of soil moisture tensions (Figure 6). At saturation the conductivity had its maximum value, and became smaller as the moisture tensions increased. A plot of the logarithm of conductivity against the logarithm of moisture tensions (Figure 6) produced an "S" shaped curve. The conductivity data of Gardner (1956), found for a soil of somewhat similar texture, showed a similar pattern of decrease with increase in tensions, although to a different degree. The conductivity values were higher than those of Gardner (1956) below 2 bars, but the difference decreased above 2 bars. The variation in the two data was probably due to following different experimental techniques as well as to differences between the soils. The rapid drop in conductivity at less than about 1.5 bars in both soils might possibly be due to poor continuity of soil moisture films. The second drop at about 10 bars might be attributed to the dominance

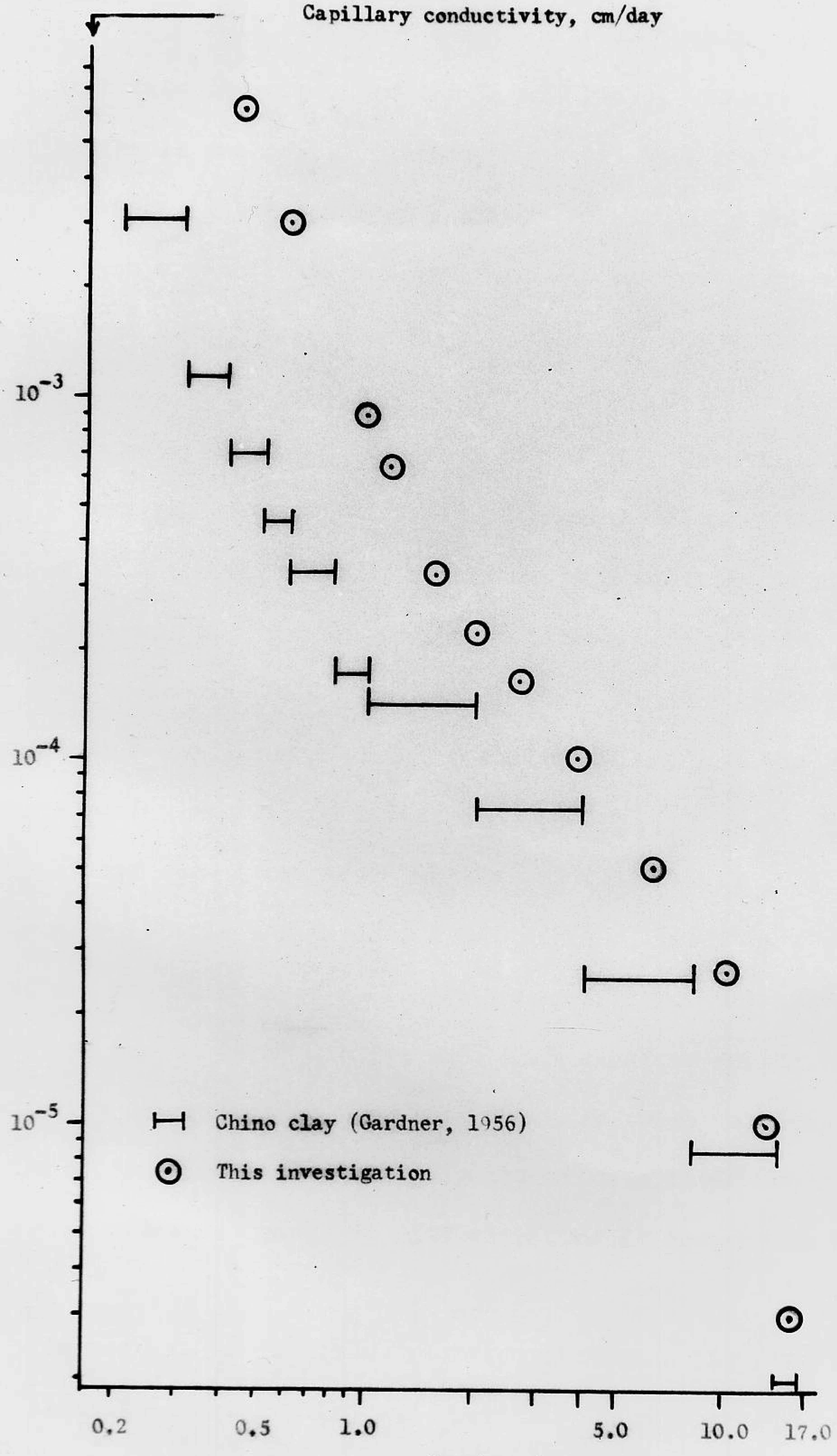

Figure 6. Capillary conductivity of soil as a function of soil moisture tension.

of water transport in the vapor phase which is much slower in amount than water transport in the liquid phase. However, further investigation is needed for clarification of these points.

Gardner (1956) reported a linear relationship for several soils between conductivity and moisture percent by volume at moisture tensions less than 1 bar, when the logarithm of conductivity was plotted against the logarithm of moisture percent by volume. The plot of the data (Figure 7) for the soil of this investigation also showed a straight line relationship up to soil moisture content by volume of 31.1 percent which corresponds to a moisture tension of about 1.5 bars. However, at greater soil moisture tensions the curve departed considerably from linearity. Since Gardner (1956) plotted only a small range of water content values, it was difficult to make a comparison beyond 1 bar.

It has been shown that temperature (Gurr _et_ _al_., 1952) and bulk density (Staple and Lehane, 1954; Gardner, 1920) have considerable effect on the rate of capillary conductivity. Therefore, temperature and state of packing were held constant during the conductivity determination. However, because these conditions vary from field conditions, the data only approximate field conductivity rates. The relative change in rate with time is assumed to be similar.

Denmead and Shaw (1962) reported that when the rate of potential evapo-transpiration was above 6 or 7 mm. per day (soil suction greater than 0.3 bars), there occurred a break in the evapo-

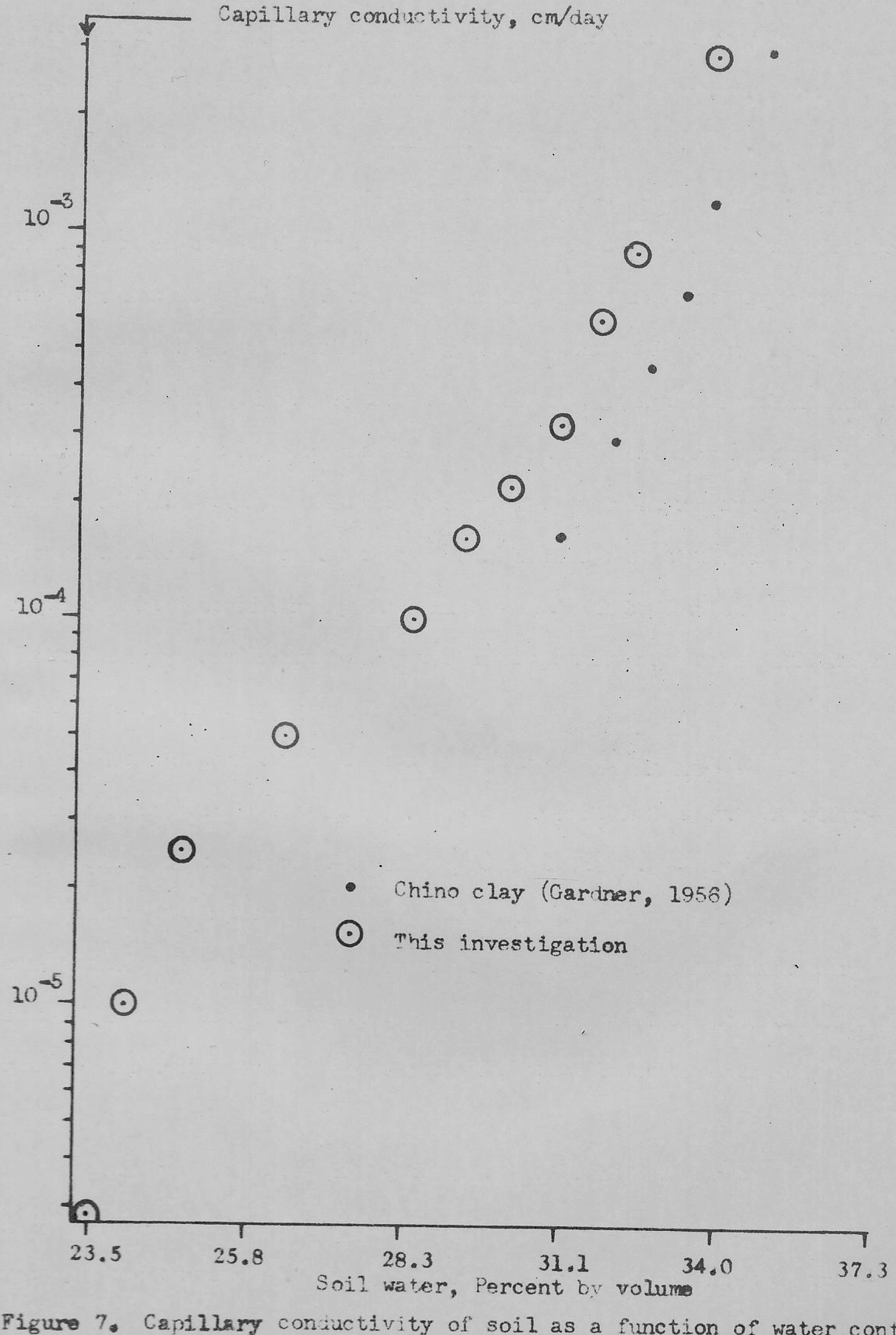

Figure 7. Capillary conductivity of soil as a function of water content

transpiration rate of corn, since the water movement to the root was insufficient to meet the plant water requirements. Gardner and Ehlig (1962) in a pot experiment found a break in evapo-transpiration when the capillary conductivity decreased to a value of 4 x 10^{-5} cm. per day (soil suction, 9 bars). This conductivity was declared to be too slow to meet evapo-transpiration of 8 mm. per day. In the field, the stomatal data of Fuehring et al. (1966) indicated that probably there was no definite break in the evapo-transpiration rate, but a gradual change over a range of combinations. Partial stomatal closure was observed under field conditions on soil similar to the soil of this experiment by Fuehring et al. (1966) when only 16 to 20 percent of the total available moisture had been consumed. At this moisture content, the laboratory capillary conductivity of the soil studied in this experiment was about 2.0 x 10^{-3} cm. per day (Figure 6). However, plants in the field are drawing water over a range of soil moisture tensions, capillary conductivity rates, and distances between root surfaces.

It was concluded that the soil under investigation does not differ greatly in water conductivity rates as compared to other soils with clay texture. As compared to the soils worked with by Gardner (1956), this soil showed good conductivity at low moisture tensions and about the same at high tensions. Since the conductivity is not out of line, the evidence of inadequate soil moisture supply for maximum plant growth, found by Fuehring et al. (1966), is assumed to be due, predominantly, to the small reservoir of soil water held at low enough tensions to meet the high evapo-transpiration demand.

Saturated Soil Permeability

Saturated permeability (Figure 8) was determined by means of a constant head permeameter (Fireman, 1946). The initial decrease in permeability was attributed to dispersion and swelling of soil particles after wetting. The subsequent increase accompanied elimination of entrapped air by solution in passing water. The final gradual decrease resulted from microbial growth clogging the soil pores (Allison 1947).

Smith and Browning (1946) classified saturated soil permeabilities basing their standard on the rate when the soils were just saturated. They reported that a saturated permeability of 0.1 to 1.0 inch per hour was an adequate permeability. Above and below this class was rapid and slow permeability, respectively. According to this standard (Smith and Browning, 1946) the soil under study, had adequate saturated permeability (0.47 inches per hour). This is further evidence that the water conductivity of these soils is not out of line with soils of similar texture.

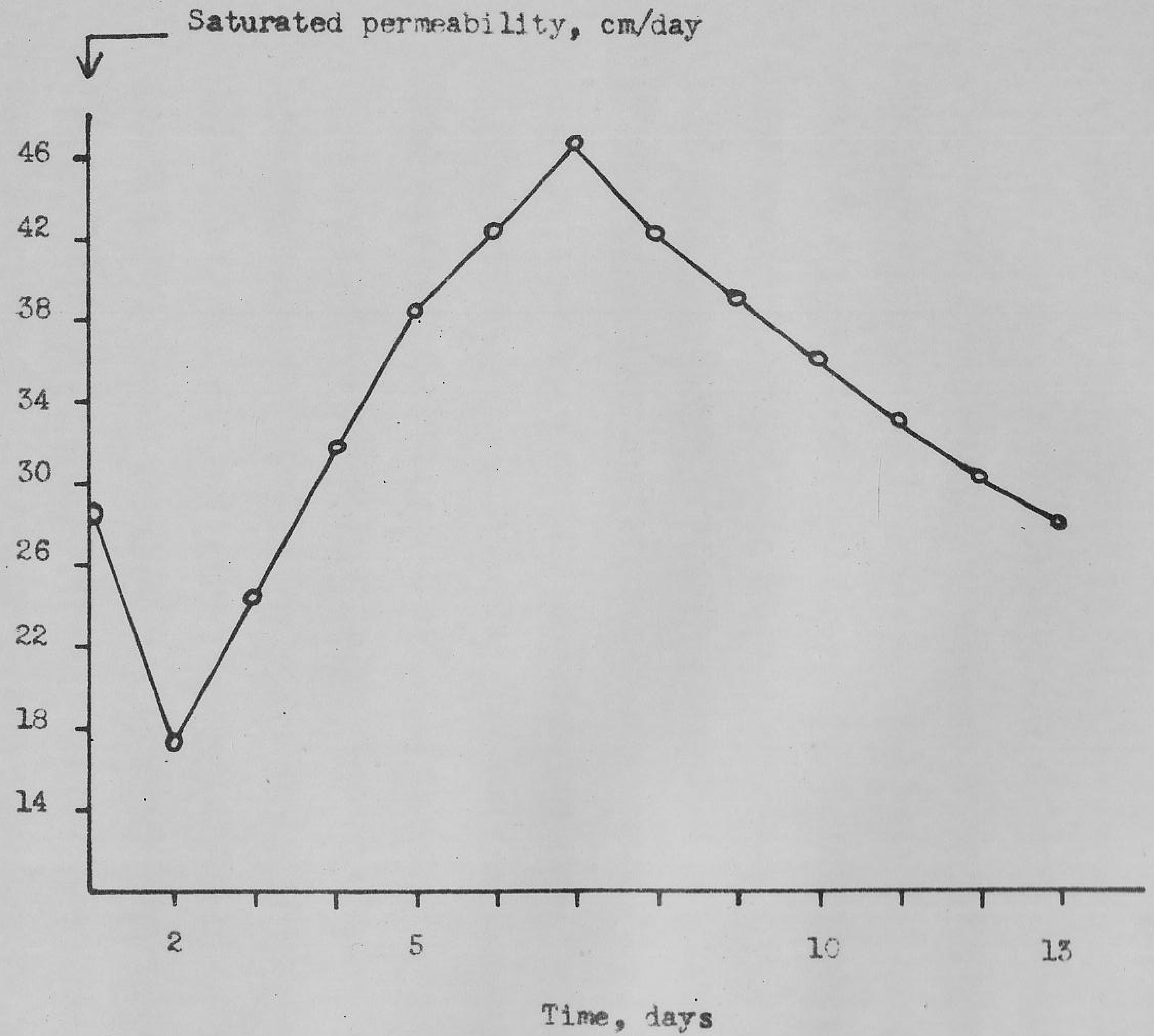

Figure 8. Saturated permeability of soil with time.

V. SUMMARY AND CONCLUSIONS

The yields of the various crops in the Beqa'a Plain, Lebanon have been reported to be reduced considerably when the irrigation interval exceeds one week (Fuehring et al., 1966). Plants start showing signs of water stress (by partial closure of stomata) 2 or 3 days after irrigation, when the evapo-transpiration is relatively high (6 or 7 mm. per day), indicating inadequate water supplying power of the soil. The purpose of this investigation was to study the reasons for these observations.

The available soil moisture capacities and the relationship to capillary conductivities were studied on typical soils of the Beqa'a Plain in Lebanon. Bulk density and textural analyses were also made to find their effect on the moisture holding characteristics of the soil.

Increasing bulk densities affected the available moisture negatively ($r = -0.64$). The surface soils had low bulk densities associated with relatively high amounts of available water as compared with subsurface soils. The amounts of water held at both field capacity and PWP increased with clay content. However, the available moisture range did not increase with the fineness of the texture.

There was a close correlation between the field capacity and moisture equivalent values ($r = +0.89$), and between the 15-bar and

PWP values ($r = +0.91$). Moisture equivalent overestimated field capacity by about 3.4 percent at the lower end of the range, and by about 2 percent at the higher end. The 15-bar (Figure 2) was about right at the lower end of the scale (18 percent), but tended to overestimate PWP by about 0.5 percent (22.5 instead of 22.0) at the higher end.

The available soil moisture ranged from 80 to 103 with an average of 91.5 mm. per meter. Almost half of the available water was held at tensions greater than 2 bars, and plants can not extract water easily from the soil even at considerably lower soil moisture tensions when transpiration rates are high. This indicated a rather low range of readily available water.

The soil had good water conductivity at low tensions and about the same at higher tensions as compared to the literature values of comparable soils. The "S" shaped curve for conductivity data of this soil compared well with that of Gardner (1956), who found a similar relationship when the logarithm of conductivity was plotted against the logarithm of soil moisture tension. The linear relationship of the logarithm of conductivity with the logarithm of water content by volume agreed with his (Gardner, 1956) data at moisture tensions less than 1 bar. Gardner (1956) did not give the results for greater moisture tensions, but the data of this study indicated considerable departure from linearity in this region.

Since the soil water conductivity is not out of line, it was concluded that the inability of the soil to maintain full plant turgor, after 2 or 3 days from irrigation is probably due to small soil reservoir of water at low enough tensions to meet the relatively high evapo-transpiration rates of the area.

It appears from this and other studies in the area that for maximum plant growth, the irrigation interval used in the area must be relatively short and the irrigation systems used should be set up with this in mind. Since increasing frequency of applying water tends to increase costs, the balance between the value of the crops raised in relation to the cost of applied water, must be carefully worked out. It appears that one week should be about the maximum irrigation interval in the Beqa'a during July and August, and for high value crops, the interval may need to be reduced to 3 to 5 days. However, more work is needed with high producing crops to determine the optimum economic interval of irrigation.

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APPENDICES

Table 4. Soil Capillary Conductivity in Relation to Soil Moisture Content and Soil Moisture Tension.

Moisture	Tension	Capillary Conductivity
Percent	Bars	Cm. per day
29.6	.30	1.9×10^{-2}
28.6	.45	6.0×10^{-3}
27.7	.61	2.9×10^{-3}
26.5	1.00	8.8×10^{-4}
25.9	1.15	6.2×10^{-4}
25.3	1.55	3.2×10^{-4}
24.6	2.00	2.2×10^{-4}
23.9	2.60	1.6×10^{-4}
23.0	3.70	1.0×10^{-4}
21.6	6.20	5.0×10^{-5}
20.4	10.00	2.6×10^{-5}
19.7	13.00	1.0×10^{-5}
19.3	15.00	2.9×10^{-6}

Table 5. Moisture Profiles at Various Sampling Intervals

Ring	1 Hour	24 Hours	4 Days	12 Days
	%	%	%	%
1	36.86	33.54	28.97	24.45
2	35.10	31.55	28.41	24.25
3	33.37	30.37	27.54	23.26
4	27.10	26.95	25.04	21.13
5	8.70	19.12	18.13	17.14
6	7.90	9.74	12.16	13.30
7	7.45	8.10	10.27	11.66
8	7.40	7.64	8.93	10.48
9	7.40	7.57	8.37	9.49
10	7.40	7.55	8.04	8.77
11	7.40	7.54	7.88	8.22
12	7.40	7.53	7.76	7.92
13	7.40	7.50	7.53	7.8

Table 6. Saturated permeability of soil with time

Time	Soil permeability
Days	cm. per day
1	28.49
2	17.53
3	24.39
4	31.67
5	38.36
6	42,30
7	46.68
8	42.08
9	39.00
10	36.12
11	33.15
12	30.34
13	28.00

Table 7. Capillary conductivity of soil as a function of moisture content in percent by volume.

Moisture content by volume	log values	Capillary conductivity
%		cm. per day
36.1	1.5575	1.9×10^{-2}
34.9	1.5428	6.0×10^{-3}
33.8	1.5289	2.9×10^{-3}
32.3	1.5092	8.8×10^{-4}
31.6	1.4997	6.2×10^{-4}
30.9	1.4900	3.2×10^{-4}
30.0	1.4771	2.2×10^{-4}
29.1	1.4639	1.6×10^{-4}
28.1	1.4487	1.0×10^{-4}
26.3	1.4200	5.0×10^{-5}
24.9	1.3945	2.6×10^{-5}
24.0	1.3802	1.0×10^{-5}
23.5	1.3711	2.9×10^{-6}