WATER MOVEMENT IN A STRATIFIED SOIL

by

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INTRODUCTION

Statement of the Problem

This project originated from observations made by researchers at the Sandyland Experimental Field at St. John, Kansas, who reported that irrigated crops such as corn, grain sorghum and alfalfa were experiencing water stress in different areas of the field. It was presumed that the consumptive use of irrigation water was not significant in increasing yield i.e., the crops did not respond well to irrigation. Further observations showed that drought stress was also occurring during hot sunny days.

Importance of the Problem

The problem discussed here is of a special interest because it does not involve a problem of higher expenses or shortage of water as one may expect. Today, the practice of irrigation in Western and South Central Kansas, where the source of most irrigation water is the Ogallala and Mead formations, becomes more expensive as water and fuel supplies are depleted. The problem is why is consumptive use of water not significant in increasing yield.

Soil Water Plant Relationships

One of the essential functions of the soil for plant use is the retention of rain or irrigation water in the soil. The soil water content governs the air content and the gas exchange of the soil, (Hillel, 1982). Therefore, water can be either beneficial or detrimental to plant growth depending on the amount that is present in the soil, especially in and around the root zone. An ample supply of water is necessary for maintenance of turgidity in the plant cells. The water brings plant nutrient elements into plant-available form. It supports microbial flora and fauna that make nutrients available to plants. It carries dissolved oxygen into the soil and it keeps the latter from getting too cold or too hot. But water can drown plants, leach out plant nutrient elements, prevent entrance of air into the soil, or can drown beneficial microbial flora and fauna. Therefore, for a better yield, the right amount of water needed by the plants is required. The water required depends upon the kind of crop, the growth stage, the soil type, texture, structure, the water table level and the climatic conditions (temperature, precipitation, pressure, wind, snow, and etc.). Once this amount and the moisture content of the soil are well defined, one should add or subtract water, i.e. by means of irrigation or drainage practices or a combination of the two techniques.

Objectives

This work was undertaken to study the water movement through the profile of the reported field soil. The following objectives were considered:

1- Design and construct a laboratory apparatus to measure the soil moisture potential of a column of soil.

2- Observe water movement through stratified soil profiles in the laboratory.

3- Conduct mechanical analyses of soil texture.

REVIEW OF LITERATURE

Soil Water Content

The moisture in the soil is one of its most essential components. It is a very important factor in the soil formation. The movement of various substances in the soil layer as a result of which the soil profile is formed, mostly takes place in the form of solutions (Rode, 1968). Numerous other soil properties depend very strongly upon water content. Included among these are mechanical properties such as consistency, plasticity, strength compactibility, penetrability, stickiness and trafficability (Hillel, 1982).

Soil moisture is a very important agricultural factor. Controlling water conditions in the soil is always an important technique in improving the productivity of agricultural lands. The water content governs the air content and the gas exchange of the soil; thus affecting the respiration of the roots, the activity of the micro-organisms and the chemical state of the soil (Kramer, 1983; Hillel,1982).

Soil Moisture Content

The amount of water contained in a unit mass or volume of soil is termed (Richards 1941, Baver, et al. 1972, and Hillel 1982) as: soil water content, soil moisture content, relative water content and soil wetness. In terms of either mass or volume ratio, the soil moisture content could be expressed in different ways:

- -Relative to the mass of the solids
- -Relative to the total mass
- -Relative to the volume of solids
- -Relative to the total volume
- -Relative to the volume of pores

The most commonly used are gravitmetric, volumetric and degree of saturation.

Gravimetric. Relative to the mass of the solids

$$P_w= M_w/M_s \qquad (1)$$

The ratio of the mass of water contained in a given unit of soil (M_w) to the mass of the solids contained in the same given unit of soil (M_s) is often referred to as the gravimetric moisture content (P_w).

Volumetric. Relative to the total volume of soil

$$P_v = V_w/V_t = V_w/(V_s + V_a + V_w) \qquad (2)$$

where P_v = the ratio of water volume V to total (bulk) soil volume V

V_s = the volume of the solid particles contained in a given unit of soil

V_a = the volume of the air contained in a given unit of soil

V_w = the volume of the water contained in a given unit of soil

Degree of saturation.

$$S= V_w/V_f = V_w/(V_w+V_a) \qquad (3)$$

This index expresses the volume of water present in the soil relative to the volume of pores. The degree of saturation ranges from 0 to unity (100 percent) in a completely saturated soil.

The volumetric and the gravimetric water content are related to each other by means of the bulk density ρ_b and the water density ρ_w .

$$P_w = P_v \rho_w / \rho_b \qquad (4)$$

or

$$P_v = P_w \rho_b / \rho_w \qquad (5)$$

$\rho_w = M_w/V_w$ is approximately equal to 1.0 g/cm^3 .

Since ρ_b is usually greater than 1.0 it follows that P_v is greater than P_w. The volumetric moisture content could be expressed as a depth

$$P_d = P_w . A_s . D/100 \qquad (6)$$

where P_d = the moisture content expressed in units of length (same unit as D)

P_w = Gravimetric moisture content expressed in percent

A_s = Apparent specific gravity

D = Desired depth (in length units) to calculate moisture content

Measurements of Soil Moisture Content

There are direct and indirect methods to measure the soil water content (Gardner et al., 1965), and as was already pointed out, there are several ways to express it quantitatively. The most common techniques used for soil moisture measurements are: a. sampling and drying b. electrical resistance and c. neutron scattering.

Sampling and drying. This method consists of removing a soil sample by augering into the soil and then determining its moist and dry weights. The dry weight is obtained after drying the sample to a constant weight. This could be done in an oven at 105 to 110 deg.C for 24 hrs, or using a microwave oven for less time. The moist weight is determined by weighing the sample as it is at the time of sampling. The loss of weight in drying, divided by the weight of the water-free soil, yields the moisture content, P_w.

$$P_w = \frac{\text{wet weight - dry weight}}{\text{dry weight}} = \frac{\text{weight loss in drying}}{\text{weight of dried sample}} \qquad (7)$$

For most soil scientists, this method was classified as an arbitrary technique. Some clay may still contain appreciable amounts of adsorbed water (Nutting, 1943) even at 105 deg.C. Some organic matter may oxidize and decompose at this temperature and the weight loss may not be due entirely to the evaporation of water. The usefulness of the sampling and drying method is chiefly limited to primary measurements.

Electrical resistance blocks. These consist of a pair of electrodes embedded in a porous body and an electrical resistance meter. The most used materials as porous bodies for such units are gypsum (Bouyouscos and Mick, 1940) for a pressure range of 100 to 1500 kPa (1 to 15 atm.) and nylon or fiberglass (Colman and Hendrix, 1949) for a pressure range less than 200 kPa (2 atm.). The electrical resistance of these bodies can be calibrated against soil moisture. Connected to a recorder, resistance blocks perform a continuous indication of soil moisture changes in situ. Their chief disadvantage is the gradual dissolution of the blocks, which affect the internal porosity and the pore size distribution of the porous body.

Neutron Scattering. This instrument was known since the late 1950's as a reliable and efficient technique for monitoring soil moisture in the field (Holmes and Jenkinson, 1959). Its main components are, a probe which contains a source of fast neutrons and a detector of slow neutrons, and a scaler to monitor the flux of scattered neutrons by the soil. Its main disadvantages are the initial cost of the instrument and the health hazard associated with the exposure to neutron and gamma radiation.

Soil Water Potential

Next to water content, the energy state of the water is the most important physical soil characteristic (Baver et al., 1972; Hillel, 1982; Hansen et al., 1979 and Richards et al., 1944). Classical physics recognizes two principal forms of energy, kinetic and potential. Since the movement of water in the soil is quite slow, its kinetic energy, which is proportional to the velocity squared, is generally considered to be negligible. Thus, potential energy is mainly responsible for the state and movement of water in the soil.

Various potentials or combinations of potentials are involved that depend upon the phenomenon under consideration.

Bayer (1972) defined the total water potential as:

$$\Psi_T = \Psi_M + \Psi_G + \Psi_P + \Psi_\Omega + \Psi_\pi \tag{8}$$

where Ψ_T = the total water potential

Ψ_M = the matrix potential

Ψ_G = the gravity potential

Ψ_P = the pressure potential

Ψ_Ω = the osmotic potential

Ψ_π = the overburden potential

The influence of the gravitational and overburden forces on the water uptake by plants is small compared to the effects of the osmotic and matric forces. The potential that has the greatest relevance in soil water-plant relations is made up of the matric and the osmotic components (Baver et al., 1972 and Kohnke, 1968).

$$\Psi_S = \Psi_M + \Psi_\Omega \tag{9}$$

This combination of potentials is referred to as soil-water potential or stress potential Ψ_S. It identifies the forces associated with water availability to plants.

Matric Potential.

Matric potential characterizes the tenacity with which water is held by the soil matrix (Hillel, 1982). It is often referred to as the capillary potential, or tension, because in the high moisture range the forces involved are primarily capillary forces.

> "It is the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool containing a solution identical in composition to the water at the elevation and the external gas pressure of the point under consideration" (Commission I, ISSS, 1963).

The sum of the matrix and gravitational potentials ($\Psi_M + \Psi_G$) is generally called the hydraulic head. It is used in evaluating the direction and the magnitude of the water-moving forces throughout the soil profile (Hillel, 1982).

Pressure Potential.

A potential that is due to either the weight of water at a point under consideration or to a gas pressure which is different from that which exists at a reference position is referred to as a pressure potential. It was also referred to as submerged, piezometric and pneumatic potential. The sum $\Psi_M + \Psi_P$ sometimes is referred to as pressure potential, Ψ_M is zero below the water table and Ψ_P is zero above it.

In terms of flow, head rather than potential terms are often used in field work. In potential terms

$$\Psi_H = \Psi_M + \Psi_P + \Psi_G \qquad (10)$$

and in head terms

$$H = H_M + H_P + z \qquad (11)$$

The hydraulic head H is positive below the water table and negative above it.

Osmotic Potential.

"Osmotic potential is the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to a pool containing a solution identical in composition with the soil water (at the point under consideration) but in all other respects identical to the reference pool" (Commission I,ISSS,1963).

Osmotic potential results from hydration of ions in the soil and can only be estimated with salinity sensors. The sum of the matric and osmotic potentials can be measured by freezing point depression or with a thermocouple.

Soil Moisture Characteristic Curve

The soil moisture content and the soil moisture potential are functionally related to each other, and the graphical representation of this relationship is termed as sorption, retention, or characteristic curves (Baver and Gardner,1972). Regardless of the nature of the forces involved, this relationship appears to be a continuous function. It can be obtained in two ways (Richards et al., 1944 and Hillel, 1982).

Desorption.

Desorption results by taking an initially saturated sample and applying increasing suction to gradually dry the soil while taking successive measurements of moisture content and pressure potential.

Sorption.

Sorption results by gradually wetting an initially dry soil sample while reducing the pressure potential. The two curves obtained are not in general identical, and at a given moisture content, the matrix potential is greater in the desorption case than that of the sorption. That is, the soil moisture characteristic is hysteretic (Figure 1.), (Richards et al., 1944; Gardner et al., 1970 and Hillel, 1982).

Figure 1. Hysteresis effect, resulting in differences between matric potential at a given water content in wetting and drying soil (Hillel, 1982).

The soil moisture characteristic curve is strongly affected by the soil texture and structure (Figure 2.), (Richards et al., 1944; Gardner et al., 1970 and Hillel, 1982).

(a) (b)

Figure 2. Typical soil moisture characteristic illustrating, (a) the textural, and (b) the structural effects.

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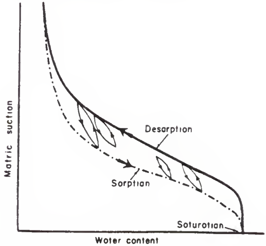

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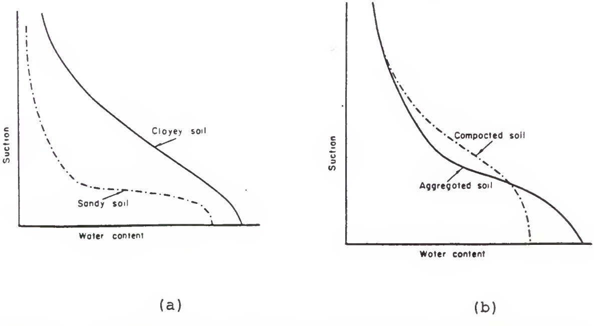

Figure 2. Typical soil moisture characteristic illustrating, (a) the textural, and (b) the structural effects.

Measurement of Soil Moisture Potential

The most commonly used devices for measurement of soil moisture potential are tensiometers, for negative pressure ranges of 0-85 kPa, and pressure plates for negative pressure ranges of 100-1500 kPa.

Tensiometers

A tensiometer is a device used to measure the moisture potential of the soil under field, greenhouse and laboratory conditions (Richards, 1941,1949). Accordingly it was proposed to measure a property of soil water rather than water content of the soil. This property was at one time called soil moisture tension (Taylor et al., 1961) and the name of one type of instrument for measuring it, tensiometer, was derived from this terminology.

The tension range covered by tensiometers extends from 0 to 85 kPa or about 0.85 atm. Therefore, they are not to be used for the full range of moisture tension. They indicate only the rate of depletion of soil moisture (Hillel, 1971, 1982). Their advantage over other moisture measuring devices is that they measure a property of soil water which is directly related to the work plants must do to extract water from the soil (Richards, 1941). Because of their usefulness in the study of water movement in the soil; tensiometers are receiving an increasing amount of attention. Numerous workers have contributed to their development. Various design arrangements have been made depending on the material, the technology available and the conditions under which measurements are taken.

Principle function of the tensiometer

A hole is bored or dug in the soil to the desired depth. The diameter of the hole should be equal to the outside diameter of the cup so the latter can be inserted firmly in the soil. If the diameter of the hole is larger, a handful of loose soil is placed into the hole. As soon as the cup is placed into the soil, a temporary connection is established between the water in the cup and the water in the soil outside (Richards, 1941 and Hillel, 1971). That is, the water in the soil near and around the cup is in hydraulic contact with the water inside the cup through the pores provided in the cup wall. Hydraulic equilibrium between these two waters is reached by means of movement of flow in or out through the cup wall. As water is removed from the soil (roots, evaporation, drainage, etc.) or added (irrigation, rainfall) corresponding changes in the level of the mercury manometer occur. For instance, as the soil water decreases, a new hydraulic equilibrium is reached by movement of the cup water to the soil. That is a suction (or a tension) is established by the soil water and a vacuum is created in the cup. This vacuum is registered on the manometer. On the other hand, an increase of soil water will lower the tension and the water will move into the cup, thus a lesser tension will be read on the manometer.

Soil Water Availability to Plants

The concept of available water is of great importance for plants. The amount of water in the soil between the field capacity and the wilting point is termed the available moisture to plants. Richards and Wadleigh (1952) produced evidence indicating that the available moisture to plants actually decreases with decreasing soil moisture content. Accordingly, a plant might suffer water stress before reaching the wilting point. Hansen et al. (1980) attempted to divide the available moisture range into readily available and decreasingly availble ranges. The concept most scientists agree on is that the availability and the effectiveness of the moisture increases with the moisture content. Agronomists rated the available moisture from 100 percent at field capacity to 0 percent wilting point. In terms of productivity, they agreed that the available moisture should not be less than 60 percent from seeding until harvesting. According to Rode (1968), 75 percent of available moisture is the minimum required during that period beginning 5-7 days before ear formation and throughout maturation and fertilization, when plant growth and transpiration are most intensive.

Field Capacity.

Veihmeyer and Hendrickson (1949) defined the field capacity as the amount of water held in the soil after excess water has drained away and the rate of downward movement has materially decreased which usually takes place within two to three days after rain or irrigation in perevious soils of uniform structure and texture. While for Hansen et al. (1980), it is the moisture content of the soil when the gravitational water has been removed.

The field capacity is strongly affected by the soil texture and the amount of organic matter. As commonly measured, the field capacity varies between 4 percent in sands to about 45 percent in heavy clayey soils, and up to 100 percent or even more in certain organic soils.

Field Capacity and Third Atmosphere Tension

The moisture content of a given soil at tension of 33 kPa (1/3 atm) has been widely accepted as representing the field capacity or moisture equivalent. Coleman (1947), Richards and Weavers (1944), Haise, Haas and Jensen (1955) and Lund (1959), all concluded that soil moisture retained against a tension of 33 kPa (1/3 atm) closely approximates the field capacity. The 33 kPa (1/3 atm) percentage according to Richards and Weavers (1944) is the percentage of moisture retained in a soil subjected to the following treatment:
a. air drying b. passage through a 2 mm round hole sieve c. wetting for a minimum of 6 hrs with an excess of water on a porous plate and d. bringing to equilibrium at 33 kPa (1/3 atm) pressure. Browning (1941) found the moisture equivalent to be equal to field capacity at about 21 percent moisture. Colman (1947) found the one third atmosphere tension to be considerably lower than field capacity in coarse soils,

equal to field capacity at moisture values around 20 percent and somewhat higher than field capacity in finer textured soils.

Richards and Weavers (1944) listed the factors affecting the moisture content of soils at field capacity as follows: a. nature and condition of the whole profile including the original moisture distribution, b. moisture transmitting properties by the soil, c. moisture retaining properties of the soil and d. the amount of water applied to the soil. They recommended the 33 kPa (1/3 atm) moisture tension as a good laboratory measure for approximating field capacity.

Wilting Point.

The soil moisture content, called wilting point, is when plants wilt and do not recover. Briggs and Shantz (1912) concluded that the value of the wilting point is independent of plant species, that is different plants in the same soil wilt at the same moisture values, while Kohnke (1968) reported that the plant species and the stage of growth affect the wilting point.

The wilting point is affected by the soil texture and may vary between 2 percent for a sandy soil to about 20 percent for a heavy clayey soil. Richards and Weavers (1944) found that the wilting point for the majority of soils they investigated to occur at tensions somewhat below 1500 kPa. Kohnke (1968) found it to average 1360 kPa. Other studies on mesophytic plants showed that the wilting point falls in the tension range of 100 to 2500 kPa. Most soil scientists and agronomists accept the 1500 kPa. for or in place of the wilting point.

MATERIALS AND METHODS

Soil Samples

The soil samples used in this study were taken from the Sandyland Experimental Field at St. John, Kansas. According to the Stafford County Soil Survey, (1978), these soils were classified as Farnum fine sandy loam. They were characterized by being nearly level and gently sloping soils with landscapes of long and medium slopes. They were formed in loamy and sandy eolien deposits.

Three PVC columns, 1.37 m (4.5 ft) in height and 0.254 m (10 in) inside diameter were used in this study. One was designated for the disturbed soil sample while the other two were used for the undisturbed soil samples. On the lateral side of each column and vertically, five holes were bored. These holes were spaced 200 mm from each other.

Disturbed Soil Sample

This sample was used for preliminary testing of the tensiometers to ensure their accuracy.

In the field, a hole about one meter deep was dug in the soil and disturbed samples were taken. Soil from each strata was used for almost one third of the volume of the cut soils at different depths, so that the sample was representative of the soil profile. These cut soils were used in the lab to fill the column prepared for the undisturbed sample. Two months were allowed for the soil to settle. Soil settlement as high as 50 mm was observed.

Undisturbed Soil Samples

The equipment used to get an intact soil profile (undisturbed soil column sample) with minimum damage to the surrounding areas was the Hydraulic Operated Equipment for Micro Plot and Root Studies (Swallow, 1982), Figure 3.

Two undisturbed soil samples 254 mm (10 in) in diameter and 1.15 m deep were obtained. The first sample, also referred to as sample no.1, was taken from a grain sorghum plot, while the second sample - sample no. 2 - was taken from an alfalfa plot. The two samples were given a 15-day period for settlement. After this time no significant settlement was observed.

After running the tensiometer tests, five undisturbed subsamples centered at the tensiometer positions were taken from the 2 columns of undisturbed soil. From each subsample an undisturbed core sample 76 mm (3 in.) in diameter and 76 mm (3 in.) in height was obtained. Each core sample, contained in a 76-mm (3-in.) inside diameter schedule 20 plastic pipe, was used for the pressure plate tests. Also from each subsample about a. 100 grams of soil was used for specific gravity b. 100 grams for apparent specific gravity and c. about 500 grams for the particle size analysis.

Figure 3. Hydraulic Operated Equipment for Micro-Plots and Root Studies (Swallow,1982).

Tensiometers

The review of literature guided the design of the tensiometers (Richards, 1941,1944,1949; Stone, 1982). The tensiometers used in this study were mercury type manometers. The main components were as shown in Figure 4:

--porous ceramic plate
--connecting tube
--sensing element

The open end of the ceramic cup was inserted tightly and glued in one end of a 100-mm piece of PVC tubing (schedule 80). A 40-mm piece of transparent plexi-glass tubing was also inserted and glued in the other end of the schedule 80 tubing. The plexi-glass was used so that any air entering the system becomes visible in the air trap. The connecting tube was a very small plastic tube (ID=1mm, OD=2mm). One end of this tubing was submerged in a beaker containing mercury while the other end was connected to the porous cup.

The tubing and the porous cup were filled with boiled water because it contains less dissolved air. The water was forced through all the tubing until all the air bubbles were swept from the system. This was done by applying pressure using a suction bulb, then a vacuum pump. The vacuum pump was applied several times to the opening of the plexiglass to gradually and totally exhaust the air rising into the air trap. The air trap was refilled with boiled water and the vacuum pump was applied several more times. The last step de-aired the ceramic cup wall and ensured that the tensiometer tubing was completely full of

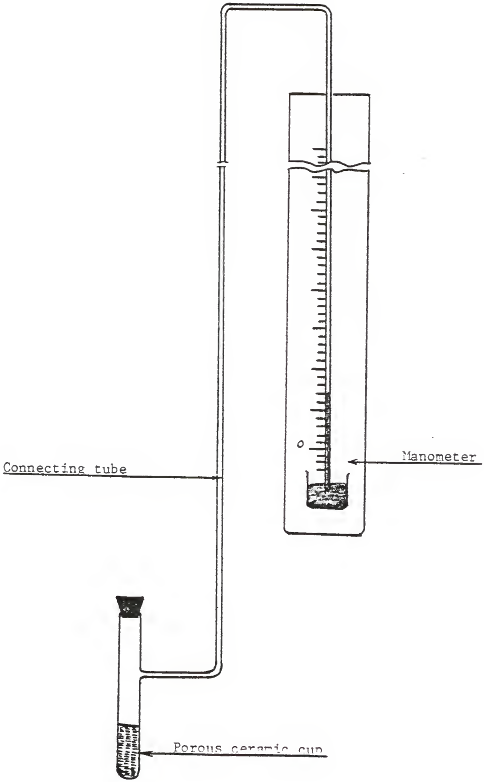

Figure 4. Schematic Diagram Showing the Essential Parts of a Tensiometer.

water. Then, the opening was closed with a rubber stopper and 4 to 8 hours were allowed for the water to evaporate from the ceramic cup wall.

The evaporation results in the mercury rising in the connecting tube by 0.60 to 0.63 m. The response of the apparatus to the moisture was tested. The ceramic cup was submerged in the water and the readings responded downward within 3 to 5 seconds and approached zero in less than 5 minutes. This was an indication of the adequacy of the instrument (Richards, 1941, 1944, 1949; Stone, 1982).

Measurement of Soil Moisture Potential

Water Movement in Soil Column (low pressure 0 to 85 kPa)

The study of the soil moisture in this range was conducted in two ways: with and without evaporation effect. The first was made possible by using a heat lamp to promote surface evaporation. Placed about 0.40 m above the soil surface, the heat lamp was used to simulate the effect of the "natural" evaporation from the soil surface. For the second case, the top of the soil column was covered by a 3 mm (1/8 in.) thick PVC lid.

After being tested in the disturbed soil column sample, the tensiometers were used to study the soil moisture potential in the undisturbed soil samples. In each soil column 5 tensiometers spaced 200 mm from each other were plugged tightly so that equilibration was not hindered by contact zone impedance. Two days were allowed for the system, the tensiometers and the soil, to reach equilibrium.

The volume of water required to raise the entire soil column to field capacity was about 2.5 l. After 2.5 l of water was gradually added to the surface, manometer readings were recorded at selected times (Appendix A). Data were collected from each column both with and without surface evaporation effects.

Calculation. The porous cup and the cup water were brought to zero tension by immersing the lower half of the cup in the water (Figure 5a). Let a designate the mercury column length when the cup tension is made equal to zero by allowing the unit to come to equilibrium with a free water surface at the middle of the cup. Adding pressures from the surface of the mercury in the pot to the midpoint of the cup gives the relation

$$13.54a + \Delta P - a - c - d = 0 \qquad (12)$$

where ΔP represents the pressure change across the meniscus. Then when the vessel of free water is removed, and the cup water tension is T, a corresponding mercury column length $\Delta a + a + b$ occurs. Adding pressure increments around the system to the center of the cup gives

$$13.54(\Delta a + a + b) + \Delta P - b - c - d = T \qquad (13)$$

subtracting (12) from (13) gives

$$T = 13.54\,\Delta a + 12.54\,b \qquad (14)$$

If Δa and b are expressed in mm, T will be in mm of water where

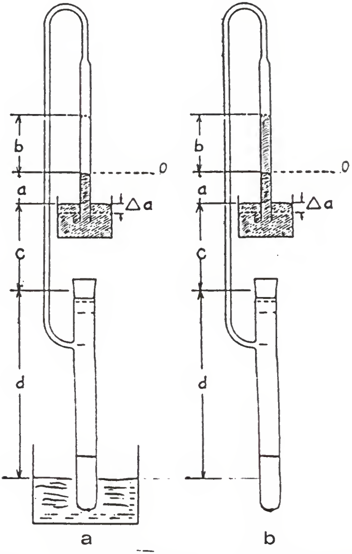

Figure 5. Manometer Arrangements for Calculating Soil Moisture Tensions at the Porous Cup.

Δa is the lowering of the mercury surface in the pot corresponding a column rise equal to b. Since the pot diameter is more than 10 times the diameter of the mercury column then Δa is less than 1 percent of b and can be neglected. From equation (14) it is seen that if we set the zero point of a scale graduated in cm at height a, the cup water tension in cm of water would be simply 12.54 b. However, it is convenient to use a special scale which would be graduated in units of length equal to cm/12.54. Such a scale will give the cup water tension in cm of water. The hydraulic head will be

$$H = -T + h \qquad (15)$$

where h is the distance between the reference line (surface of soil) and the tensiometer's position (h is negative).

Soil Moisture Characteristic Curve (100 to 1500 kPa)

The soil moisture equipment used was a pressure plate instrument (Figure 6). The test procedure as described by Woodford (1979) was:

a) The ceramic plate of the pressure cells containing the sample was placed into a saturation tray. The sample was saturated thoroughly, by adding gradually distilled water to the saturation tray.

b) After removing the excess water, the ceramic plate containing the sample was mounted into the extraction chamber. The desired pressure (100 kPa initially) was applied to the plate extractor.

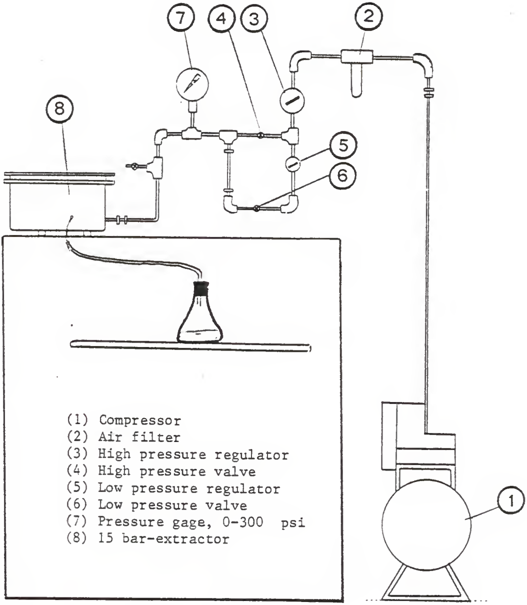

Figure 6. Arrangement and Set up of Equipment for Determining Soil Moisture Retention Values

c) Twenty-four hours were allowed for flow from the extraction chamber to reach equilibrium. Then the ceramic plate and the sample were removed and weighed. The weight of the sample at the applied pressure, ceramic pressure plate and the PVC core was recorded, W_1.

d) The ceramic plate and the sample were placed again in the extraction chamber and the next desired pressure was applied. Steps c and d were repeated until reaching the last desired pressure (15 bars).

e) The sample was then dried to constant weight in an oven at 105 deg.C. The weight of the oven dried sample, ceramic plate and the PVC core was recorded, W_2.

Calculation. The moisture content was calculated as follows:

$$w = [(W_1 - W_2)/(W_2 - W_3)] \times 100 \qquad (16)$$

$$w = (W_w/W_s) \times 100 \qquad (17)$$

where

w = moisture content, percent by weight

W_1 = weight of wet soil at desired pressure + weight of the ceramic plate + weight of PVC core, g

W_2 = weight of the oven dried sample + ceramic plate + PVC core, g

W_3 = weight of ceramic plate + PVC core, g

W_w = $W_1 - W_2$ (weight of water), g

W_s = $W_2 - W_3$ (weight of the oven dried sample), g

Mechanical Analyses

In order to determine the particle size distribution of the soil samples, mechanical analyses which consisted of the following tests, were conducted.

Specific Gravity.

Specific gravity of soil generally refers to the specific gravity of mineral grains (soil solids). Specific gravity, G_s, is defined as:

$$G_s = \frac{\text{unit weight of soil solids only}}{\text{unit weight of water}} \qquad (18)$$

It is usually reported on the value of the unit weight of water at 20 deg.C so:

$$G_s = G_{st}\,(\text{at T, deg.C})\ \frac{(\text{at T, deg.C})}{(\text{at 20 deg,C})} \qquad (19)$$

$$= G_{st}\,(\text{at T, deg.C})A$$

where

$$A = \frac{\gamma_w\ (\text{at T, deg.C})}{\gamma_w\ (\text{at 20 deg.C})} \qquad (20)$$

γ_w = unit weight of water

Apparent Specific Gravity.

It is the ratio of the dry weight of a unit of volume of soil as it exists in place to the unit weight of water. The following formulas show the relationship of porosity and void ratio to apparent and true specific gravity.

$$A_s = G_s\ (1 - n/100) \qquad (21)$$

$$G_s = A_s (1 + e) \qquad (22)$$

where

e = void ratio

= volume of voids divided by volume of solids

n = porosity, in percent

= volume of voids divided by total volume x 100

Particle Size Analyses.

Particle size analyses refers to sieve and hydrometer analyses. The procedure, of these mechanical tests is described in most soil mechanics books (Das, 1982).

Grid Surveying.

A grid-type survey was established by Ten Eyck (1983) of the NE 1/4 of NE 1/4 of Sec. 16 T24S R13W. This section (420 m x 420 m) is bordered to the north by a county road and to the east by a highway (US 281). The survey was based on an existing datum irrigation well with elevation of 583.81 m which is located about 10 m south and 13 m west of the SW corner of the grid. All grid coordinates were positive because they were measured eastward and northward (Appendix B). This survey was conducted to determine the ground surface elevation and the clay surface elevation. The elevation of the clay surface was determined by subtracting the depth to the clay layer from the ground surface elevation. The depth to the clay layer was determined by taking a soil core sample at each point.

RESULTS AND DISCUSSION

Mechanical Analyses

The apparent and the true specific gravity for the 5 levels (5 depths: 0.15 m, 0.35 m, 0.55 m, 0.75 m and 0.95 m) at the two locations (grain sorghum plot and alfalfa plot) are presented in Table 1.

Table 1. Textural Classification Based on Specific Gravity

	Soil Sample		Specific	Gravity	Designations[a]
Site	Depth(m)	Level	(G_s)	(A_s)	
	0.15	1	2.64	1.64	sand
Grain Sorghum plot 1	0.35	2	2.70	1.27	clay
	0.55	3	2.78	1.25	clay
	0.75	4	2.71	1.45	sandy loam
	0.95	5	2.63	1.62	sand
	0.15	1	2.65	1.64	sand
Alfalfa plot 2	0.35	2	2.73	1.25	clay
	0.55	3	2.73	1.28	clay
	0.75	4	2.69	1.45	sandy loam
	0.95	5	2.67	1.65	sand

a General ranges of G for various soils, (Das, 1982)

There are significant differences in the soil texture throughtout the profiles studied. The particle size tests (sieve and hydrometer analyses) showed that the soil profiles occur in layers, which are also called beds or strata. The results presented in Table 2 show the predominance of 4 layers (Figures 7 and 8).

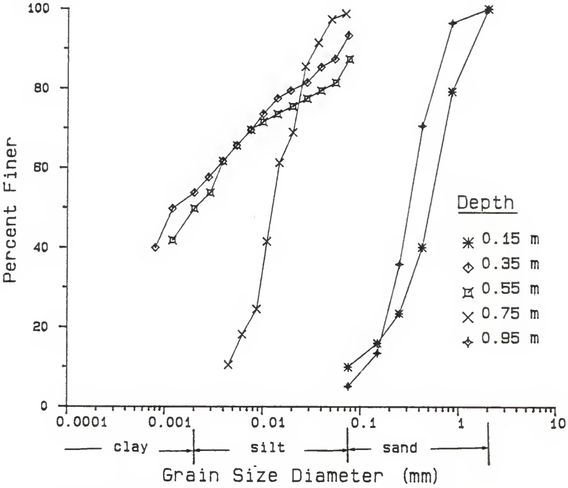

Figure 7.Particle size analyses, sample 1

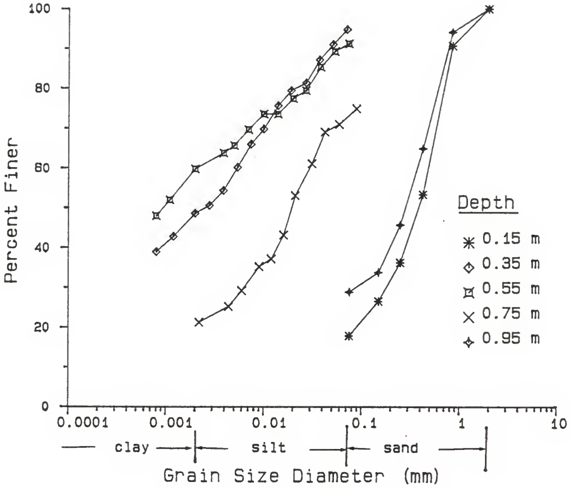

Figure 8.Particle size analyses, sample 2

The profiles studied consisted of 4 layers of different thicknesses:

sand = 0.3 m thick and includes level 1
clay = 0.35 m thick and includes levels 2 and 3
sandy loam = 0.2 m thick and includes level 4
sandy > 0.2 m thick and includes level 5

Table 2. Textural Classification Based on Grading

	Soil Sample		Sand	Silt	Clay	Designations[b]
Site	Depth(m)	Level	(%)	(%)	(%)	
Grain Sorghum plot 1	0.15	1	90.1	4.9[c]	5.0[c]	sand
	0.35	2	30.5	15.8	53.7	clay
	0.55	3	30.5	15.8	53.7	clay
	0.75	4	80.2	9.9[c]	9.9[c]	sandy loam
	0.95	5	94.9	2.5[c]	2.4[c]	sand
Alfalfa plot 2	0.15	1	82.2	8.9[c]	8.9[c]	sand
	0.35	2	34.1	17.4	48.5	clay
	0.55	3	30.4	13.8	55.8	clay
	0.75	4	68.4	10.4	21.2	sandy clay
	0.95	5	99.0	0.5[c]	0.5[c]	sand

b. From Textural Triangle (SI Classification)
c. Estimated

The sandy layers occurring at levels 1 and 5 consisted of a poorly but uniformly-graded soil, while the clayey layers (levels 2 and 3) were well-graded. The only difference between the two samples occurred at the third level. For sample No. 1, level 3 was made up mainly of silty particles which occurred in a poor but uniformly-graded texture while for sample No. 2, the texture was well-graded.

The grid-type surveying data was plotted in a 3-dimensional plot as shown in Figures 9 and 10. The ground surface and the clay surface appear as a recurring sequence of nearly level, undulating, and hummocky landscapes. Also by examining the two figures, it appears that the depression areas occur almost at the same coordinates for both ground and clay surfaces. The variation between the ground and the clay surface configuration is significant. The average mean depth (ground surface level-clay surface level) is found to be 0.62 m with a standard deviation of 0.30 m. On one hand, the statistical analyses of the clay surface level showed that the north-south strips are significantly different from each other ($p<.0001$) while the east-west strips are not significantly different ($p>.164$). On the other hand, statistical analyses showed that the east-west strips are significanly different ($p<.0002$) while the north-south strips are not significantly different ($p>.152$). For the clay surface level, the significance in the north-south strips generated significant east-west slopes (0.7 percent), i.e., a westward topography while for the ground surface level, the significance in the east-west strips generated significant north-south slopes (0.6 percent) that is, a southward topography as reported by the Soil Conservation Service, (1978).

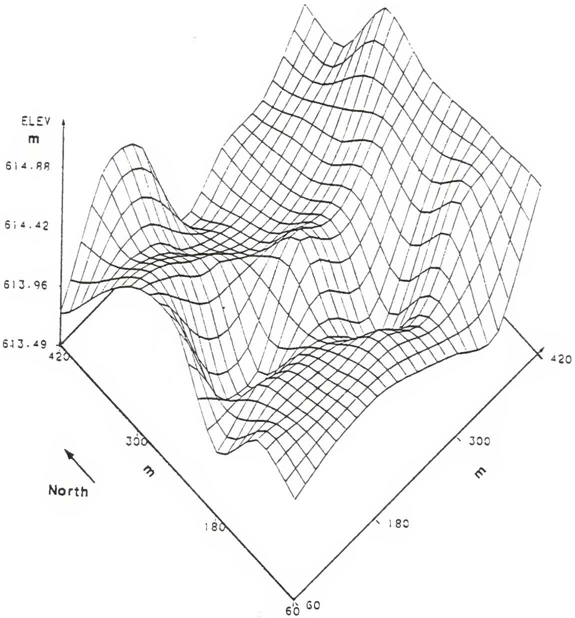

Figure 9. Ground Surface Configuration.

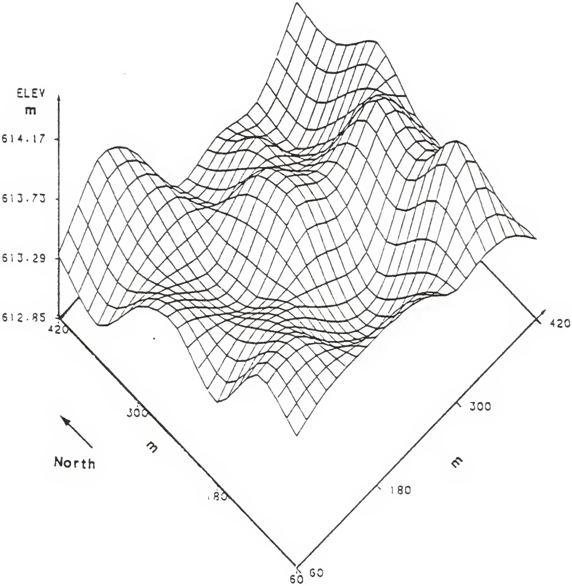

Figure 10. Clay Surface Configuration.

Soil Moisture Potential

The bottom of the column was simply supported so that a free water and/or air movements through the bottom of the soil column would take place. Thus, the water movement through the soil profile in the field would be much slower than that in the laboratory.

Sample 1, Grain Sorghum Plot

Figures 11-14 show the matrix potential as a function of time while figures 15-18 show how water moves in the soil profile (hydraulic head as a function of time). During the first 100 minutes after adding 2.5 l of water to the top of the soil column, the wetting front moved downward as shown in Figures 13 and 17. During the period of 100 to 180 min. there was an interaction between levels 1 and 2. The hydraulic head of the second level became higher than that of levels 1 and 3. Thus, the water was moving from level 2 to levels 1 and 3 at the same time. For the next 180 min., level 1 continued to drain out smoothly while its hydraulic head was decreasing; levels 2 and 3 were completely saturated (pressure potential head = 0) as shown in Figures 13 and 17. The water was moving downward from levels 2 to 3 and from level 3 to level 4, and upward from level 2 to level 1. From 360 min. to 3600 min. levels 1 and 2 continued to drain out while their hydraulic heads were decreasing and the wetting front continued to move downward from level 3 to level 4 until 12300 min. (9 days) when the water started moving upward

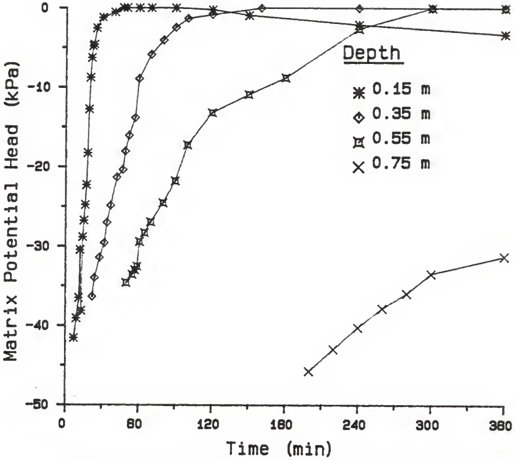

Figure 11. Matrix Potential as a Function of Time for Sample 1; Without Surface Evaporation.

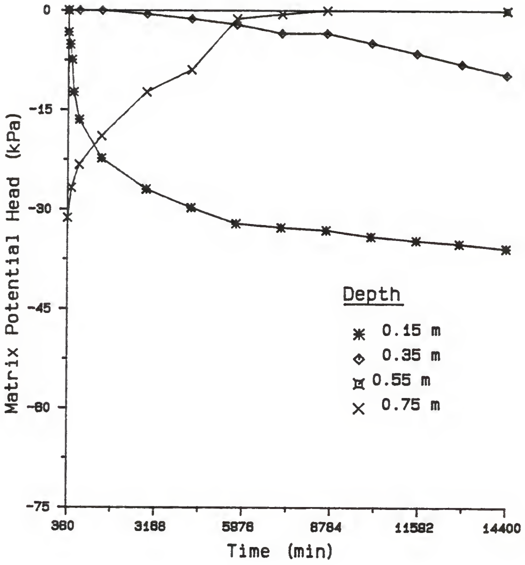

Figure 12. Matrix Potential as a Function of Time for Sample 1 Without Surface Evaporation.

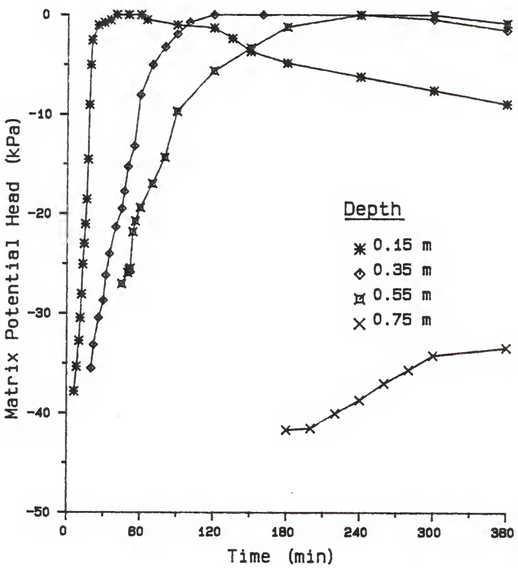

Figure 13. Matrix Potential as a Function of Time for Sample 1 With Surface Evaporation.

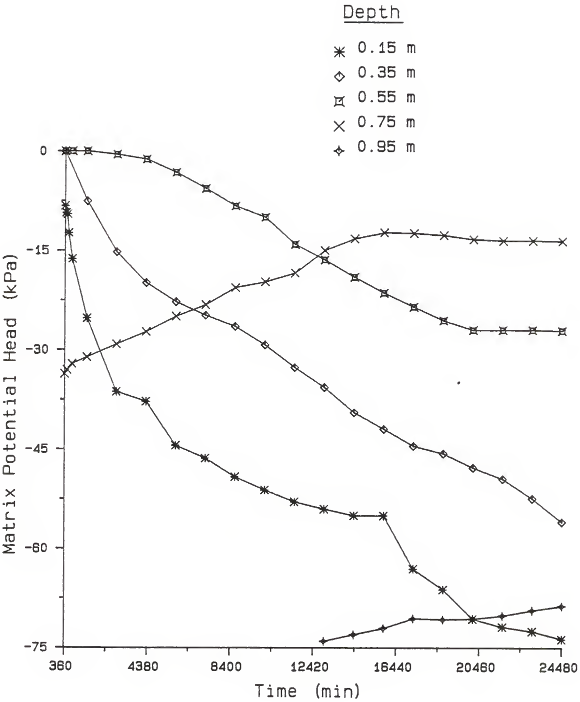

Figure 14. Matrix Potential as a Function of Time for Sample 1; With Surface Evaporation.

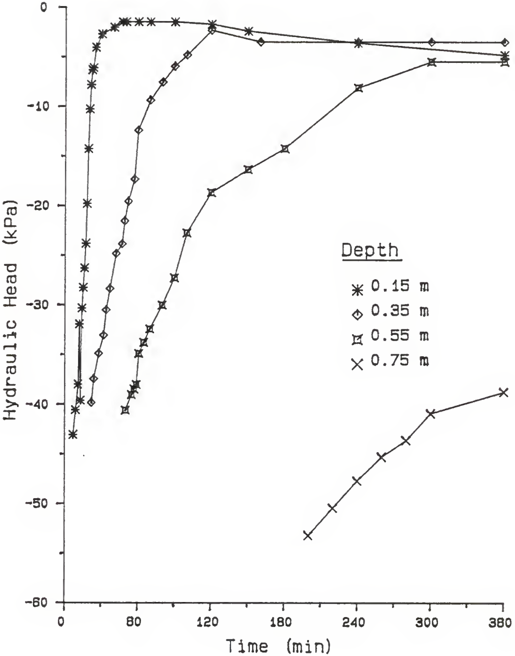

Figure 15. Hydraulic Head as a Function of Time for Sample 1; Without Surface Evaporation.

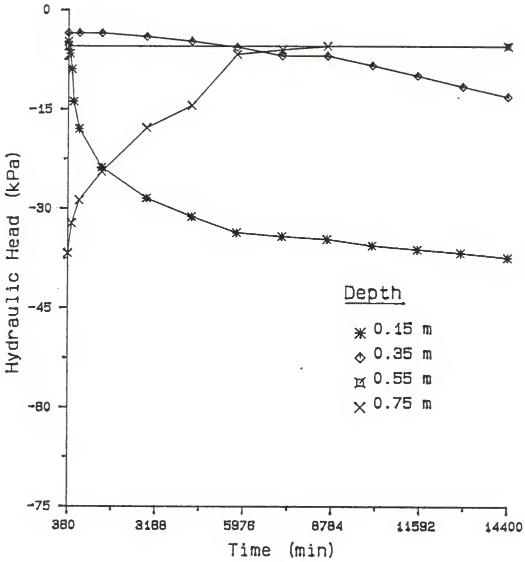

Figure 16. Hydraulic Head as a Function of Time for Sample 1; Without Surface Evaporation.

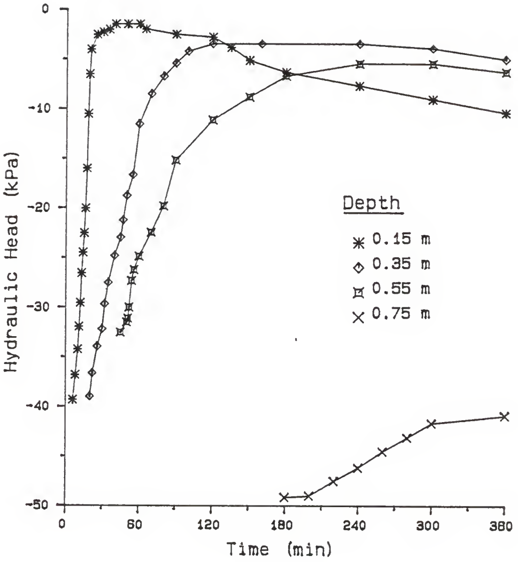

Figure 17. Hydraulic Head as a Function of Time for Sample 1; With Surface Evaporation.

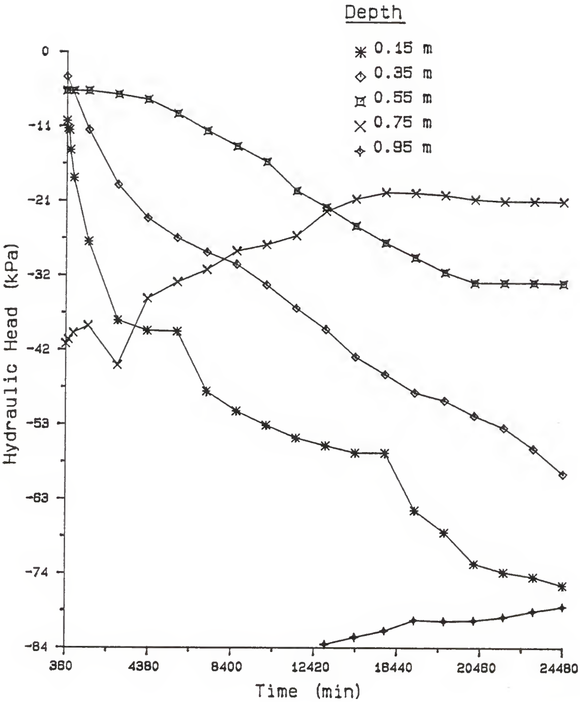

Figure 18. Hydraulic Head as a Function of Time for Sample 1; With Surface Evaporation.

from levels 4 to 3 from levels 3 to 2 and from levels 2 to 1 and downward from levels 4 to 5 (Figures 14 and 18). At the ninth day the wetting front reached level 5 (Figures 14 and 18), and during the next 8 days the water movement was mainly upward, and no significant moisture was recorded at level 5.

The examination of the pressure potential heads (Figures 13 and 14) showed that level 1 reached 33 kPa (0.33 atm.) in 2 days while it took the second level 10 days. The third level remained nearly saturated. The same experiment, conducted over a period of 10 days without evaporation effects showed that level 1 reached 33 kPa in 5 days while levels 2 and 3 were nearly and completely saturated respectively as shown in Figures 12 and 16.

Sample 2, Alfalfa Plot

Figures 19-26 show the matrix potential and hydraulic head as a function of time for both with and without surface evaporation. After adding 2.5 l of water to the top of the soil column, the wetting front moved downward for the first 3 hours as shown in Figure 25. The water moved from the surface to level 1, from level 1 to level 2 and from level 2 to level 3. During the following 2300 min. (Figure 26), while level one experienced evaporation and a drainage effects, level 2 was observing a complete saturation (its pressure potential head was zero). The water was moving down from level 2 to 3 and from levels 3 to 4 and upward from levels 2 to 1, because the hydraulic head of level 2 was higher than that of levels 1, 3, and 4. For the next 9700 min. (6.75 days), levels 1, 2, and 3 were drying out due to

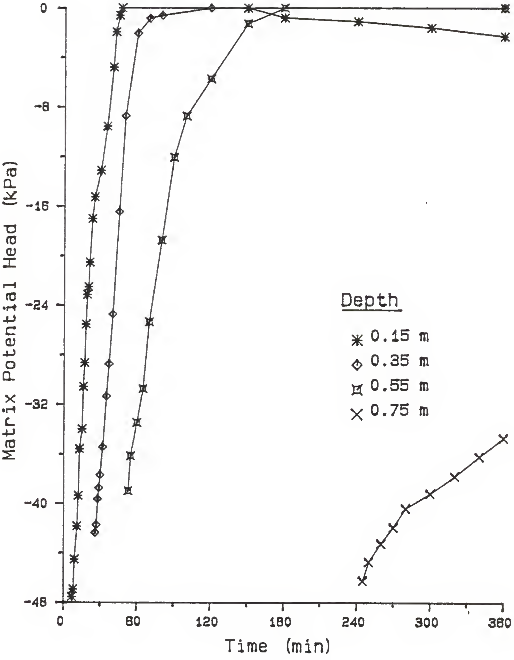

Figure 19. Matrix Potential as a Function of Time for Sample 2; Without Surface Evaporation.

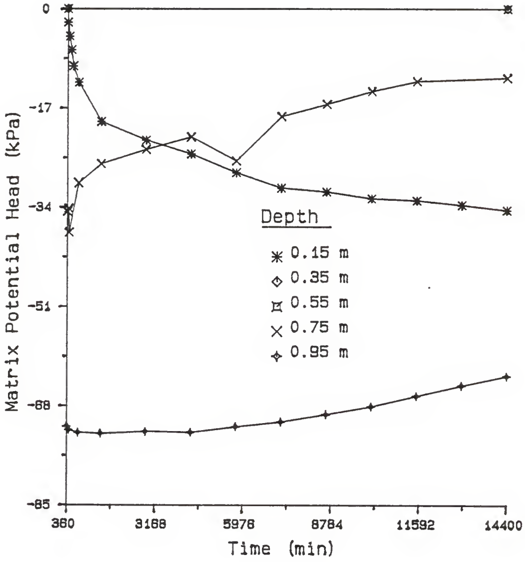

Figure 20. Matrix Potential as a Function of Time for Sample 2; Without Surface Evaporation.

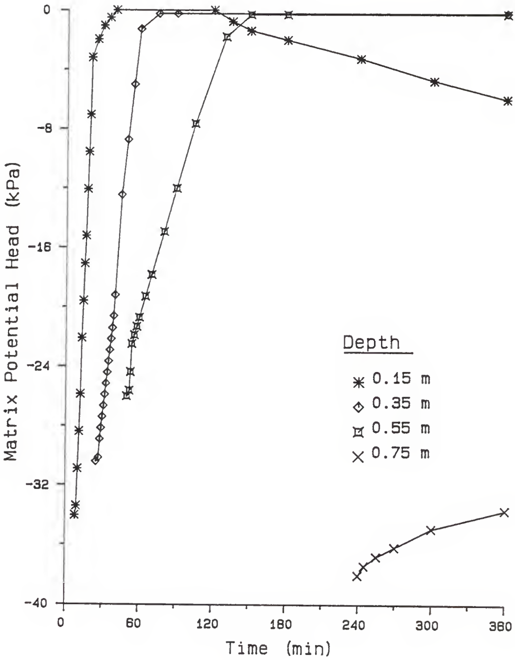

Figure 21. Matrix Potential as a Function of Time for Sample 2; With Surface Evaporation.

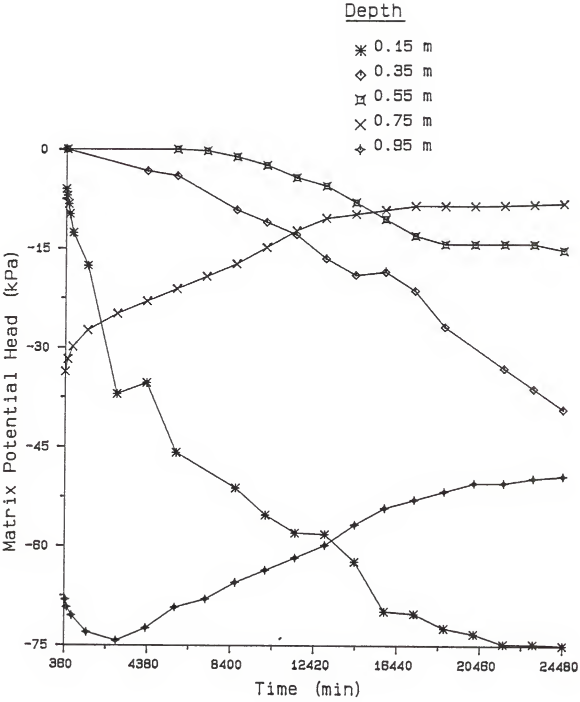

Figure 22. Matrix potential as a Function of Time for Sample 2; With Surface Evaporation.

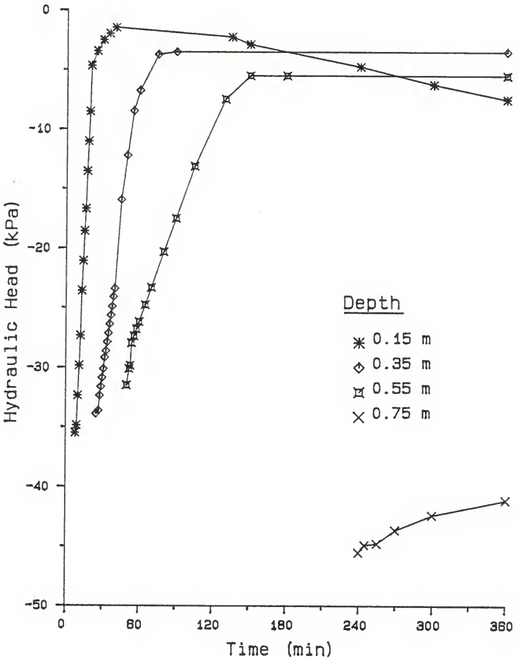

Figure 23. Hydraulic Head as a Function of Time for Sample 2; Without Surface Evaporation.

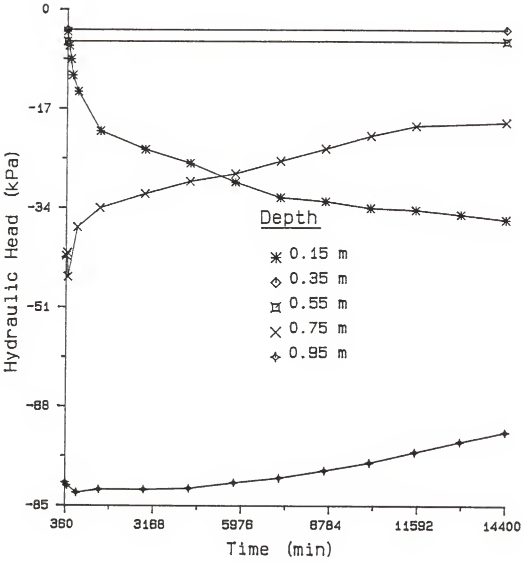

Figure 24. Hydraulic Head as a Function of Time for Sample 2; Without Surface Evaporation.

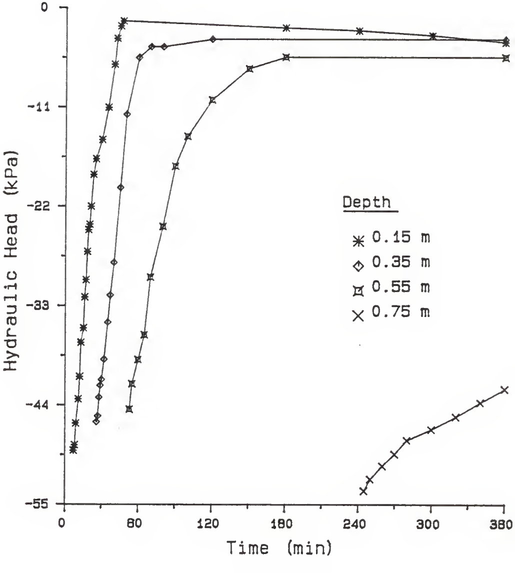

Figure 25. Hydraulic Head as a Function of Time for Sample 2; With Surface Evaporation.

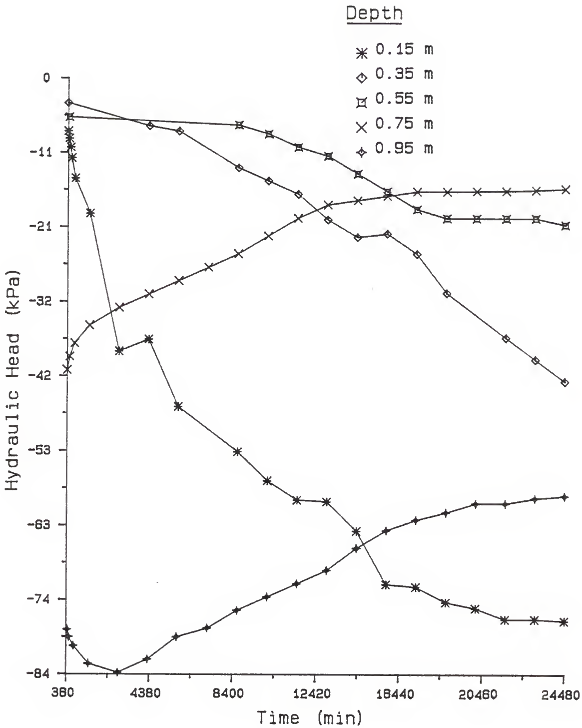

Figure 26. Hydraulic Head as a Function of Time for Sample 2; With Surface Evaporation.

the evaporation effects and the slow drainage, while the water movement was upward from levels 3 to 2 and from levels 2 to 1 and from level 1 to the top surface. The only downward movement was that from levels 3 to 4 and from levels 4 to 5. After 12000 min. (8.3 days) the only level that observed a downward movement was level 4 into level 5.

The same experiment was performed again but without evaporation effects and for 10 days only. It showed that levels 2 and 3 remained completely saturated while it took the first level 6 days to reach 33 kPa (Figures 23 and 24).

This analysis showed that for the top layer which is mainly a sandy soil, a relatively rapid infiltration and evaporation took place resulting in an important loss of water. The second and the third levels which consisted of clayey soil were more "conservative" vis-a-vis the component water. The layer at these two levels will tend to retain water for a long period of time until it is lost by evaporation or slow drainage through the substrata or by horizontal drainage if there is any appreciable slope. However, in the analysis of the clay surface configuration, we found that there were appreciable slopes and some depression zones too. These slopes are responsible for the horizontal drainage from the higher elevated points (saddle) to the depression areas. Thus, the high elevated areas in the field tend to dry out quickly, after being wetted, while the lower depression areas tend to remain saturated for a long period of time because of the well-provided horizontal drainage.

Because of the similarities between the two samples, the pressure plate test was run for sample 1 only. The analyses of the results showed that the wilting point (presumably occurring at 1500 kPa) was quite different from one level to another, (Figure 27). Level 3 had the highest wilting point and level 1 had the lowest. The range of the wilting point for the studied soil was 4-13 percent of dry weight. The results are presented in Table 3.

Table 3. 1500-kPa Water Content of Five Different Levels for Sample No. 1

Soil Sample		Wilting Point	
Depth (m)	Level	Soil Moisture Tension (kPa)	Soil Moisture Content (%)
0.15	1	1500	4.4
0.35	2	1500	10.0
0.55	3	1500	13.0
0.75	4	1500	7.4
0.95	5	1500	4.9

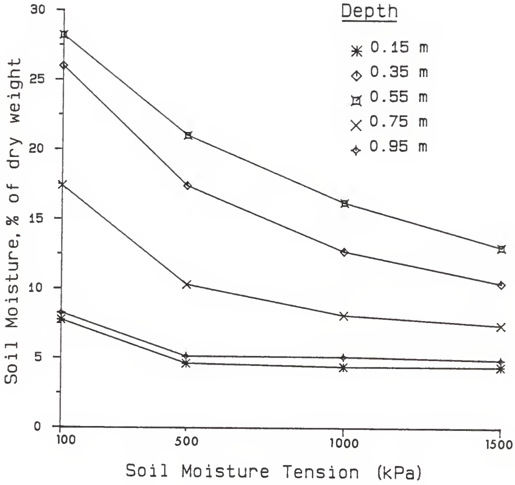

Figure 27. Soil Moisture Characteristic Curve ; Sample 1.

CONCLUSIONS

The soil profiles studied were stratified. There were four layers of various thicknesses. The top layer was sandy soil and was 0.30 m thick, while the second layer was made of heavy soil (clay) and 0.35 m thick. A 0.2 m thick sandy loam type of soil layer was sandwiched between the clay layer (the second layer) and a sandy layer.

The clay surface configuration had a westward topography, while the ground surface level had a southward topography. Both surface configurations were undulating (hummocky landscapes). The average depth of the clay layer was 0.62 m with a standard deviation of 0.30 m.

The profile discontinuity in the pore size distribution decreased the water movement, especially across the discontinuity boundary (when compared to a uniform profile). If the discontinuity is made of a layer of finer texture, such as clay, than the one above it, water will drain faster than through the fine pored layer. Water will then accumulate in the clay layer and will not move down until the layer is nearly saturated. But the existence of appreciable slopes (0.7 percent) in the clay surface configuration and the resistance to the water flow by the fine pores will cause the elevated area to drain faster while the depression remains saturated for a long period of time. The experiment showed that whether subjected to evaporation effects or not, the bottom of the clay layer referred to as level 3 remained completely saturated, while the top layer (sandy soil) drained quickly after being wetted.

The root zone depth for the crops used (corn, grain sorghum and alfalfa) was in the order of 0.60 m to 0.70 m. Crops planted in the saddle areas will have most of their roots in the sand. Consequently they will suffer a drought stress because of the properties of the sand vis-a-vis the water retention, because of the high evaporation (more than 60 in/year) and because of the significant slopes of the clay surface. But those planted in the depression areas will suffer from root development problems and eventually an excess of water. Hence, care must be exercised in irrigating these soils to prevent adverse effects of water and poor aeration.

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APPENDIX A

TENSIOMETER DATA

Time min	Tensiometer Readings cm Hg	Matrix Potential kPa	Hydraulic Head kPa
0.15 m depth for grain sorghum without surface evaporation			
7	33.1	-41.6	-43.1
9	31.6	-39.1	-41.6
11	29.1	-36.5	-38.0
12	24.3	-30.5	-32.0
13	30.4	-38.1	-39.6
14	23.0	-28.8	-30.3
15	21.3	-26.8	-28.3
16	19.8	-24.8	-26.3
17	17.8	-22.3	-24.8
18	14.6	-18.3	-19.8
19	10.2	-12.8	-14.3
20	7.0	-8.8	-10.3
21	5.0	-6.3	-7.8
22	3.8	-4.8	-6.3
23	3.7	-4.6	-6.1
25	2.0	-2.6	-4.0
30	0.9	-1.2	-2.7
40	0.4	-0.5	-2.0
47	0.0	0.0	-1.5
50	0.0	0.0	-1.5
60	0.0	0.0	-1.5
70	0.0	0.0	-1.5
90	0.0	0.0	-1.5
120	0.2	-0.2	-1.7
150	0.7	-0.9	-2.4
240	1.7	-2.1	-3.6
360	2.6	-3.3	-4.8
420	4.1	-5.1	-6.6
480	5.9	-7.5	-8.9
540	9.8	-12.4	-13.9
720	13.1	-16.5	-18.0
1440	17.8	-22.3	-23.8
2880	21.5	-26.9	-28.5
4320	23.7	-29.8	-31.3
5760	25.6	-32.2	-33.7
7200	26.1	-32.7	-34.2
8640	26.4	-332.	-34.7
10080	27.2	-34.1	-35.6
11520	27.7	-34.7	-36.2
12900	28.1	-35.3	-36.8
14400	28.7	-36.0	-37.5

Time min	Tensiometer Readings cm Hg	Matrix Potential kPa	Hydraulic Head kPa
0.35 m depth for grain sorghum without surface evaporation			
22	28.9	-36.3	-39.8
24	27.1	-34.0	-34.9
28	25.0	-31.4	-34.9
32	23.6	-29.6	-33.1
34	21.5	-27.0	-30.5
37	19.8	-24.9	-28.4
42	17.0	-21.3	-24.8
47	16.2	-20.4	-23.9
49	14.9	-18.1	-21.6
52	12.8	-16.1	-19.6
57	11.1	-13.9	-17.3
60	7.1	-8.9	-12.4
70	4.7	-5.9	-9.4
80	3.2	-4.1	-7.6
90	2.0	-2.5	-6.0
100	1.1	-1.3	-4.8
120	0.7	-0.9	-4.4
160	0.0	0.0	-3.5
360	0.0	0.0	-3.5
720	0.0	0.0	-3.5
1440	0.0	0.0	-3.5
2880	0.4	-0.6	-4.1
4320	1.0	-1.3	-4.8
5760	1.7	-2.1	-5.6
7200	2.8	-3.5	-7.0
8640	2.8	-3.5	-7.0
10080	3.9	-4.9	-8.4
11520	5.2	-6.5	-10.0
12960	6.5	-8.1	-11.6
14400	7.8	-9.7	-13.2

Time min	Tensiometer Readings cm Hg	Matrix Potential kPa	Hydraulic Head kPa
0.55 m depth for grain sorghum without surface evaporation			
50	27.5	-34.6	-40.1
55	26.7	-33.5	-39.0
57	26.3	-33.0	-38.5
59	25.9	-32.5	-37.0
61	23.4	-29.4	-35.0
65	22.5	-28.3	-33.8
70	21.5	-27.0	-32.4
80	19.6	-24.5	-29.9
90	17.4	-21.8	-27.3
100	13.7	-17.3	-22.8
120	10.5	-13.2	-18.7
150	8.7	-10.9	-16.4
180	7.0	-8.8	-14.3
240	2.1	-2.6	-8.1
300	0.0	0.0	-5.5
360	0.0	0.0	-5.5
14400	0.0	0.0	-5.5
0.75 m depth for grain sorghum without surface evaporation			
200	36.5	-45.7	-53.2
220	34.2	-43.0	-50.5
240	32.1	-40.2	-47.7
260	30.2	-37.8	-45.3
280	28.7	-35.9	-43.4
300	26.7	-33.5	-41.0
360	24.9	-31.8	-38.8
480	21.3	-26.7	-34.2
1440	15.1	-18.9	-26.4
2880	9.8	-12.3	-19.8
4320	7.2	-9.0	-16.5
5760	1.0	-1.2	-8.7
7200	0.4	-0.6	-8.1
8640	0.0	0.0	-7.1
14400	0.0	0.0	-7.1

Time min	Tensiometer Readings cm Hg	Matrix Potential kPa	Hydraulic Head kPa
0.15 m depth for grain sorghum with surface evaporation			
6	30.2	-37.8	-39.3
8	26.1	-35.3	-36.8
10	26.1	-32.7	-34.2
11	24.3	-30.5	-34.0
12	22.4	-28.1	-29.6
13	20.0	-25.1	-26.6
14	18.3	-23.0	-24.6
15	16.8	-21.0	-22.5
16	14.8	-18.6	-20.1
17	11.1	-14.6	-16.0
18	7.2	-9.0	-10.5
19	4.0	-5.0	-6.5
20	2.0	-2.6	-4.1
25	0.8	-1.1	-2.6
30	0.6	-0.8	-2.3
35	0.4	-0.6	-2.1
40	0.0	0.0	-1.5
50	0.0	0.0	-1.5
60	0.0	0.0	-1.5
90	0.8	-1.0	-2.5
120	1.0	-1.3	-2.8
180	3.8	-4.9	-6.4
240	5.0	-6.5	-7.7
300	6.0	-7.6	-9.1
360	7.1	-8.9	-10.4
420	7.4	-9.3	-10.8
540	9.9	-12.4	-13.9
720	13.0	-16.3	-17.8
1440	20.2	-25.3	-26.8
2880	29.0	-36.4	-37.9
4320	30.1	-37.8	-39.3
5760	35.5	-44.5	-46.0
7200	37.0	-46.4	-47.9
8640	39.2	-49.2	-50.7
10080	40.8	-51.2	-52.7
11520	42.2	-52.9	-54.4
12960	43.2	-54.1	-55.6
14400	43.9	-55.1	-56.6
15840	43.9	-55.0	-56.5
17280	50.3	-63.1	-56.5
18720	52.8	-66.2	-68.7

20160	56.4	-70.7	-72.2
21600	57.3	-71.9	-73.4
23040	57.8	-72.5	-74.0
24480	58.8	-73.7	-75.2
0.35 m depth for grain sorghum with surface evaporation			
20	28.3	-35.5	-39.0
22	26.4	-33.1	-36.6
26	24.3	-30.4	-33.9
30	22.9	-28.7	-32.2
32	20.9	-26.2	-29.7
35	19.1	-24.0	-27.5
40	17.0	-21.3	-24.8
45	15.5	-19.5	-23.0
47	14.2	-17.8	-21.3
50	12.2	-15.3	-18.8
55	10.5	-13.2	-16.7
60	6.4	-8.0	-13.6
70	4.0	-5.0	-8.5
80	2.6	-3.3	-6.7
90	1.5	-1.9	-5.4
100	0.6	-0.8	-4.3
120	0.0	0.0	-3.5
160	0.0	0.0	-3.5
240	0.0	0.0	-3.5
300	0.4	-0.5	-4.0
360	1.2	-1.5	-5.0
1440	6.1	-7.6	-11.0
2880	12.2	-15.3	-18.8
4320	15.9	-19.9	-23.4
5760	18.2	-22.8	-26.3
7200	19.8	-24.8	-28.3
8640	21.1	-26.5	-30.0
10080	23.4	-29.3	-32.8
11520	26.1	-32.7	-36.2
12960	28.5	-35.7	-39.2
14400	31.5	-39.5	-43.0
15840	33.5	-42.0	-45.5
17280	35.6	-44.6	-48.0
18720	36.4	-45.7	-49.2
20160	38.0	-47.8	-55.3
21600	33.5	-49.5	-53.0
23040	41.9	-52.5	-56.0
24480	44.7	-56.0	-59.5

Time min	Tensiometer Readings cm Hg	Matrix Potential kPa	Hydraulic Head kPa
0.55 m depth for grain sorghum with surface evaporation			
45	22.0	-27.0	-32.5
50	20.6	-25.9	-31.4
51	20.4	-25.6	-31.1
52	20.3	-25.5	-31.0
54	17.4	-21.8	-27.3
56	16.5	-20.7	-26.2
60	15.5	-19.4	-24.9
70	13.5	-17.0	-22.5
80	11.4	-14.3	-19.9
90	7.7	-9.7	-15.2
120	4.5	-5.6	-11.1
150	2.7	-3.3	-8.8
180	1.0	-1.2	-6.7
240	0.0	0.0	-5.5
300	0.0	0.0	-5.5
360	0.7	-0.8	-6.3
720	0.7	-0.8	-6.3
1440	0.7	-0.8	-6.3
2880	0.7	-0.8	-6.3
4320	1.1	-1.3	-6.8
5760	2.6	-3.2	-8.7
7200	4.5	-5.7	-11.2
8640	6.6	-8.3	-13.8
10080	8.0	-10.0	-15.5
11520	11.2	-14.1	-19.6
12960	13.2	-16.5	-22.0
14400	15.2	-19.1	-24.6
15840	17.1	-21.4	-26.9
17280	18.7	-23.5	-29.1
18720	20.4	-25.6	-31.1
20160	21.6	-27.1	-32.6
21600	21.5	-27.0	-32.5
23040	21.5	-27.0	-32.5
24480	21.7	-27.2	-32.7

Time min	Tensiometer Readings cm Hg	Matrix Potential kPa	Hydraulic Head kPa
0.75 m depth for grain sorghum with surface evaporation			
180	33.2	-41.7	-49.2
200	33.1	-41.5	-49.0
220	32.0	-40.0	-47.5
240	30.9	-38.7	-46.2
260	29.5	-37.1	-44.6
280	28.4	-35.6	-43.1
300	27.3	-34.2	-41.7
360	26.7	-33.4	-41.0
480	26.4	-33.1	-40.6
720	25.6	-32.1	-39.6
1440	24.8	-31.1	-38.6
2880	23.3	-29.2	-36.7
4320	21.8	-27.3	-34.8
5760	19.9	-25.0	-32.5
7200	18.5	-23.2	-30.7
8640	16.4	-20.6	-28.1
10080	15.7	-19.7	-27.2
11520	14.7	-18.4	-25.9
12960	12.0	-15.0	-22.5
14400	10.6	-13.3	-20.8
15840	9.8	-12.3	-19.8
17280	9.9	-12.4	-19.9
18720	10.1	-12.7	-20.2
20160	10.6	-13.3	-20.8
23040	10.8	-13.6	-21.1
24480	10.8	-13.6	-21.1
0.95 m depth for grain sorghum with surface evaporation			
12960	59.0	-74.0	-83.5
14400	58.2	-73.0	-82.5
15840	5705	-72.1	-81.6
17280	56.3	-70.6	-80.1
18720	56.4	-70.8	-80.3
20160	56.3	-70.7	-80.1
21600	55.9	-70.2	-79.7
23040	55.3	-69.4	-78.9
24480	54.8	-68.7	-78.2

Time min	Tensiometer Readings cm Hg	Matrix Potential kPa	Hydraulic Head kPa
0.15 m depth for alfalfa without surface evaporation			
7	37.9	-47.5	-49.0
8	37.4	-46.9	-48.4
9	35.5	-44.5	-46.0
11	33.3	-41.8	-43.3
12	31.4	-39.4	-40.9
13	28.3	-35.5	-37.0
15	27.1	-34.0	-35.5
16	24.4	-30.6	-32.1
18	20.4	-25.6	-27.1
19	18.4	-23.1	-24.6
20	17.9	-22.5	-24.0
21	16.3	-20.5	-22.0
25	12.2	-15.3	-16.8
30	10.4	-13.1	-14.6
35	7.7	-9.6	-11.4
40	3.8	-4.8	-6.3
45	0.5	-0.6	-2.1
50	0.0	0.0	-1.5
90	0.0	0.0	-1.5
180	0.6	-0.8	-2.3
240	0.9	-1.1	-2.6
300	1.3	-1.6	-3.1
360	1.8	-2.3	-3.8
420	3.8	-4.8	-5.3
540	7.8	-9.8	-11.3
720	10.0	-12.6	-14.1
1440	15.5	-19.4	-20.4
2880	17.9	-27.5	-24.0
4320	19.9	-24.9	-26.4
5760	22.4	-28.1	-29.6
7200	24.5	-30.7	-32.2
8640	25.0	-30.7	-32.9
10080	26.0	-32.6	-33.1
11520	26.5	-32.9	-34.4
12960	27.1	-34.0	-35.5
14400	27.6	-34.6	-36.1

Time min	Tensiometer Readings cm Hg	Matrix Potential kPa	Hydraulic Head kPa
0.35 m depth for alfalfa without surface evaporation			
26	33.8	-42.4	-45.9
27	33.3	-41.7	-45.2
28	31.6	-39.6	-43.1
29	30.9	-38.7	-42.2
30	30.1	-37.7	-41.2
32	28.2	-35.4	-38.9
35	25.0	-31.3	-34.8
37	22.9	-28.7	-32.2
40	19.7	-24.7	-28.2
45	13.2	-16.5	-19.9
50	6.9	-8.7	-12.2
60	1.7	-2.1	-5.6
70	0.6	-0.8	-4.3
80	0.5	-0.6	-4.1
120	0.0	0.0	-3.5
150	0.0	0.0	-3.5
180	0.0	0.0	-3.5
360	0.0	0.0	-3.5
1440	0.0	0.0	-3.5
0.55 m depth for alfalfa without surface evaporation			
53	31.1	-39.0	-44.5
55	28.8	-36.1	-41.6
60	26.7	-33.5	-39.0
65	24.5	-30.7	-36.2
70	20.2	-25.3	-30.8
80	15.0	-18.8	-24.3
90	9.6	-12.1	-17.6
100	6.9	-8.7	-14.2
120	4.5	-5.7	-11.2
150	1.0	-1.3	-6.8
180	0.0	0.0	-5.5
240	0.0	0.0	-5.5
300	0.0	0.0	-5.5
360	0.0	0.0	-5.5
1440	0.0	0.0	-5.5

Time min	Tensiometer Readings cm Hg	Matrix Potential kPa	Hydraulic Head kPa
0.75 m depth for alfalfa without surface evaporation			
245	36.9	-46.3	-53.8
250	35.6	-44.7	-52.2
260	34.3	-43.3	-50.8
270	33.4	-41.9	-49.4
280	32.2	-40.4	-47.9
300	31.3	-39.2	-46.7
360	27.7	-34.7	-42.2
420	26.6	-33.3	-40.8
720	23.8	-29.9	-37.4
1440	21.1	-26.5	-34.0
2880	19.2	-24.1	-31.6
4320	17.5	-21.9	-29.4
5760	16.5	-20.7	-28.2
7200	14.8	-18.5	-26.0
8640	13.1	-16.4	-24.9
10080	11.3	-14.2	-22.7
11520	10.0	-12.5	-20.0
14400	9.5	-11.9	-19.4
0.95 m depth for alfalfa without surface evaporation			
360	57.0	-71.5	-81.0
420	57.5	-72.1	-81.6
720	57.9	-72.6	-82.1
1440	58.0	-72.7	-82.2
2880	58.0	-72.7	-82.2
5760	57.1	-71.6	-81.1
7200	56.4	-70.7	-80.2
8640	55.4	-69.5	-79.0
11080	54.4	-68.2	-78.7
11520	52.9	-66.3	-76.8
12960	-51.5	-64.6	-74.1
14400	50.2	-62.9	-72.4

Time min	Tensiometer Readings cm Hg	Matrix Potential kPa	Hydraulic Head kPa
0.15 m depth for alfalfa with surface evaporation			
8	27.1	-34.0	-35.5
9	26.6	-33.4	-34.9
10	24.6	-30.9	-32.4
11	22.3	-28.4	-29.9
12	20.7	-25.9	-27.4
13	17.6	-22.1	-23.6
14	15.6	-19.6	-21.1
15	13.6	-17.1	-18.6
16	12.1	-15.2	-16.7
17	9.7	-12.2	-13.7
18	7.6	-9.6	-11.1
19	5.6	-7.0	-8.5
20	2.6	-3.2	-4.7
25	1.6	-2.0	-3.5
30	0.8	-1.0	-2.5
35	0.5	-0.6	-2.1
40	0.0	0.0	-1.5
120	0.0	0.0	-1.5
150	1.1	-1.4	-2.9
180	1.6	-2.0	-3.5
240	2.6	-3.3	-4.8
300	3.8	-4.8	-6.3
360	4.8	-6.0	-7.5
420	4.8	-6.0	-7.5
540	5.6	-7.0	-8.5
720	7.8	-9.8	-11.3
1440	10.1	-12.7	-14.2
2880	14.0	-17.6	-19.1
4320	29.5	-37.0	-38.5
5760	28.1	-35.3	-36.8
8640	36.5	-45.8	-46.3
10080	40.8	-51.2	-52.7
11520	44.1	-55.3	-56.8
12960	46.3	-58.0	-59.5
15840	49.7	-62.3	-63.8
17280	56.0	-70.2	-71.7
18720	57.7	-72.4	-73.9
20160	58.4	-73.2	-74.7
21600	59.7	-74.7	-76.2
23040	59.7	-74.7	-76.2
24480	59.8	-75.0	-76.5

Time min	Tensiometer Readings cm Hg	Matrix Potential kPa	Hydraulic Head kPa
0.35 m depth for alfalfa with surface evaporation			
25	24.2	-30.4	-33.9
27	24.0	-30.1	-33.6
29	22.4	-28.1	-31.6
31	21.2	-26.6	-30.1
33	20.2	-25.1	-28.6
35	18.8	-23.6	-27.1
37	17.7	-22.2	-25.7
39	16.4	-20.6	-24.1
45	9.9	-12.4	-15.9
50	6.9	-8.7	-12.2
55	4.0	-5.0	-8.5
60	1.0	-1.3	-5.8
75	0.0	0.0	-3.5
90	0.0	0.0	-3.5
360	0.0	0.0	-3.5
4320	2.6	-3.3	-6.8
5760	3.2	-4.0	-7.5
8640	7.3	-9.2	-12.7
10080	8.8	-11.0	-14.5
11520	10.3	-12.9	-16.4
12960	13.2	-16.5	-20.0
14400	15.2	-19.0	-22.5
15740	14.8	-18.5	-22.0
17280	17.1	-21.4	-24.9
18720	21.5	-26.7	-30.4
21600	26.5	-33.2	-36.7
23040	28.9	-36.2	-39.7
24480	31.3	-39.3	-42.8
0.55 m depth for alfalfa with surface evaporation			
50	20.7	-26.0	-31.5
52	20.4	-25.6	-31.1
53	19.5	-24.4	-29.9
54	17.9	-22.5	-28.0
56	17.5	-21.9	-27.4
58	17.0	-21.3	-26.8
60	16.5	-20.7	-26.2
65	15.4	-19.3	-24.8
70	14.2	-17.8	-23.3

80	11.9	-14.9	-20.4
90	9.6	-12.0	-17.5
105	6.1	-7.7	-13.2
130	1.4	-1.8	-7.3
150	0.0	0.0	-5.5
360	0.0	0.0	-5.5
5760	0.0	0.0	-5.5
7200	0.2	-0.2	-5.7
8640	1.0	-1.2	-6.7
10080	1.9	-2.4	-7.7
11520	3.4	-4.3	-9.8
12960	4.5	-5.6	-11.1
14400	6.5	-8.1	-13.6
15840	8.5	-10.7	-16.2
17280	10.4	-13.1	-18.6
18720	11.4	-14.3	-19.8
23040	11.4	-14.3	-19.8
24480	12.4	-15.5	-21.0
0.75 m depth for alfalfa with surface evaporation			
240	30.3	-38.0	-45.5
245	29.8	-37.4	-44.9
255	29.3	-36.8	-44.3
270	28.9	-36.2	-43.7
300	27.8	-34.9	-42.4
360	26.8	-33.6	-41.1
480	25.4	-31.8	-39.3
720	23.8	-29.9	-37.4
1440	21.9	-27.4	-34.9
2880	19.9	-24.9	-32.4
4320	18.3	-23.0	-30.5
5760	16.8	-21.1	-28.6
7200	15.3	-19.2	-26.7
8640	13.8	-17.3	-24.8
10080	11.8	-14.8	-22.3
11520	9.8	-12.3	-19.8
12960	8.3	-10.4	-17.9
14400	7.8	-9.8	-17.3
15280	7.3	-9.2	-16.7
17280	6.9	-8.6	-16.1
18720	6.9	-8.6	-16.1
20160	6.9	-8.6	-16.1
21600	6.8	-8.5	-16.0
23040	6.6	-8.3	-15.8
24480	6.5	-8.2	-15.9

Time min	Tensiometer Readings cm Hg	Matrix Potential kPa	Hydraulic Head kPa
0.95 m depth for alfalfa with surface evaporation			
420	54.4	-68.2	-77.7
480	55.3	-69.3	-78.8
720	56.2	-70.5	-79.0
1440	58.2	-73.0	-82.5
2880	59.3	-74.3	-83.8
4320	57.7	-72.4	-81.9
5720	55.3	-69.3	-78.8
7200	54.2	-68.0	-77.5
8640	52.2	-65.5	-75.0
10080	49.2	-63.6	-73.1
11520	49.2	-61.7	-71.2
12960	47.8	-59.9	-69.4
14400	45.2	-56.7	-66.2
15840	43.2	-54.2	-63.7
17280	42.3	-53.0	-62.5
18720	41.2	-51.7	-61.2
20160	40.3	-50.5	-60.0
21600	40.2	-50.4	-59.9
23040	39.6	-49.7	-59.2
24480	39.4	-49.4	-58.9

APPENDIX B

GRID DATA

Coordinates		Ground elevation	Clay elevation
x (m)	y (m)	z (m)	z (m)
60	60	614.29	613.84
60	120	614.42	613.96
60	180	614.45	613.96
60	240	614.32	613.96
60	300	614.14	613.68
60	360	613.99	613.71
60	420	614.81	613.44
120	60	614.42	613.99
120	120	614.35	613.96
120	180	614.32	613.56
120	240	614.32	613.35
120	300	614.11	613.50
120	360	614.66	614.17
120	420	614.78	613.55
180	60	613.99	613.47
180	120	614.20	613.71
180	180	614.11	613.56
180	240	613.93	613.26
180	300	613.59	613.20
180	360	614.26	613.71
180	420	614.75	613.38
240	60	614.60	613.71
240	120	613.75	613.50
240	180	613.65	613.32
240	240	614.35	613.68
240	300	614.08	613.50
240	360	614.42	613.84
240	420	614.72	613.41
300	60	614.60	613.56
300	120	613.17	613.26
300	180	614.17	613.26
300	240	613.93	613.60
300	300	613.90	613.32
300	360	614.14	613.26
300	420	614.87	613.65
360	60	614.23	613.11
360	120	614.23	613.41
360	180	613.93	613.44
360	240	613.74	613.07
360	300	613.75	613.26
360	360	613.99	612.26
360	420	614.23	613.32
420	60	613.74	613.32
420	120	614.51	613.71
420	180	614.39	613.44

420	240	613.50	613.89
420	300	613.79	612.95
420	360	613.80	612.89
420	420	614.23	613.32

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a. x was measured from south to north

b. y was measured from west to east

c. z was the elevation

WATER MOVEMENT IN A STRATIFIED SOIL

by

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AN ABSTRACT OF A MASTER'S THESIS

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ABSTRACT

The soil profiles studied were stratified; made of at least 4 layers: sand, clay, sandy loam and sand. The stratification of the soil profile affected the movement and the redistribution of the water in the soil. When water reaches the clay, the very fine pores of this layer resist water flow. Although water does pass through the clay, it moves very slowly. When water passes through the fine soils (clay) and reaches the coarser layer (sand), it stops until enough water accumulates to nearly saturate the soil above it.

The stratification of the soil profile consisted of impeding layers, since the presence of any layer at any depth retards the movement of the water out of the layers above it. The presence of slowly permeable layers, such as clay, transmit water slowly for a long period of time after irrigation. As a result, the irrigation water will remain in the soil until it is lost by evapotranspiration and by slow drainage through the substrata, unless an appreciable slope exists. But the presence of appreciable slopes was of great importance, since the clay surface configuration is made of depressions and saddles. Those slopes cause the elevated areas to drain quickly, while the depression areas remain saturated. In either case, the crop would suffer from a stress of excess or shortage of water. Hence, care must be exercised in irrigating these soils to prevent adverse effects of excess water and poor aeration.