

SOIL MOISTURE VARIABILITY:
A FIELD APPLICATION OF
TIME DOMAIN REFLECTOMETRY

by

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ABSTRACT

Soil moisture variability and available water content are influenced by grain size distribution, organic content, bulk density and soil structure. Each of these soil characteristics is discussed in relationship to one another and soil moisture variability. A mathematical model is derived for estimating moisture content at field capacity, permanent wilting point and maximum available water content. Seven soil classes are included, ranging from clay to sandy loam.

A brief description of four methods for determining moisture content are presented: Time Domain Reflectometry (TDR), gravimetrics, porous resistance blocks and neutron scattering. The advantages and disadvantages of each method are discussed.

The design of a field study using TDR for determining in situ soil moisture content is presented. TDR lends itself to this application, since it is a non-destructive procedure allowing for repetitive moisture determinations at the same location. Field portability and ease of operation enhance its use.

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CHAPTER 1

INTRODUCTION

Soil moisture content and spatial variability are directly associated with soil texture, organic matter content, porosity, permeability and bulk density. All of these factors are related to soil structure and a change in any one of them will ultimately affect soil moisture distribution. These physical soil factors can themselves vary in response to changes of topography and depth within the soil column.

1.1 Goals and Objectives:

Scope of the Study

The purpose of this thesis is to achieve two objectives: firstly, to examine the physical soil characteristics that influence soil moisture variability, and secondly, to derive a simple model that can be used to estimate available water content.

Field observations and laboratory analysis were limited to examining the soil moisture distribution for the top 30 cm of soil depth. All of the variables used in the model should be physical soil characteristics that are easily obtained. The duration of the field study (collection of in situ moisture data) covered the time period between June 19 and August 27, 1980.

1.2 Choice of Study Area

A study site, field plot #19, was selected at the Animal Research Centre, Federal Department of Agriculture, Ottawa (Figure 1). This site provided the range of physical factors required to meet the research objectives, including: a variety of soil types ranging from loamy sand to clay; a moderately-low variation in topography, so that the influence of slope and elevation could be investigated; and a uniform drainage provided by a grid of drainage tile located at a depth of about one metre. Based on the presence of this tile the following assumptions were made:

- 1) Water that infiltrates to the depth of the drainage tile will be directed away from the study plot.
- 2) The water table, underlying the study plot, will be below the depth of the drainage tile.
- 3) The wetting and drying periods, as determined for the top 30 cm of soil depth, will be primarily related to precipitation events and not to any upward movement of moisture from the water table.

In addition, agrometeorological research was conducted at the study site by the Department of Agriculture prior to and during this field study. A meteorological field station was situated near the south-east corner of the test plot and throughout most of the summer provided basic climatic data (precipitation, temperature, wind speed and direction, incoming and net radiation). The precipitation record is of particular importance to this study, since this information was used to define periods of wetting and drying.

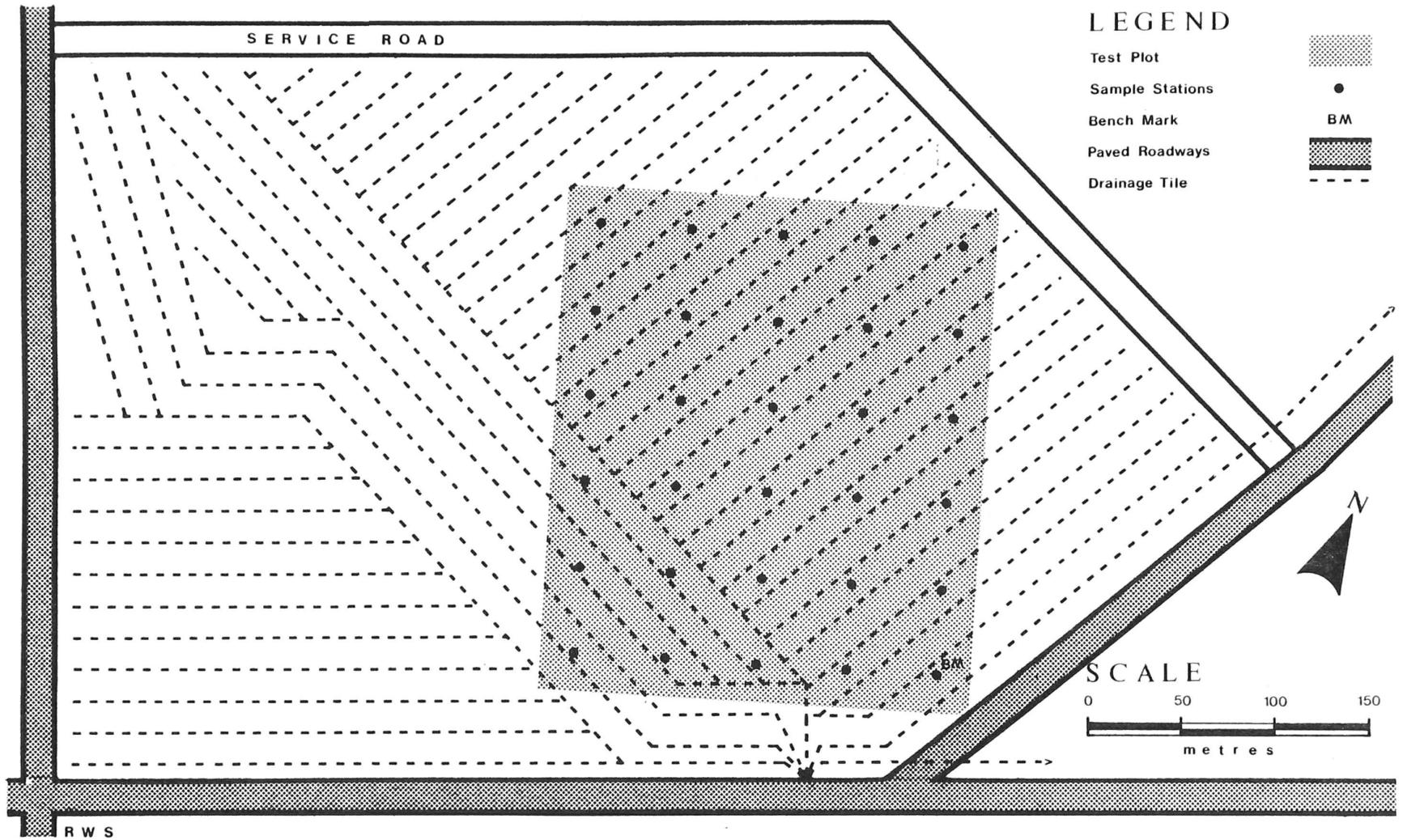


FIGURE 1. SITE LOCATION MAP

1.3 Research Assumptions

Field survey showed that the dimensions of the study plot correspond to a rectangle 200 metres by 250 metres with a maximum elevation difference of 1.98 metres. Based on the physical size and the elevation difference the following assumptions were made:

- 1) Recorded precipitation values are representative of the study area: this precipitation was evenly distributed over the entire plot.
- 2) Surface runoff was not a significant factor as a result of the moderately-low variations in both slope and elevation.
- 3) During the period of the field project a crop of feed corn was growing on the study site, thus providing a uniform vegetation cover. Therefore, evapotranspiration rates were assumed to be uniform across the study area.

The assumptions of uniform supply of moisture and uniform drainage over the study area mean, therefore, that variations in soil moisture content in the top 30 cm of soil should be directly related to the physical properties of the soil found at each sampling location.

1.4 Methodology

Collection of field data required the establishment of a grid system from which repetitive soil moisture observations could be made and soil samples taken. The grid provided a uniform distribution of equally spaced sampling stations.

Soil moisture data were used to construct a series of isopleth maps. These maps provided a means to show areal moisture distributions and for

determining wetting and drying patterns.

Core samples were taken at each of the sampling stations and used for soil fraction analysis and in determining soil moisture retention characteristics. Data obtained from the soil analysis were used to determine grain size distribution (soil type), organic matter content and to construct soil maps. Pressure plate and pressure membrane apparatus were used to determine residual soil moisture content at field capacity and at the permanent wilting point. These data were used to estimate the available water content for the soil type found at each sampling station.

A number of first order regressions were undertaken to test the strength of potential relationships, if any, that existed between variables: grain size, elevation, moisture content and available water content. Potential relationships between grain size and organic matter content, grain size and bulk density, and bulk density with moisture content were also examined.

CHAPTER 2

FACTORS AFFECTING SOIL MOISTURE CONTENT

Soil texture and structure are the primary factors that affect the water content of any soil. Moisture infiltration is dependent on bulk density, aggregate stability, pore size distribution and permeability. These factors are all interrelated.

2.1 Soil Structure

Soil structure refers to the mutual arrangement, orientation and organization of primary soil particles into clusters or aggregates. These clusters are separated from one another by planes of weakness and possess properties unlike an equal mass of individual soil particles.

There are four main categories that may be used to describe the principle types of soil structure: structureless, blocklike, platelike and prislake (Canadian System of Soil Classification, 1978:137). The importance of soil structure cannot adequately be studied without considering its interrelationship with other soil properties, such as: particle density, bulk density, aggregate stability, pore size distribution and permeability. All of these factors will affect the distribution and movement of soil moisture.

2.1.1 Particle Density

The particle density for a specific soil is a constant and does not vary with the amount of pore space found between the primary particles. It is a direct ratio between the mass of the soil particles and their volume:

$$\rho_p = \frac{M_s}{V_s} \quad (1)$$

where: ρ_p = particle density (g/cm^3)
 M_s = mass of the soil particles (g)
 V_s = volume of the soil particles (cm^3)

The SI units for particle density are Kg/m^3 ; however, the fractional SI units of g/cm^3 are commonly used.

For most mineral soils the particle density will vary between 2.5 g/cm^3 and 2.8 g/cm^3 and will usually have an average around 2.65 g/cm^3 (Marshall and Holmes, 1979:10). This value does not vary significantly for different soil types provided there are no large variations in organic content or mineralogical composition (Foth and Turk, 1972:49).

2.1.2 Bulk Density

Bulk density is usually defined as mass per unit volume of oven dry soil and is expressed as g/cm^3 . The bulk density (ρ_b) value is always smaller than that of particle density (ρ_p) since the

calculations include those volumes attributed to air contained in pore spaces:

$$\rho_b = \frac{M_s}{V_t} \quad (2)$$

where: ρ_b = dry bulk density (g/cm^3)
 M_s = mass of the soil particles (g)
 V_t = total volume of soil particles and pore space

Care must be taken in the collection of core samples to preserve the natural structure of the soil. Any change in structure is likely to alter the amount of pore space and likewise the bulk density. Soil mass and pore space vary from horizon to horizon: both are affected by soil texture and structure.

Bulk density tends to increase with depth in the soil profile. This is primarily due to compaction resulting from an increase in overburden pressure and a decrease in soil disturbance. Cultivation will contribute to a lower bulk density for soils found in the plough layer, and at the same time, is suspected for the increase in compaction of soils below the cultivated layer. Compaction to depth will result from the seasonal movement of farm machinery on the soil surface.

The particle size distribution of a soil also influences bulk density. Small particles tend to 'bridge' more than their larger counterparts with the result, they pack much more loosely (Marshall and

Holmes, 1979:10). Soils containing a mixture of soil sizes, in which the smaller particles fill the gaps formed between the larger particles, tend to pack more densely. The bulk density of fine textured and coarse textured surface soils will usually be in the range of 1.0 g/cm^3 to 1.3 g/cm^3 and 1.3 g/cm^3 to 1.8 g/cm^3 respectively (Foth and Turk, 1972:47). Greater structural development in the fine textured surface soils accounts for their lower bulk density as compared to more sandy soils. "In general, the rule that fine textured soils have more pore space and lower bulk densities than coarse textured soils may hold true when comparable structural conditions exist, as in the case when samples taken from plow layers are compared" (Foth and Turk, 1972:48).

Organic soils have a very low bulk density relative to that of the common mineral soils. Considerable variation may exist depending on the nature of the organic matter and the moisture content at the time of sampling. Values ranging from 0.2 g/cm^3 to 0.6 g/cm^3 are common (Foth and Turk, 1972:48).

2.1.3 Aggregate Stability

In order to produce aggregates there must be some mechanism(s) which bond the primary soil particles together into persistent forms. The formation and stability of these aggregates is primarily related to the colloidal fraction present in the soil. Some of the more common colloids that produce aggregation include: oxides of iron, aluminum and manganese; organic matter, including microbial gums; and the quantity and type of clay minerals present (Hillel, 1980:100; Pitty,

1979:105-107; Foth and Turk, 1972:40). Flocculation of soil clay is a necessary condition for aggregate formation; however, by itself this process will not create macroaggregates or macropores necessary for adequate aeration and water movement. In subsoils where the organic matter content and the level of microbial activity are low, iron oxide is commonly the most effective colloid-producing aggregation (Foth and Turk, 1972:45).

Soil aggregates and their arrangement (soil structure) can be of major importance in determining soil productivity, since they greatly affect the water, air and temperature regimes within the soil. Soil structure will also influence the mechanical properties of the soil, which in turn affect germination, root penetration and growth. Localized effects of compaction or disturbance may result from improper cultivation, irrigation and drainage operations. The top layer of soil, corresponding to the plough layer, is particularly vulnerable to structural deterioration.

2.2 Water Infiltration

Infiltration is the process whereby water enters the surface strata of the soil and percolates downward toward the water table. The rate and amount of infiltration is related to permeability, which is, itself, related to porosity and pore size distribution. Water movement is also related to the number of interconnections (passages) between pores and the stability of the soil grains. The maximum rate at which a soil in any given condition is capable of absorbing water is called its infiltration capacity.

2.2.1 Pore Size Distribution

The macroscopic size of most soil peds will result in the existence of interped spaces that are much larger than those that can exist between adjacent soil particles. These spaces serve as corridors for root extension and for the movement of air and water through the soil. "It is this effect of structure on the pore space relationship that makes structure so important" (Foth and Turk, 1972:38).

The percentage of pore space may be calculated from the bulk density and particle density:

$$\frac{\rho_b}{\rho_p} \times 100\% = \% \text{ soil particles} \quad (3)$$

$$100\% - \left(\frac{\rho_b}{\rho_p} \times 100\% \right) = \% \text{ pore space} \quad (4)$$

where: ρ_b = dry bulk density (g/cm^3)
 ρ_p = particle density (g/cm^3)

Porosity is normally expressed as a percentage and indicates the total volume of all pores; thus, no distinctions are made between pores of different size or shape.

"Since water molecules are strongly adsorbed onto the surfaces of the soil particles, as adhesion water, pore size is of great importance to the movement of water into and through the soil. By contrast, the weak attraction between soil particles and air results in the air movement being primarily related to the volume of the vacant soil pores and not to their size" (Foth and Turk, 1972:50-51).

It is quite common for a soil to be very porous and at the same time be slowly permeable to water. This may be demonstrated by comparing the permeability of sandy and clayey soils.

Sandy Soils. The total volume of pore space found in a sandy soil is much lower than that found in a clay of equal volume. However, a greater proportion of these pores are of a larger size and results in a freer movement of water and air. Consequently, sandy soils will generally have a low water holding capacity.

Clay Soils. Although clay soils have a greater total volume of pore space the size of the individual pores (micropores) restricts water movement and aeration. Clay minerals also have a much greater surface area exposed to the bonding of adsorption water. Fine textured clay soils will generally have a much higher water holding capacity. However, the largest quantities of available water may not necessarily coincide with soils containing the highest clay content, since a higher suction will be required to make this water available for plant growth.

2.2.2 Permeability

Permeability is directly related to the number of passages or interconnections between pore spaces. Most aspects of soil wetting processes and the water balance as a whole, including surface runoff, are controlled largely by the permeability of the soil (Pitney, 1979:120).

Theoretically, there is an exponential increase in permeability to the fourth power with an increase in pore size (Hillel, 1980:168):

$$Q = \pi R^4 \times \frac{\Delta p}{8\eta L} \quad (5)$$

where: Q = flow (permeability)

R = radius of the capillary tube

Δp = change in pressure

η = viscosity of the soil water

L = length of the capillary tube

This equation, known as Poiseuille's Law, illustrates that volume flow rate is proportional to the pressure drop per unit distance and to the fourth power of the radius of the capillary tube.

Permeability can be directly affected by the swelling of clays. In dry clays, water movement will be primarily through soil filled shrinkage cracks, since the small nature of the micropores will tend to restrict water movement. Conversely, during wetting certain clays will approach zero permeability as soil swelling tends to close the shrinkage cracks. The permeability of a soil will depend on the continuity, stability and persistence of the macropores with time (Pitty, 1979:121).

2.3 Factors Affecting Infiltration

The infiltration capacity of any soil is affected by the combined interaction of many factors. These factors may cause the infiltration capacity to differ from one location to another, produce variations from time-to-time at any given location or cause variations with both location and time.

2.3.1 Depth of Surface Detention and Thickness of the Saturated Layer

During the initial stages of a rainfall event, rain water will infiltrate into the soil mainly through surface cracks principally under the influence of gravity. As the surface layer of soil becomes saturated, capillarity will aid the flow of water through macropores and intervening passages. Theoretically, the configuration of these pores and the connecting passages form tiny capillary tubes that conform to theories of hydraulic flow. In reality the natural configuration (geometry) of these voids is much more complex.

The total pressure or head that results in moisture flow is composed of the addition of two components (Wisler and Brater, 1959:105):

- i) the pressure that is produced by the depth of surface detention (D), and
- ii) the pressure that corresponds to the height of water contained in the capillary tubes (L).

Figure 2 illustrates this relationship.

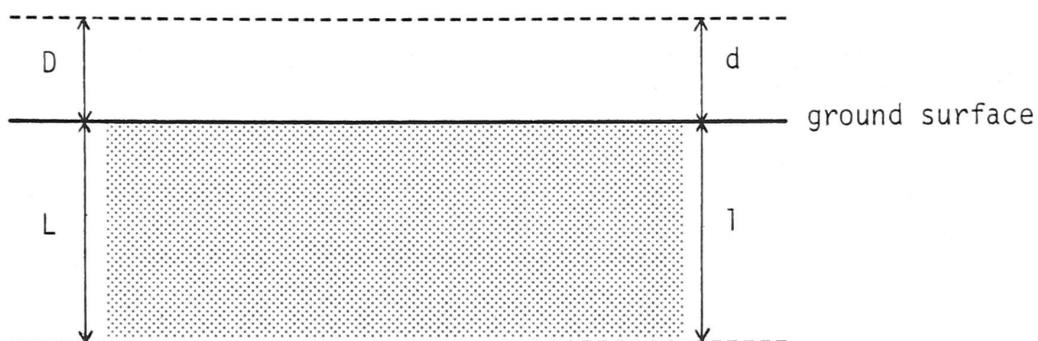
The force of gravity is opposed by the development of capillary suction, the magnitude of which is related to the surface tension which exists across the menisci of water films in contact with neighboring soil grains (Carson, 1977:98):

$$S = 2 \times \frac{T_s}{R} \quad (6)$$

where: S = capillary suction (dynes/cm²)

T_s = surface tension of water (dynes/cm)

FIGURE 2. RELATIONSHIP BETWEEN SURFACE DETENTION
AND THICKNESS OF THE SATURATED LAYER



where: d = depth of surface detention

l = depth of saturated layer

D = pressure produced by depth of surface detention

L = pressure corresponding to the height of water in
the capillary tubes

R = radius of curvature of the menisci (cm)

This resistance to water movement is proportional to the length of the capillary tubes, which is approximately equal to the thickness of the saturated layer.

At the beginning of a rainfall, and when the depth of surface detention (d) and the length of the capillary tubes (l) are of the same order of magnitude, the force of gravity will be large compared to capillary suction. This is one reason why the rate of infiltration is relatively high at the beginning of a rainfall event (Wisler and Brater, 1959:105).

When the length of the capillary tubes (l) is large, compared to the depth of surface detention (d), any change in (l) will result in a corresponding and nearly equal effect between the force of gravity and capillary suction. Under these conditions the rate of infiltration will be nearly constant (Wisler and Brater, 1959:105).

2.3.2 Existing Soil Moisture

Existing moisture contained in the upper soil layer presents two opposing factors that affect infiltration rates (Wisler and Brater, 1959:105). Firstly, if the soil is dry at the beginning of a rain, the wetting of the top layer will create a strong capillary potential just below the surface which will supplement the gravitational force. The initial infiltration rate will also tend to be very high in soils that contain large shrinkage cracks. Secondly, when subjected to wetting, colloids present in the soil will swell and reduce the

infiltration capacity during the initial period of rainfall. The shrinking and swelling soil colloids may also be partly responsible for seasonal variations found in infiltration rates.

2.3.3 Inwash of Fine Soil Materials

Raindrops, as they collide with soil particles or clods, will dislodge many of the primary soil particles. This breakdown of structure will release fines which can clog surface soil pores, thus forming a layer of reduced porosity and permeability at the surface of the soil. Excessive surface runoff and erosion may result if infiltration rates are exceeded.

2.3.4 Compaction Due to Rainfall

Compaction resulting from rainfall can cause the surface of exposed clay soils to be worked into an impermeable condition. Ponding of water will occur where surface compaction has taken place and during periods of intense rainfall may result in excessive surface runoff and erosion. Soils composed principally of clean sands are affected very little by rain compaction and are thus able to maintain relatively high infiltration rates.

2.3.5 Vegetation Cover

The presence of a dense vegetation cover, such as grass or forest growth, will tend to promote high infiltration rates. Vegetation cover will provide some protection from compaction by intercepting and/or breaking the fall of raindrops. A layer of decaying organic

matter and the formation of humus will aid the development of good soil structure and will also promote the activity of borrowing insects and animals.

Open crops, such as potatoes or corn, will provide little protection from rain compaction and only a partial cover of organic matter. Infiltration rates may tend to be relatively low in areas covered by such crops (Wisler and Brater, 1959:106).

CHAPTER 3

METHODS OF DETERMINING SOIL MOISTURE CONTENT

In the past, researchers have used numerous methods to determine or estimate soil moisture content. Three of the more common methods have been based upon gravimetric determination, electrical resistivity and neutron scattering. A new method, TIME DOMAIN REFLECTOMETRY (TDR), has been developed to estimate the volumetric water content of an undisturbed soil in the field. Under conditions normally found in the soil, the TDR method is not affected by many of the problems that the other methods are subject to.

3.1 Time Domain Reflectometry

Time Domain Reflectometry (TDR) is a form of pulse reflection measurement that is used to determine the propagation velocity and reflection of electromagnetic waves in a transmission line. When a transmission line is connected to the TDR unit a broad band electrical pulse, provided by a small step-voltage, will travel down the length of the line remaining unaltered as long as the electrical characteristics of the line remain the same. Discontinuities in the line will result in the partial reflection and partial transmission of the electrical pulse at every impedance mismatch. By determining the position of the electrical start and end points of the transmission

line it is possible to calculate the corresponding travel time, dielectric constant and volumetric water content of a soil sample (Topp et al., 1980:574-582).

The Tektronix 1502 TDR unit is available commercially as an electrical cable tester. It provides a 200mV step-voltage which has an incident rise time of less than 0.1 nanosecond. This rise time covers a wide bandwidth of frequencies up to a maximum of 3.5 GHz (Patterson, 1980).

3.1.1 Dielectric Properties of Soils

The electrical permittivity of a substance describes its ability, relative to that of a vacuum, to store electrical potential energy while under the influence of an electrical field. Since the permittivity of a dielectric is always greater than that of a vacuum, it is often expressed as being the relative permittivity (K') of the dielectric (Krause and Carver, 1973:57).

$$K' = \frac{E'}{E_0} \quad (7)$$

where: K' = the relative permittivity of the dielectric

E' = the permittivity of the dielectric

E_0 = the permittivity of a vacuum

Both E' and E_0 are expressed in Farads per metre (F/m), and K' is a dimensionless ratio. The relative permittivity (K') of air is so close to unity that for most applications air may be considered as equivalent to a vacuum.

Within a disperse system, such as a loose wet soil, K' is related to the volumetric ratios of its components. Most importantly, K' is highly sensitive to the volume of water present in the soil (Topp et al., 1980:574; Davis et al., 1977; Chernyak, 1964:20). Due to this sensitivity, the dielectric constant (K^*) of a natural soil may be used as a measure of its water content. The dielectric constant (K^*) will vary with changes in temperature, soluble salt content and with soil mineralogy. As such, K^* is not a true constant.

For most common soil minerals, K^* does not exceed 10 to 12 (Chernyak, 1964:20). Normally values fall in the range of 2 or 3 for dry bulk soils, whereas K^* of water is approximately equal to 81.5. Therefore, any change in the amount of water present in a soil has a marked effect on its overall dielectric constant (Chernyak, 1964:20).

The dielectric constant is often expressed in complex notation involving capacitance and conductance. Davis and Annan (1977) define the complex dielectric constant as:

$$K^* = K' + j\left(K'' + \frac{\sigma_{dc}}{wE_0}\right) \quad (8)$$

where: K^* = the complex dielectric constant

K'' = the imaginary component of K^*

j = an imaginary number ($-1^{1/2}$)

σ_{dc} = the low-frequency conductivity

w = angular frequency ($2\pi f$)

Over the frequency range of 1MHz to 1GHz, the effective operating range of TDR, the real part (K') of the complex dielectric constant (K^*) is not strongly frequency dependent (Davis and Annan, 1977). However, at higher frequencies a second dielectric parameter, dielectric loss, also becomes important. The dielectric loss of a soil describes the total amount of energy dissipated as heat (Chernyak, 1964:25). Davis and Annan (1977) define the dielectric loss tangent as:

$$\text{Tan}\delta = (K'' + \frac{\sigma_{dc}}{\omega E_0}) / K' \quad (9)$$

If the loss term is significantly less than 1.0, then K^* is approximately equal to K' . Thus for low-loss and nearly homogeneous materials K' approximates K^* . Topp et al. (1980:575) refer to the measurable portion of the complex dielectric constant (K^*) as being the apparent dielectric constant (K_a).

The magnitude of dielectric loss is not determined solely by the value of the through current but, to a certain extent, it depends on the frequency of the applied electrical field and the soil structure (Chernyak, 1964:25). Conversely, for a given frequency, the magnitude of the dielectric losses is dependent on moisture content, chemical composition, mineralization of ground water, and the quantity and composition of the clay fraction (Chernyak, 1964:25).

The relative permittivity (K') in the 1MHz to 1GHz range appears to be highly sensitive to the volumetric water content (θ_v) and weakly sensitive to soil type and soil density. Von Hippel (1954) indicated

that K' for water varied only slightly with temperature (80.1 at 20°C to 87.7 at 0°C) and showed minimal frequency dependence from direct current to about 3.0 GHz. Dielectric loss ($\text{Tan}\delta$) is also small in this range. With water at 25°C, $\text{Tan}\delta = 0.04$ at 1.0 MHz and 0.016 at 3.0 GHz (Von Hippel, 1954). Davis and Annan (1977) also indicated that the dielectric loss was considerably less than K' in the frequency range 1.0 MHz to 1.0 GHz.

3.1.2 Determining Volumetric Water Content From the Apparent Dielectric Constant

The apparent dielectric constant (K_a) can be determined for a medium in which the dielectric losses are small by measuring the trace length of the incident pulse. When parallel transmission lines are used, with the TDR unit, the crt display (cathode ray tube) will show a line trace as illustrated in Figure 3. (A) denotes the point where the parallel transmission lines are attached to the head connector. The precise location of this point can be determined by recording and comparing the characteristic trace of the head connector before and after connecting the transmission lines. Each probe has its own characteristic trace. (B) denotes the point where the electrical pulse encounters the end of the transmission line. The horizontal distance, A to B, represents the trace length of the incident pulse and can be used to calculate the one-way travel time, as follows. The horizontal scale setting of the TDR unit can be converted to a time axis by using (Patterson, 1980:21):

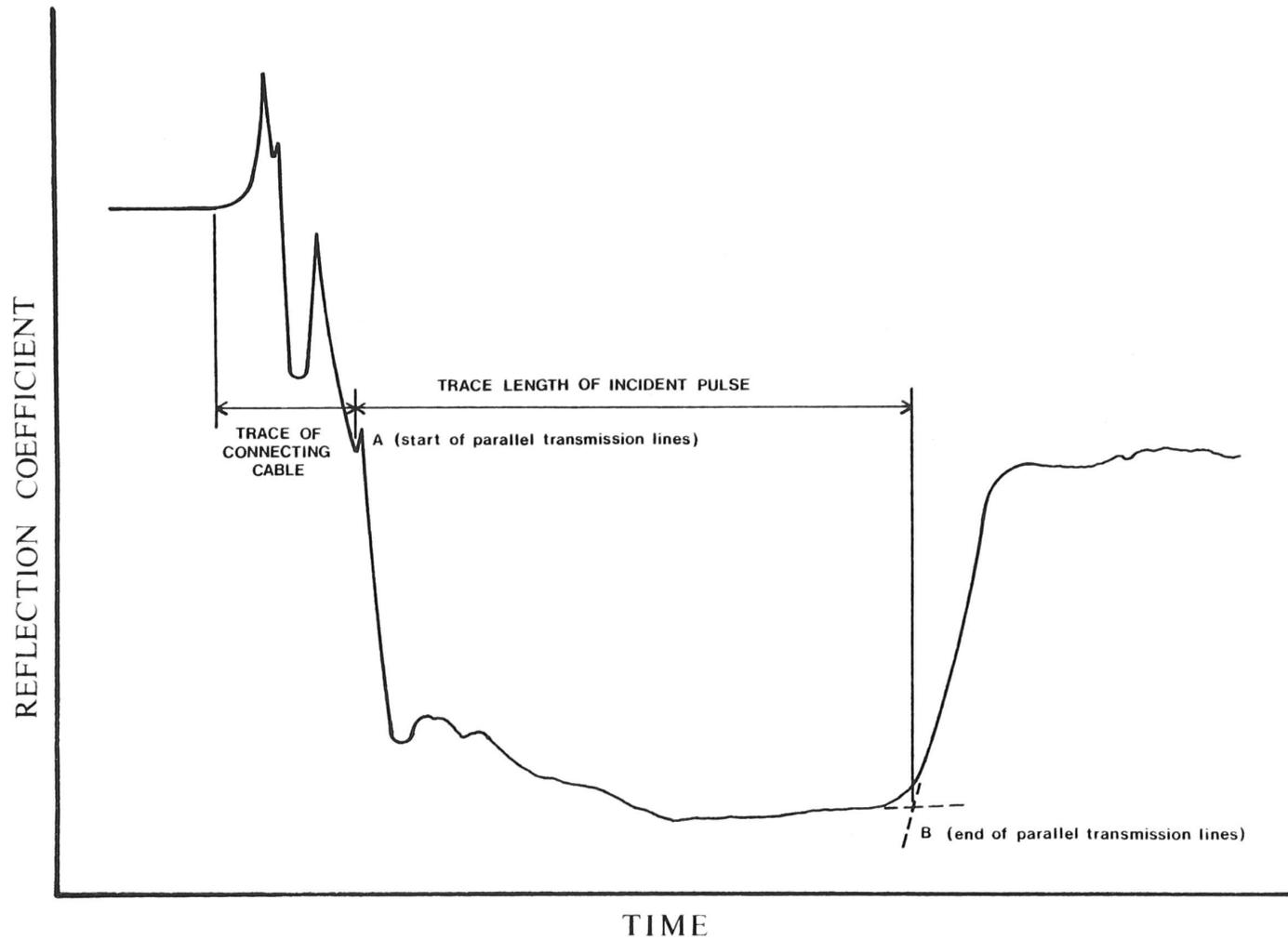


FIGURE 3. DETERMINING TRACE LENGTH OF THE INCIDENT PULSE

$$\text{time (tt)} = \frac{\text{metres/division}}{c} \times \text{no. of divisions} \quad (10)$$

where: time (tt) = one-way travel time of the incident pulse (ns)

no. of divisions = trace length of the incident pulse on the crt display

metres/division = horizontal scale on the TDR

c = free-space velocity (0.3 m/ns)

The propagation velocity (V_p) of the pulse can be determined when the travel time (tt) and the length of the transmission line (l) are known (Patterson, 1980:20):

$$V_p = \frac{l}{tt} \quad (11)$$

In complex notation, the propagation velocity (V_p) is determined by (Topp, et al., 1980:575):

$$V_p = \frac{c}{\left\{ K' \times \frac{1 + (1 + \text{Tan}^2 \delta)^{1/2}}{2} \right\}^{1/2}} \quad (12)$$

For low loss materials, where $\tan \delta$ is substantially less than 1.0, the propagation velocity (V_p) can be expressed as (Davis and Annan, 1977):

$$V_p = \frac{c}{K_a^{1/2}} \quad (13)$$

Thus, K_a can be determined if the transmission line length (l) is known and the travel time (tt) is measured. This is accomplished by equating equation 11 with 13 (Patterson, 1980:20):

$$V_p = \frac{l}{tt} = \frac{c}{K_a^{1/2}} \quad (14)$$

$$K_a^{1/2} = \frac{(c \times tt)}{l} \quad (15)$$

therefore:

$$K_a = \left\{ \frac{(c \times tt)}{l} \right\}^2 \quad (16)$$

Once K_a has been determined, the corresponding volumetric water content (θ_v) can be calculated from the empirical relationship of Topp et al., (1980:580):

$$K_a = 3.03 + 9.3 \theta_v + 146.0 \theta_v^2 - 76.7 \theta_v^3 \quad (17)$$

This relationship was constrained to pass through ($K^* = 81.5$ and $\theta_v = 1.0$) the data point for pure water at 20°C. Topp et al. (1980:580) found that for general application to mineral soils, this relationship could be used to determine volumetric water content with a standard error of estimate of 1.3% over the complete range of water contents tested. Many of the data points falling outside of this range occurred at low or very high water content extremes, which are less often

encountered in the field (Topp, et al., 1980:580).

3.1.3 Factors Affecting the Use of Time Domain Reflectometry

Topp et al. (1980:574-582) determined the relationship between the apparent dielectric constant (K_a) and the volumetric water content (θ_v) by applying the TDR technique to coaxial transmission lines filled with soil. Using fine-grained mineral soils, ranging from 9% to 66% clay content, the TDR technique gave effectively the same K_a versus θ_v relationship. Soil density variations did not appear to affect the water contents; however, they were found to significantly affect the lateral distribution of water within the soils tested. Difficulties were encountered in determining bulk densities values which were needed for converting gravimetric values to a volumetric basis.

Soils containing a high percentage of clay-size particles were found to show a smaller variation in the value of K_a , determined for a corresponding change in θ_v , to approximately a total of 10% volumetric water content (Smith and Patterson, 1981:13). This relationship may be a result of the large exposed surface area of the individual clay particles and their effect upon the dielectric constant of the first few molecular layers of water (bound water) surrounding each of the soil particles (Topp, et al., 1980:574; Wang and Schmutge, 1980). Chernyak (1964:21) suggests that the bound water may be dielectrically saturated and will appear to have a much lower dielectric constant than that of pure water.

An increase in the quantity of clay-size particles should result

in a corresponding increase in the volume of bound water contained in the soil. This increase of bound water should also be accompanied by two opposing processes (Chernyak, 1964:21): a decrease in the overall dielectric constant; and the development of electrical double-layers, their polarization, and an overall increase in the dielectric constant. As the distance between the mineral surface and the bound water increases, the effects of molecular attraction will become less, and a corresponding increase in the dielectric constant will result.

Recent experimentation by Smith and Patterson (1981:13) has indicated that the relationship between K_a and θ_v for granular materials showed a vertical displacement and less curvature, when graphically represented, than that found for fine-grained mineral soils by Topp et al. (1980). This relationship was previously noted by Patterson (1980:23-26) for materials containing large quantities of crushed stone.

Table 1 illustrates the dielectric values of water corresponding to the temperature range of 0°C to 50°C . It would seem, therefore, that the relationship between K_a and θ_v should be temperature dependent. A series of experiments by Chernyak (1964:48-49) included the use of fine-grained quartz sands that were saturated with distilled water, 0.1% aqueous solution of NaCl or saturated aqueous solutions of $\text{CaSO}_4 \cdot n\text{H}_2\text{O}$. The test results showed an indirect relationship between increasing temperature and the corresponding value of K_a . Similar results were recorded when using distilled water and for solutions of NaCl, and $\text{CaSO}_4 \cdot n\text{H}_2\text{O}$. The only difference was in the absolute values of the dielectric constant and in the rate of its decrease. For

TABLE 1. DIELECTRIC VALUES OF WATER FOR THE
TEMPERATURE RANGE OF 0°C TO 50°C

| TEMPERATURE/ DIELECTRIC CONSTANT (K*) | 0 | 10 | 20 | 25 | 30 | 40 | 50 |
|---------------------------------------------|-------|-------|-------|-------|-------|-------|-------|
| a_{K^*} | 87.83 | 83.86 | 80.08 | 78.25 | 76.47 | 73.02 | 69.73 |
| b_{K^*} | 87.7 | | 80.1 | | | | |

a) Chernyak, 1964:23

b) Von Hippel, 1954

mixtures of pure water and fine-grained sands the empirical relationship between temperature and K_a approached a straight line.

Experiments with compact samples of low moisture content revealed a completely different relationship between temperature and K_a (Chernyak, 1964:49). The value of K_a , as determined for all of the samples, increased with increasing temperature. Chernyak (1964:50) suggests that this relationship may be affected by changes in the mineralogical composition and microstructure of the samples and in the distribution of water within them. For all of the samples tested, Chernyak noted that a rise in temperature was accompanied by an increase in dielectric losses.

In more recent investigations, Wobschall (1978) and Davis and Annan (1977) reported that in the 1.0 MHz to 1.0 GHz frequency range K_a did not vary significantly as the temperature ranged from 0°C to 30°C. Topp et al. (1980:580) observed an increase in attenuation (greater scattering of data points) as temperature increased. Their findings show that as the temperature ranged from 10°C to 36°C the variation in K_a was less than the experimental error of $\pm 1 K_a$, as determined at 20.5°C. Data shows that K_a is temperature dependent; however, the variation in K_a is within the limits of experimental error for the range of temperature experienced in the field during this study.

The dielectric constant of electrolytes depends on their nature and concentration. For low concentrations, in ground water, it is sufficiently accurate to assume that their dielectric constants are equal to those of pure water (Chernyak, 1964:20).

A comparison of K_a versus θ_v by Topp et al. (1980:580) indicated that the salt concentrations normally present in a soil-water system had no measurable effect on K_a . The dissolved salts did not alter the travel time of the voltage-step in the medium; however, there was an increase in attenuation as it travelled in the soil which may make it difficult or impossible to obtain a K_a estimate using a probe of given dimensions. The relationship between K_a and θ_v was characterized by greater scattering of data points as the concentration of the salt solution was increased. Increased attenuation was also observed as the soil temperature was increased, as the soil texture became finer and as the water content increased.

3.2 Gravimetric Method

The gravimetric method is a direct sampling procedure that allows for the calculation of the total water content (not including interstitial water) found in the soil. Collection of samples does not involve any special difficulties since the preservation of the natural soil structure is not required.

The gravimetric method is generally accepted as a standard approach for determining mass moisture content. For this reason it is often used in the calibration of various electrical, resistance and thermal soil moisture detecting equipment. Under controlled field and laboratory conditions this method may be one of the more accurate; however, there are a number of difficulties inherent in the procedure.

3.2.1 Procedure

A known mass (g) of soil is placed in a drying oven at 105°C for approximately twenty-four hours. Following thorough drying the soil sample is allowed to cool in a desiccator containing a drying agent. When cooling has been completed, the soil sample is reweighed and the loss in weight is attributed to the evaporation of water initially present.

$$W_m = \frac{g_1 - g_2}{g_2 - g_3} \quad (18)$$

where: W_m = mass wetness (gravimetric wetness)
 g_1 = mass of drying tin and fresh soil sample
 g_2 = mass of drying tin and oven-dried soil
 g_3 = mass of drying tin

The units derived in using the gravimetric approach are g water/g dry soil.

To derive the volumetric water content (θ_v) from the gravimetric determination, the bulk density of the soil sample must be known.

$$\theta_v = W_m \times \frac{\text{bulk density of dry soil}}{\text{density of water}} \quad (19)$$

The units derived in determining θ_v are: g/g X g cm⁻³/g cm⁻³.

The measurement of bulk density, particularly in the field, is difficult and subject to errors. Some of the difficulties likely to be encountered are examined in Sections 3.2.2 and 4.3.

3.2.2 Problems Associated With the Gravimetric Method

The gravimetric method is both time consuming and requires the use of laboratory facilities; there is also the possibility that samples may be subjected to desiccation during storage and/or transit. Variations caused by natural heterogeneity and root distribution will require that numerous samples be taken to accurately determine the water content of any plot or area (King, 1967:273).

Some clays may retain relatively large quantities of absorbed water even after drying at 105°C for twenty-four hours. This difficulty may be overcome by drying the soil samples at substantially higher temperatures for shorter periods of time (i.e., 400°C for four hours). Since organic materials present in the samples will be ashed at these higher temperatures, it is necessary to first determine the organic content of the samples. Such a procedure is described in Section 4.4.2.

Collection of soil samples in the field for later analysis in the laboratory is a destructive procedure. Therefore, repetitive measurements cannot be taken at precisely the same location each time.

3.3 Resistance Method

Methods utilizing the electrical properties of soils and soil-water solutions have been developed to determine moisture content. Physical properties related to heat capacity, thermal conductivity and

electrical resistivity are fundamental to these approaches. Since electrical resistance and thermal conductivity of a soil are primarily dependent on the amount of water present, it is possible to use these properties as an index of soil moisture content.

3.3.1 Factors Affecting Resistivity

The major factors affecting the electrical resistivity of a soil-water system include: quantity of water present, mineral composition, soil texture and the concentration of soluble salts.

There is a direct relationship between the quantity of soil water and the conductivity of the soil-water system. As a result of their dipole nature, water molecules are easily attracted to both positively and negatively charged soil particles. This attraction tends to lessen the electrostatic interaction between particles, thus contributing to chemical dissociation within the soil-water system. The water component acts as a solvent and the soil grains act as solute particles. The easy dissociation of electrolytes in water helps to explain the high dielectric constant for water (Soydemir, 1971:11).

The electrical conductivity of any soil will vary with mineral composition, particularly with the type and amount of clay present. There tends to be a direct relationship between electrical conductance and chemical dissociation (Soydemir, 1971:8). In clays, dissociation takes place on the mineral surfaces and results in excessive numbers of free ions. The large exposed surface area, characteristic of clay minerals, results in a higher degree of dissociation, and consequently a higher electrical conductivity (Soydemir, 1971:9-10).

The average particle size will also affect the overall electrical conductance of a soil-water system. For a given clay concentration there is an apparent increase in conductance with a decrease in mean particle size (Soydemir, 1971:10). The smaller clay particles, at a specific clay-water concentration, will have a much larger surface area exposed to chemical dissociation and isomorphic substitution. The increase in free ions will result in a higher electrical conductivity.

Grain size distribution will also influence the electrical conductivity of the system. This is related to the geometry of the pore spaces varying for different distributions. It should be noted however, that the mineral particles themselves have a significantly low electrical conductivity when compared to that of the soil water (Soydemir, 1971:10).

Electrical conductivity may be affected to a large extent by the type and concentration of salts present. The potential for chemical dissociation will increase with the addition of dissolved salts. This will result in a larger number of free ions that may contribute to an increase in electrical conductivity.

3.3.2 Resistance Blocks

Resistance blocks consist of a pair of sensing elements (electrodes) that are placed into the soil and have a known electrical voltage applied across them. The electrical resistance between the electrodes is then measured by means of a Wheatstone Bridge. When the soil moisture content is high, the electrical resistance of the soil-water solution

will be low, and the heat generated by the applied voltage will be rapidly conducted away from the resistance leg of the Bridge. As the soil moisture content becomes less the thermal conductivity of the soil is lowered. The resulting increase in temperature, associated with the increase in electrical resistance, will cause the Bridge to be thrown out of balance. The degree to which the Wheatstone Bridge is out of balance is an indirect measure of the soil moisture content.

To insure adequate ground contact the electrodes may be enclosed in porous resistance blocks, such as: gypsum, fiberglass, nylon or a combination of these materials. When placed in direct contact with the soil, a state of equilibrium develops between the matric potential (suction) of the resistance blocks and that of the soil. In effect, this procedure involves measuring the electrical resistance of the porous blocks following the establishment of equilibrium. Each pair of resistance blocks must be calibrated in order to determine the actual moisture content that corresponds to each of the resistance values.

The electrical resistance of the soil-water system, as determined with the resistance blocks, will depend on: the relative affinity of the soil and the resistance blocks for water, the amount of water present in the system, the rate of water flow between the soil and the resistance blocks, and the electrical conductivity of the soil-water solution within the electrical influence of the electrodes (Taylor and Ashcroft, 1972:270).

The shape and dimensions of the resistance blocks must be

carefully selected to minimize the response time (lag time) while maintaining the efficiency of the blocks. They should also be of sufficient size to insure that the lines of electrical force remain inside the resistance blocks.

3.3.3 Problems Associated With the Use of Resistance Blocks

Soils may differ substantially from one another in terms of their individual soil moisture versus suction relationships. For this reason the porous blocks should be calibrated for each soil under investigation. They may be calibrated by embedding them in soil placed in a porous plate or pressure membrane apparatus (Tanner, Abrams and Zubriski, 1948; Haise and Kelly, 1946 - referenced by Taylor and Ashcroft, 1972:272). There may also be a significant variation between blocks made of identical materials; consequently, a calibration curve should be derived for each of the resistance blocks used. Hillel (1980:127) suggests that calibration relative to soil suction (matric potential) values is the preferred approach.

In most circumstances there is a time lag prior to the establishment of equilibrium between the resistance blocks and the surrounding soil. The time lag is primarily a result of the hydraulic properties of the block; however, inadequate contact with the soil may also produce the same results. This effect, as well as sensitivity, may not be constant through the entire range of soil moisture conditions.

All resistance blocks tend to be sensitive to dissolved salts to some extent. However, blocks composed of fiberglass or nylon show much higher degrees of sensitivity (Taylor and Ashcroft, 1972:270;

Chang, 1977:194; and Hillel, 1980:127). Gypsum blocks are favored because of their buffering capacity that makes them less vulnerable to minor changes in salt concentrations (Chang, 1977:194; Hillel, 1980: 127-128). However, gypsum blocks have properties that make them difficult to calibrate precisely: the calibration may drift with time.

3.4 Nuclear Method

The use of nuclear methods for determining soil moisture content is based on the scattering and moderation of fast neutrons by hydrogen atoms. In natural soils hydrogen may be present in several forms, including that which is present in soil water, and as non-water hydrogen existing in the crystalline structure of the clay minerals, in amorphous material, in hydroxides and in organic matter. However, the majority of the hydrogen occurs in the adhesion and cohesion water contained in the soil.

When a thermal neutron detector is placed near a neutron source in a medium containing hydrogen, the atomic activity registered is due almost entirely to neutrons that have been slowed down by hydrogen atoms. Other atoms present in the soil play a negligible part in this process. The degree of interaction between the fast neutrons and the hydrogen atoms may be used as an indirect measure of soil moisture content.

3.4.1 Neutron Scattering

As high energy neutrons are emitted into the soil the majority will undergo a decrease in velocity (loss of kinetic energy) as they collide with the nuclei of other atoms present in the soil. The rate at which this slow-down occurs depends on the mass of the nucleus in collision with the neutron and the probability that the two will collide. The high energy neutrons may either be scattered or captured by the atomic nuclei that they are in collision with.

The probability that a neutron will collide with the nucleus of an atom is dependent on the atom's scattering cross-section. For most elements, this value is low, usually increasing with a decrease in neutron energy. The scattering cross-section of the hydrogen atom, however, is larger than that for most of the other atoms present in soils.

Due to the similarity in mass between the hydrogen atoms and the neutrons, the former are more effective (relative to atoms of larger mass) in decreasing the kinetic energy and slowing of the neutrons (Gardner and Kirkham, 1952). Atoms having a much larger mass may impart some of their own kinetic energy to the neutrons and result in the maintaining or increasing of neutron velocity.

Soil elements that have a high absorption or capture cross-section will absorb a certain percentage of the neutrons, thus causing erroneously low readings of thermal-neutron activity. Elements having relatively large cross-sections (associated with low neutron energy) include: boron, nitrogen, chlorine and iron. Variations in the

concentrations of these or other elements may cause differences in calibrations between soils.

The absence of charge and low energy level of thermal neutrons facilitates their absorption by suitable atomic nuclei such as ^{10}B or ^6Li . The consequent nuclear reactions produce ionization that can be detected with the aid of proportional counter tubes or scintillation counters. Scintillation counters, although more sensitive to neutrons, are also more responsive to gamma radiation.

3.4.2 Neutron Source

Several small portable sources of high energy neutrons are available, and to varying degrees all produce some gamma radiation (Long and French, 1967:149-150). Under most circumstances, the source materials are chosen for their longevity so they can be used for a number of years without appreciable change in radiation flux. The use of americium-beryllium (half life of 458 years) has been preferred to that of radium-beryllium (half life of 1620 years) as a neutron source. Both materials emit hazardous radiation; however, a mixture of americium-beryllium emits much lower levels and on a safety basis is preferred for normal field applications (Hillel, 1980:129).

3.4.3 Neutron Depth Probe

There are essentially two types of nuclear meters used in soil moisture investigations: the surface meter, which is used to determine near surface moisture content, and the depth probe, used to determine water content at greater depths. Both of these instruments operate

in much the same manner; however, emphasis will be placed on the latter due to its measurement capability at greater depth.

The volume of soil sampled, with the depth probe, tends to be spherical in shape and depending on the moisture content may vary from 15 cm to 50 cm in diameter (DeVries and King, 1961: and Van Bavel, et al., 1961). The maximum diameter sampled, at the lowest moisture contents generally encountered in soils, is about 60 cm (2 ft.). This diameter will diminish rapidly with only a slight increase in moisture content. Access tubes made of aluminum or plastic are used to lower the probe to the desired depth.

Normally, the depth probe cannot be centered at depths shallower than 25 cm to 30 cm without some of the fast neutrons escaping through the ground surface, lowering the slow neutron density and count rate (Grant, 1975:124-129; Pierpoint, 1966:189-192). This low degree of spatial resolution renders the depth probe unsuitable for detection of water-content discontinuities (i.e., wetting fronts or boundaries between layers). The relatively large volume monitored can, however, be an advantage in water balance studies since the larger soil volume is generally more representative of field conditions.

Access tubes may lead to surface runoff infiltrating into the soil should voids develop along the tube/soil contact. Water entering the soil in this manner could seriously affect the natural distribution of soil moisture and the accuracy of the soil moisture determinations.

3.4.4 Need for Calibration

Ideally, the soil used in the calibration procedure should be

homogeneous in structure, density and moisture content, and the volume large enough to be infinite to the neutron flux. Variations in structure, grain size and density will ultimately affect the possibility of having a uniform distribution of moisture. If the volume of soil around the source is too small, as is the situation when taken near the ground surface, some of the fast neutrons may escape to the atmosphere and go uncounted. Sources of error related to instrumental and soil moisture variance are discussed by Hewlett et al. (1964:19-24) and Bell and Eeles (1967:1-3). Van Bavel (1962:405) discusses the accuracy that may be attained in using neutron probes for determining soil moisture content.

Calibration in situ presents a number of difficulties. The determination of soil moisture content from readings taken in the field is not sufficiently accurate to be used as a calibration standard. There are usually significant variations in any soil-moisture system that may result from point-to-point differences in grain size, bulk density, organic content, soil structure and/or soil mineralogy. As a result, there is no control over moisture content in the field and it is impossible therefore, to reproduce accurate results (ASTM 293, 1960:17). Since the complete control of all important parameters is necessary for accurate calibration, it must be undertaken in the laboratory (ASTM 293, 1960:18).

Calibration performed in the laboratory, however, will not be totally representative of the soil conditions present in the field. When natural soil materials are used, they are most often disturbed samples, in which the natural soil structure and soil density have

been altered. Difficulties arise when attempting to use natural soils that have a broad range of grain sizes, particularly in achieving a uniform density and moisture distribution throughout the sample. Because of the natural variations that exist between soils, each soil under investigation should be individually calibrated.

3.5 Comparison of Methods: Advantages of Using Time Domain Reflectometry

The electrical theory basic to the understanding of TDR may appear to be rather complex; however, the procedures required to operate the equipment, to take moisture readings, and the interpretation of these readings is easily accomplished. By using the empirical relationship presented by Topp, et al., (1980:580) accurate in situ moisture contents can be determined with a standard error of estimate of 0.013 (e.g., 1.3%).

Some difficulties may be encountered during the insertion of relatively long soil probes, especially when this procedure is required prior to each moisture determination. Many of these problems can be overcome however, through the placement of semi-permanent soil probes at selected sites, for the duration of the study period(s).

The use of TDR does not require the collection of soil cores for later analysis in the laboratory. Soil moisture readings can be taken in situ without disturbing the natural structure of the soil, thus avoiding the possibility that samples would be subjected to desiccation during transit and/or storage. Since the TDR method is non-destructive, repetitive measurements can be taken at specific sites.

3.5.1 Soil Texture and Bulk Density

Soil texture and bulk density will directly affect the relationship between the matric potential of the resistance blocks and that of the soil. The matric potential of soils having a large clay fraction will tend to be much higher than for those composed primarily of silt and/or sand. Therefore, each porous block should be individually calibrated. Matric potential is not a factor when using the TDR.

Variations in bulk density will result in a non-uniform distribution of soil moisture. This is a factor related to the non-homogeneous nature of soil found in situ and may complicate the use of porous resistance blocks and the neutron depth probe. Variations in bulk density and the resulting distribution of soil moisture do not detract from the use of TDR: the technique is used to determine the average volumetric water content (θ_v) along the transmission line.

3.5.2 Mineral Composition

TDR is not affected by mineral composition to the same extent as the porous resistance blocks or neutron probe techniques.

In fine-grained, mineral soils chemical dissociation of the clay fraction will directly affect resistivity values. Excessive numbers of free ions will result in a higher electrical conductivity and consequently lower resistance values. Chemical dissociation is not a significant factor when using the TDR, due to the large difference in the dielectric constant of water (81.5), soil (2 to 3) and air (1.0).

Any change in the overall dielectric constant would be primarily related to a change in water content.

Probability of atomic collision, atomic cross-section and neutron capture are factors to be considered when using the neutron depth probe. However, they are not relevant factors when using the TDR technique.

3.5.3 Soluble Salt Content

High concentrations of dissolved salts will affect the relationship between the matric potential of porous resistance blocks and that of the soil. The resulting osmotic effect will indicate a higher matric potential and a lower moisture content than actually exist. Conversely, an increase in chemical dissociation will result in an increase in electrical conductivity, a corresponding decrease in resistivity and may indicate an erroneously high water content.

Experimentation with TDR, involving extremely high concentrations of salts in solution, have shown an increase in K_a (Patterson and Lewis, 1981:16). This increase is persistent and is presumed to be due to the effect of increasing electrical conductivity. The TDR technique is not significantly affected by salt concentrations normally found in soils (Topp, et al., 1980:580).

3.5.4 Probe Configuration

The volume of soil being tested is directly related to the configuration of the parallel probes being used. Electromagnetic flux generated by the TDR unit is concentrated in a pattern lying between

the parallel legs of each probe set. Only a very small portion of the electrical flux will extend beyond this configuration. Therefore, the parallel probes may be used within a few centimetres of the ground surface without a significant loss of electromagnetic flux.

Changes in either the length or the spacing between the two elements (legs) of each probe can be used to vary the volume of soil being tested. Such changes will also affect the recorded travel time (tt) of the incident pulse: travel time is directly related to transmission line length (Formula 11):

$$V_p = \frac{l}{tt}$$

$$tt = \frac{l}{V_p}$$

Variations in either travel time or transmission line length will affect the apparent dielectric constant (Formula 16):

$$K_a = \left\{ \frac{(c \times tt)}{1} \right\}^2$$

Each probe configuration will therefore require testing to determine its precise electrical characteristics and corresponding volumetric water content (θ_v). Once these electrical characteristics have been determined, recalibration is not required since calibration does not drift with time, as is the situation when using porous resistance blocks.

Soil probes can either be placed in the vertical or horizontal position depending on the type of data required (Smith and Patterson, 1981:7,9). The potential versatility offered by parallel probes allows for studying many aspects of soil moisture regimes, such as: infiltration rates, the movement of wetting fronts, soil moisture distribution and water content discontinuities. The volume of soil being tested does not vary with moisture content: spatial resolution offered by the TDR technique is superior to that of the neutron depth probe.

CHAPTER 4

FIELD AND LABORATORY PROCEDURES

The collection and laboratory analysis of field samples comprise the initial two phases required in the preparation of raw field data for final analysis. Field and laboratory procedures are summarized in the form of a flow chart (Table 2). The procedures are numbered in the order that they were undertaken.

4.1 Sampling Grid

The establishment of a surveyed grid provided the basis for systematic soil sampling and soil moisture observations. Control points were located at the intersection of grid lines and their relative elevations determined by standard surveying techniques (Figure 4). Orientation of the grid was designed to provide complete spatial coverage of the study plot.

The advantages and limitations of control point coverage, as related to point density and the relationship between control points, is discussed by Davis (1973:301-310). Yeates (1974:48-50) discusses the problems associated with clustering and the introduction of experimental bias to random and systematic sampling techniques.

The grid consisted of thirty (30) individual stations covering an area 200 metres by 250 metres. Gridlines were located at 50 metre

TABLE 2. FLOW CHART SHOWING FIELD AND LABORATORY PROCEDURES

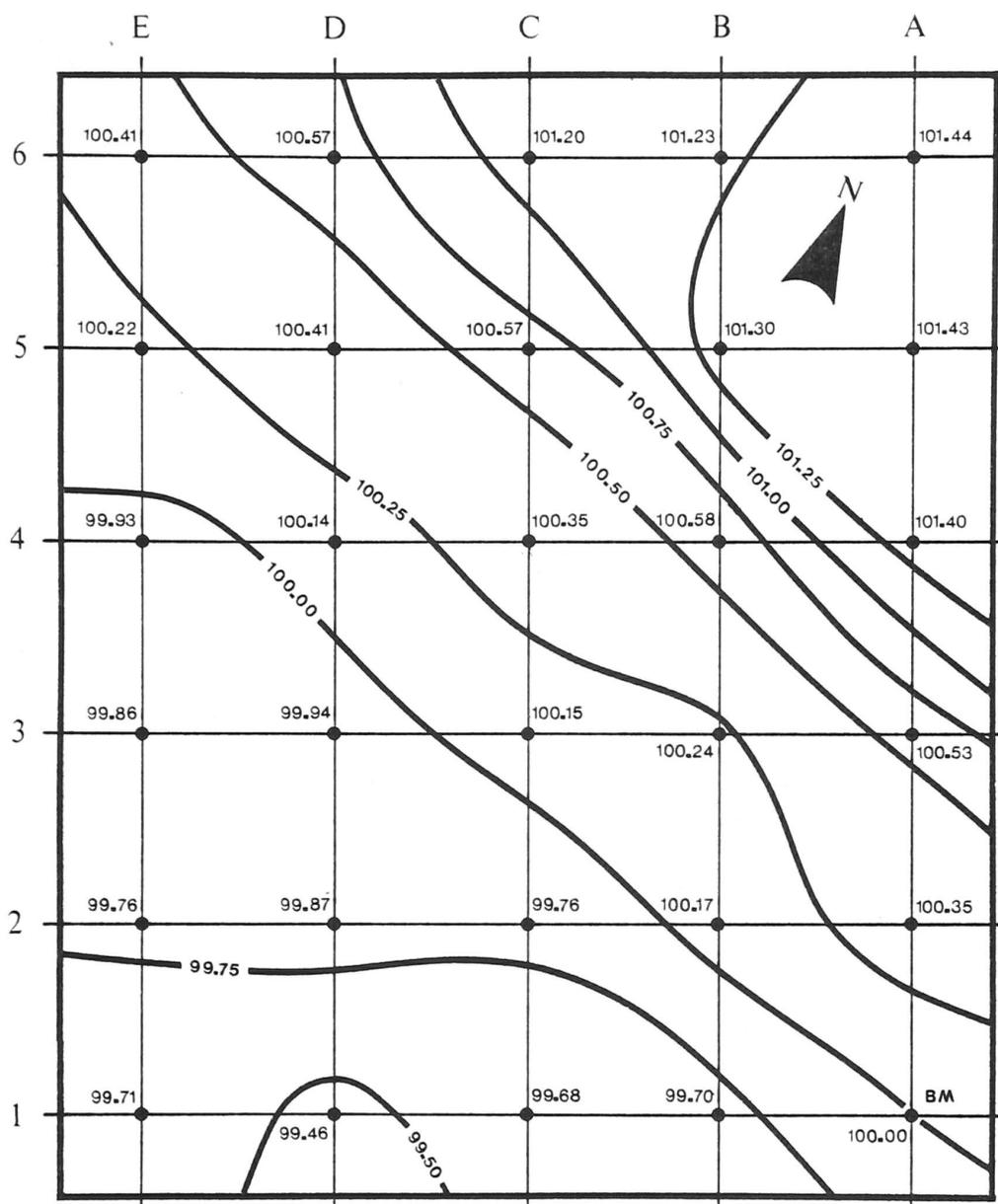
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- I SURVEYING OF SAMPLING GRID
 - i) Location of Sampling Stations
 - ii) Establish Station Elevations

 - II COLLECTION OF SOIL MOISTURE DATA
 - i) Establish Soil Moisture Variability
 - ii) Establish Wetting and Drying Patterns

 - III COLLECTION OF CORE SAMPLES
 - i) Provide Samples for Soil Fraction Analysis
 - ii) Provide Samples for Soil Moisture Tension Determinations (SMT)

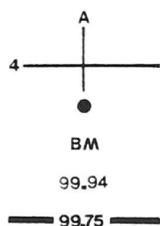
 - IV SOIL FRACTION ANALYSIS
 - i) Determine Grain Size Distribution and Soil Classification
 - ii) Determine Organic Matter Content

 - V SOIL WATER POTENTIAL (SMT)
 - i) Determine Residual Water Content at Field Capacity and at the Permanent Wilting Point
 - ii) Estimate Available Water Content
-



LEGEND

- Grid Lines
- Sample Stations
- Bench Mark (A-1)
- Elevation (metres)
- Contour Lines



SCALE

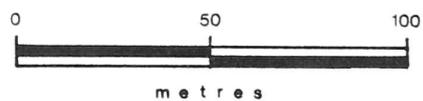


FIGURE 4. TOPOGRAPHIC MAP OF STUDY PLOT

intervals in both north-south and east-west directions. Station number (A-1) was established as the bench mark (BM) and was assigned a reference elevation of 100.0 metres. All of the remaining twenty-nine (29) stations had their elevations determined relative to the bench mark (BM). A wooden stake, approximately 45 cm in length and painted florescent orange, was used to mark each of the station locations.

The grid was located to maximize access and convenience. North-south grid lines were oriented parallel to corn and furrow rows, thus allowing convenient access to each of the stations. Some difficulties were encountered when locating stations along east-west grid lines since they were oriented perpendicular to crop rows.

To minimize edge effects the grid system was located well within the area of crop growth. Edge effects would result from changes in surface cover (i.e., grass cover, roadways) and could possibly affect microclimatic conditions, soil moisture regimes and/or crop growth. The study plot was bordered by roadways and areas of grass cover.

4.2 Soil Moisture Readings

Soil moisture readings, using the TDR, were taken over two depth intervals: 0 cm to 15 cm and 15 cm to 30 cm. The top layer corresponds to plough depth and is composed of disturbed soil, while the underlying layer remained essentially undisturbed. Moisture readings were taken within corn rows (between corn plants) to overcome difficulties arising from the compaction and disturbance of soil in adjacent furrows.

Soil moisture readings were taken regularly, at each of the stations, between June and August of 1980. Isopleth maps showing variations in moisture content were constructed from the data obtained.

The parallel probes required by the TDR technique were not left in place throughout the duration of the study. Prior to each set of moisture readings the stainless steel probes were installed, vertically from the ground surface, to the required depth. A template and a section of steel rod (same diameter as the probe) were used to form pilot holes to a depth of 10 cm. The 15 cm probes were then placed into these guide holes and set to depth. In turn, the 15 cm deep holes were used as pilots for the 30 cm probes. This procedure made it possible to calculate the average volumetric water content (θ_v) for the two soil intervals.

The pilot holes allowed for easier placement of the probes; however, the possibility of creating air spaces between the soil particles and the probes also increased. When using the TDR technique as described, it is not possible to differentiate between the volume of air gaps ($K^* \sim 1.0$) and common mineral soils ($K^* \sim 2-3$), owing to the small difference between their respective dielectric constants. "The apparent dielectric constant (K_a) is insensitive to the soil dielectric constant when the latter is large. As a result, a small measurement error in K_a can produce gross errors in the estimate of the true dielectric constant" (Annan, 1977b:62). The presence of an air gap will cause K_a to be lower than the true dielectric constant (Annan, 1977a:58). Difficulties were most apparent when attempting to insert the probes

into hard packed clay. Few problems were encountered in areas having high percentages of silt or sand.

Readings were taken over the same time period (1:00 p.m. to 5:00 p.m.) on three afternoons every week between June 19 and August 27, 1980. This provided a systematic basis for the analysis of wetting and drying cycles. During periods of rainfall, soil moisture readings were taken the afternoon following the event. On such occasions the sampling timetable was adjusted to suit the individual circumstances. For example, if it was raining on a Monday afternoon, moisture readings would be then taken on Tuesday and Thursday of that week. Moisture readings were not taken at precisely the same location each time. Sampling locations were randomly selected within a 3.0 metre radius of each station, in an attempt to obtain representative data and to minimize possible bias.

4.3 Core Sampling

Core samplings were taken to determine the range of soil moisture and bulk density values that could be expected at an individual site. Initially, nine cores were taken at each of eight stations.

Prior to coring, in situ volumetric water contents were determined using the TDR with the 15 cm long probe. Each core was taken in precisely the same location as the TDR reading. The water content and bulk density of each core were later determined gravimetrically in the laboratory (Section 3.2).

The coring equipment consisted of nine sections of plastic PVC tubing of approximately 30 cm in length. All of the coring tubes were driven into the ground to a depth of 15 cm, rotated and lifted vertically. The depth of the resulting hole was measured to check the length of sample removed. The samples were sealed in plastic bags to minimize loss of soil moisture by evaporation. Additional core samples (0 cm to 15 cm depth) were taken at all thirty stations and used in determining soil type and in soil moisture suction tests.

Following the corn harvest, core samples of the top 30 cm were acquired from the Department of Agriculture, Meteorological Branch. The core samples were taken at all thirty stations with the aid of a coring truck and were also used in determining soil type and in soil moisture suction tests.

4.4 Soil Fraction Analysis

The soil type found at each of the thirty station locations was classified according to grain size distribution. Pipette analyses were performed on all of the soil samples taken from the 0 cm to 15 cm and 0 cm to 30 cm depths. Each of the soil classes identified correspond to those of the Soil Survey Manual, United States Department of Agriculture, (1951).

4.4.1 Sample Splitting

All of the soil samples were allowed to air-dry for approximately two to three days. Aggregated soil particles were then broken down to individual soil grains by using a rubber tipped pestle and ceramic mortar. A sample splitter was then used to divide each of the air-dried samples into a series of representative subsamples of approximately equal size.

4.4.2 Initial Moisture and Organic Content (Air-dried Samples)

Three soil subsamples of approximately 30 g were selected from each of the stations and used to determine initial moisture content, organic content and grain size distribution. A three phase analysis was adopted with each stage utilizing one of the three subsamples.

Initial Moisture Content

Prew weighed soil samples were placed in a soils oven at 105⁰C for approximately twenty-four hours. After drying was complete the

samples were allowed to cool in a desiccator. The samples were then reweighed to determine their dry-weight.

$$\begin{array}{l} \text{Soil} \\ \text{Sample} \end{array} + \begin{array}{l} \text{Heating} \\ @ 105^{\circ}\text{C} \end{array} = \begin{array}{l} \text{Soil Mineral} \\ \text{Content} \end{array} + \begin{array}{l} \text{Organic} \\ \text{Matter} \end{array} \quad (20)$$

$$\text{Loss in Sample Weight} = \text{Initial Moisture Content} \quad (21)$$

The 105°C temperature is not high enough to destroy the organic matter. Therefore, the dry-weight includes both mineral and organic material.

Organic Content

Prewighed samples were placed in a soils oven at 400°C for approximately four hours. Following the completion of heating the samples were allowed to cool in a dry atmosphere. The samples were then reweighed to determine their dry-weight. Heating the samples in this manner will have two major effects. The initial moisture present in the soil will be evaporated away, and secondly, the organics in each of the samples will become ashed (destroyed) and consequently will no longer have a significant weight.

$$\begin{array}{l} \text{Soil} \\ \text{Sample} \end{array} + \begin{array}{l} \text{Heating} \\ @ 400^{\circ}\text{C} \end{array} = \begin{array}{l} \text{Soil Mineral} \\ \text{Content} \end{array} \quad (22)$$

$$\begin{array}{l} \text{Loss in Total} \\ \text{Sample Weight} \end{array} = \begin{array}{l} \text{Initial Moisture} \\ \text{Content} \end{array} + \begin{array}{l} \text{Organic} \\ \text{Content} \end{array} \quad (23)$$

$$\begin{array}{l} \text{Organic} \\ \text{Content} \end{array} = \begin{array}{l} \text{Loss in Total} \\ \text{Weight} \end{array} - \begin{array}{l} \text{Initial Moisture} \\ \text{Content} \end{array} \quad (24)$$

The loss in weight, attributed to the initial moisture and organic content, was then recalculated as a percentage based on the original wet-weight of the soil sample. This percentage was then applied as a correction factor to the corresponding soil sample used in the grain size analysis.

4.4.3 Pipette Analysis

The principle supporting the use of the pipette analysis for determining grain size distributions is contained within Stokes' law (Taylor and Ashcroft, 1972:129-131). Particles of equal mass will settle at equal rates with larger particles settling more quickly than smaller ones. In its simplest form, Stokes' law states that the settling velocity will vary as the square of the particle diameter (Krumbein and Sloss, 1963:96).

Pretreatment of the soil samples involved the destruction of organic matter with hydrogen peroxide (Day, 1965:554,559-560). A large portion of the organic material was oxidized to form carbon dioxide that was volatilized during the reaction. The remainder was either reduced to plant cellulose or converted to soluble compounds of low molecular weight. In effect, the hydrogen peroxide breaks down the clay-humus aggregating bonds, thus allowing for easier and more complete dispersion of the soil particles. Following the completion of pretreatment a dispersing agent was added to each of the soil samples.

The pipette method of particle size analysis requires that the mineral particles be dispersed homogeneously throughout the soil-water

solution. This was accomplished through the addition of calgon (sodium metaphosphate, NaPO_3) as a dispersing agent. Precisely 10 ml of a calgon-water solution (50 g of calgon dissolved in 1000 ml of deionized water) was added to each of the soil samples. The soil, water and calgon solution was then left to stand for approximately eighteen hours. To compensate for the additional weight, resulting from the inclusion of the dispersing agent, a correction factor was applied. A factor of 0.0125 g was subtracted for each of the 25 ml pipette samples taken.

Following pretreatment each of the soil-water solutions was thoroughly mixed for three minutes with the aid of a standard milk shake mixer (ASTM D 422-63:119-120). The additional agitation helped to insure a homogeneous mixture by destroying residual soil particle aggregation.

Sand Fraction. In turn, each of the soil samples was wet-sieved using a fifty micron sieve. This procedure separated the sand-sized particles from the clay and silt fractions. The sand fractions were then transferred to preweighed containers and placed into a soils oven at 105°C for approximately twenty-four hours. After drying was complete the percentage of sand was calculated on a dry-weight basis. The clay and silt fractions were then transferred to a sedimentation cylinder and the latter was filled with deionized water to 1000 ml.

Silt and Clay Fractions. A series of 25 ml pipette samples were drawn to determine the following grain size intervals: ≥ 50 microns,

<20 microns, <5 microns and <2 microns. Since the rate of sedimentation is partly dependent on temperature, the soil-water solutions were left overnight in the settling flasks, so that the temperature of the solutions stabilized at room temperature.

Grain Fractions <50 microns. Prior to sampling, each of the soil-water solutions was brought to a state of homogeneity. This was accomplished by using a brass mixing rod, in vertical motions, for approximately two minutes.

When the soil particles were totally brought in to suspension, three pipette samples were drawn, while maintaining mixing. The average percentage (dry-weight) of these samples was determined and should be representative of the total silt and clay fractions prior to settling.

Grain Fractions <20 microns. Particle sizes <20 microns were obtained by taking pipette samples, at selected times, following the commencement of sedimentation. To minimize disturbances inherent in the technique, single pipette samples were taken at those times indicated in Table 3 (Day, 1965:548). All of the pipette samples were placed into preweighed drying tins and dried in a soils oven at 105°C for approximately twenty-four hours. When drying was complete the samples were allowed to cool in a dessicator and then reweighed. The percentage of each soil fraction was calculated relative to the total dry-weight of the corresponding soil sample.

TABLE 3. ACCUMULATIVE SETTLING TIMES FOR
SILT AND CLAY SIZED PARTICLES

| GRAIN SIZE | ACCUMULATIVE SETTLING TIME ^a | |
|--------------------------------|-----------------------------------------|----------|
| \leq 50 microns ^b | 0 | |
| \leq 20 microns ^b | 4 mins. | 48 secs. |
| \leq 5 microns ^b | 1 hr. | 17 mins. |
| \leq 2 microns | 8 hrs. | 0 mins. |

- a) Settling times shown are calculated for water at a temperature of 20°C.
- b) Three grain size intervals were determined for the total silt fraction to aid in calculating mean and medium grain sizes for each soil samples.

Due to the accumulative nature of the pipette analysis grain size intervals were determined on a residual basis.

4.4.4 Limitations of the Pipette Analysis

If we assume that dispersion and disaggregation are complete, there are a number of other conditions and assumptions related to the use of Stokes' Law Model that must be considered (Taylor and Ashcroft, 1972:130-131). These are primarily concerned with particle size (diameter), shape and density.

The lower limit occurs in the fine-grain sizes where Brownian motion, at the molecular level, begins to affect the sedimenting particles. This motion may cause very small particles to remain indefinitely in suspension. "For practical purposes, 0.5 microns may be taken as the limiting diameter for freely sedimenting systems" (Griffiths, 1967:58).

For coarse materials, the upper limit occurs in the range of 50 to 70 microns. The larger grains settle at a much greater velocity and in doing so create turbulence. This turbulence will affect the settling velocities of much smaller particles contained in the same sample. "In practice a particle diameter of 50 to 55 microns is generally taken as the upper limit" (Griffiths, 1967:58).

Settling velocities, as determined from Stokes' Law, assume the soil grains to be spherical in shape and that they will settle at a uniform rate. This assumption may not be totally correct, particularly when dealing with the sheet silicates (clay minerals). Irregular surfaces will tend to create turbulence that may reduce or result in erratic sedimentation rates.

It is also assumed that quartz, with a specific gravity of

2.65 g/cm³, is the main soil constituent. The amount of quartz could vary substantially from one soil to the next, thus affecting the specific gravity of the sample.

4.5 Soil Water Potential

Soil water potential, rather than actual water content, is the major factor in determining many of the physical and geotechnical properties of soils. Each soil type will have its own characteristic water potential curve. Such curves illustrate the relationship between moisture content and the force (or suction) with which water is held in the soil. This relationship can be examined in the laboratory by using pressure plate and pressure membrane apparatus (ASTM D2325-68:344-350; ASTM D3152-72:479-486).

4.5.1 Soil Moisture Tension Determinations

The procedure followed involves the application of known air pressures to water saturated soil samples and then determining the amount of moisture retained once a state of equilibrium has been established at each corresponding pressure. At equilibrium the soil moisture tension (SMT) of the soil should equal the applied pressure. Tests were limited to those pressures corresponding to field capacity and permanent wilting point.

Pretreatments were not performed on the soil samples in an effort to retain as many natural characteristics as possible. Specifically, the soil samples were not treated with hydrogen peroxide to remove the humic material; nor was a dispersing agent used.

Aggregated soil particles were broken apart by using a rubber tipped pestle and ceramic mortar.

Due to the small volume of soil used in each of the tests, soil particles larger than medium sand-size were removed. Results from the grain size analysis indicated that the largest individual soil grains were within the medium sand-size fraction. There were a few larger grains present; however, their numbers were not significantly large ($\ll 1.0\%$) to bias test results through their removal.

Field capacity corresponds to the maximum quantity of moisture retained by a soil following unrestricted drainage due to gravity, and is affected exclusively by soil characteristics, including texture, structure, organic content, uniformity and depth (Taylor and Ashcroft, 1972:299-301). It also serves as a practical measure for the upper limit of available moisture in an unsaturated soil.

At field capacity the soil moisture tension (SMT) is low and plant roots can easily absorb water by osmosis. The pressure (or tension) generally accepted as corresponding to this value is 33 kilopascals.

Permanent wilting results from an inadequate supply of moisture to support plant growth. This is often associated with a high soil moisture tension (SMT) that inhibits the absorption of sufficient water by osmosis. A water deficit develops within the plant and wilting eventually occurs (Foth and Turk, 1972:80).

The permanent wilting point is estimated to coincide with a pressure (or tension) of 1515 kilopascals, and is normally considered as the lower limit of available water for plant growth. It is not a

precise value; the actual wilting point is directly related to the biophysiological characteristics of each plant type and may vary significantly between plant species (Rose, 1979:204; Taylor and Ashcroft, 1972:307-308).

4.5.2 Available Water Content

The amount of water available for plant growth can be estimated from soil moisture values corresponding to field capacity and the permanent wilting point:

$$AWC = WC_{fc} - WC_{wp} \quad (25)$$

where: AWC = available water content

WC_{fc} = water content at field capacity

WC_{wp} = water content at the permanent wilting point

The quantity of available water may vary considerably with plant species, root distribution, environmental and soil characteristics (Rose, 1979: 204).

CHAPTER 5

DATA ANALYSIS

The objectives incorporated into the data analysis were to deal specifically with two related subject areas: an overview of the factors affecting soil moisture content and distribution, including an examination of potential relationship(s) between topography, soil type and soil moisture; and the derivation of a simple model to estimate available water content using physical soil parameters. Field observations provided data for topography (obtained from survey), soil texture and soil moisture conditions. The field data were augmented by soil fraction analysis, grain size analysis and soil moisture tension determinations performed in the laboratory.

A series of first order regressions were performed to determine if any linear relationships existed between variables. In the initial stages of the analysis there was no attempt to average the soil moisture values obtained. The use of an averaging technique may have resulted in the loss of data by de-emphasizing natural variations in soil moisture content.

5.1 Soil Fraction Analysis

Soil fraction analysis consisted of the identification and analysis of three basic soil components: initial moisture content,

grain size distribution and the amount of organic material present in each soil sample. The quantity of each component was determined on a gravimetric basis as described in Section 4.4.

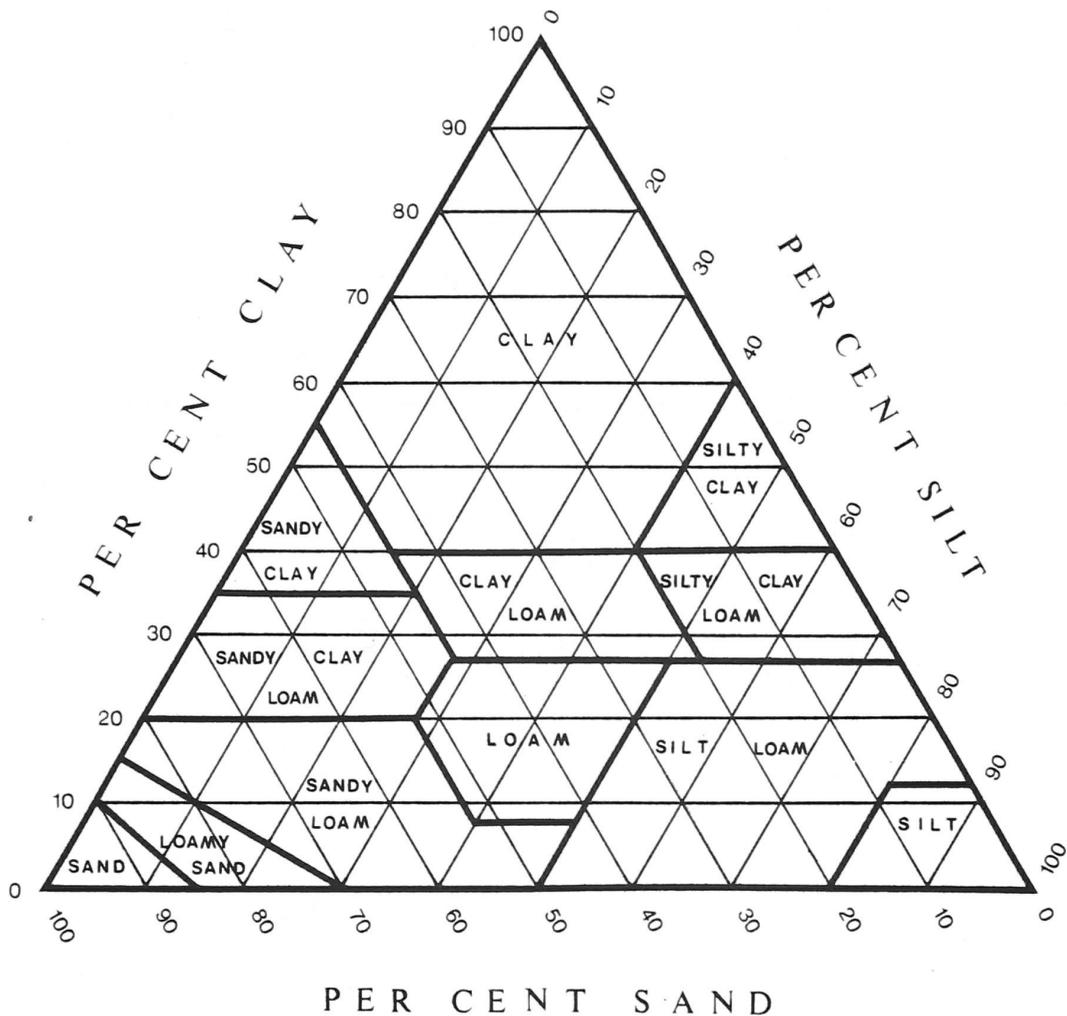
5.1.1 Soil Classification by Grain Size

Data obtained from the grain size analysis was used to establish the predominant soil type found at each of the station locations. Tables 16, 17 and 18 (Appendix II) summarize this data and list the corresponding soil type for each soil layer.

Figure 5 shows the relationship between the size of the soil particle fractions and the twelve soil classifications identified by the Canadian System of Soil Classification, 1978. For mapping purposes, the twelve soil classifications were summarized into three major groupings: clays, clay loams and loams. The distribution of these larger soil groupings is shown in Figures 6 and 7.

The areal distribution of the sand, silt and clay-size fractions closely follow the elevation contours. Sandy soils predominate at the higher elevations and grade into silty clay loam, clay loam and silty clay. Clay-rich soils are found at depth within the soil column, at the foot of slopes and in shallow depressions. Silt-size particles are more uniformly distributed across the study plot; however, they were found to be mainly associated with the clay-rich soils.

First order regression analysis shows a strong relationship between grain size and elevation (Table 4). Values of the Pearson correlation coefficient (r) vary between 0.78 and 0.91, suggesting a high degree of linear association between the two variables. The



SOIL CLASSIFICATION BY GRAIN SIZE

| | | |
|------------------------|---|---------------|
| CLAY - C | } | CLAYS |
| SILTY CLAY - SiC | | |
| SANDY CLAY - SaC | | |
| CLAY LOAM - CL | } | CLAY LOAMS |
| SILTY CLAY LOAM - SiCL | | |
| SANDY CLAY LOAM - SaCL | | |
| SILT - Si | } | LOAMS |
| SILT LOAM - SiL | | |
| LOAM - L | | |
| SANDY LOAM - SaL | | |
| LOAMY SAND - LSa | | |
| SAND - Sa | | |

FIGURE 5. TEXTURAL TRIANGLE

SOIL CLASSIFICATION MAPS

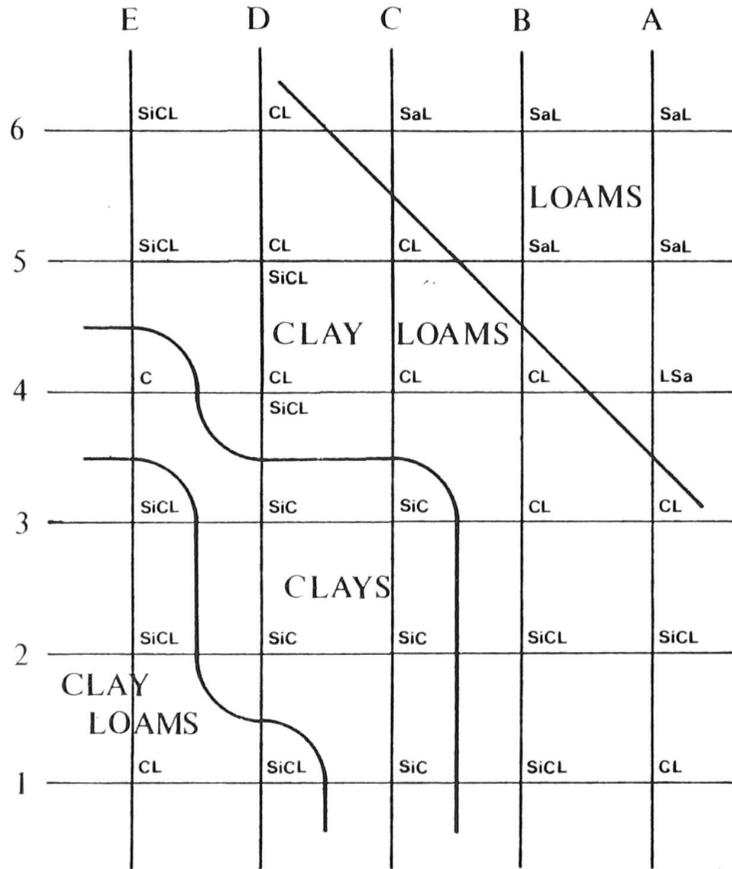


FIGURE 6. 0 cm to 15 cm DEPTH

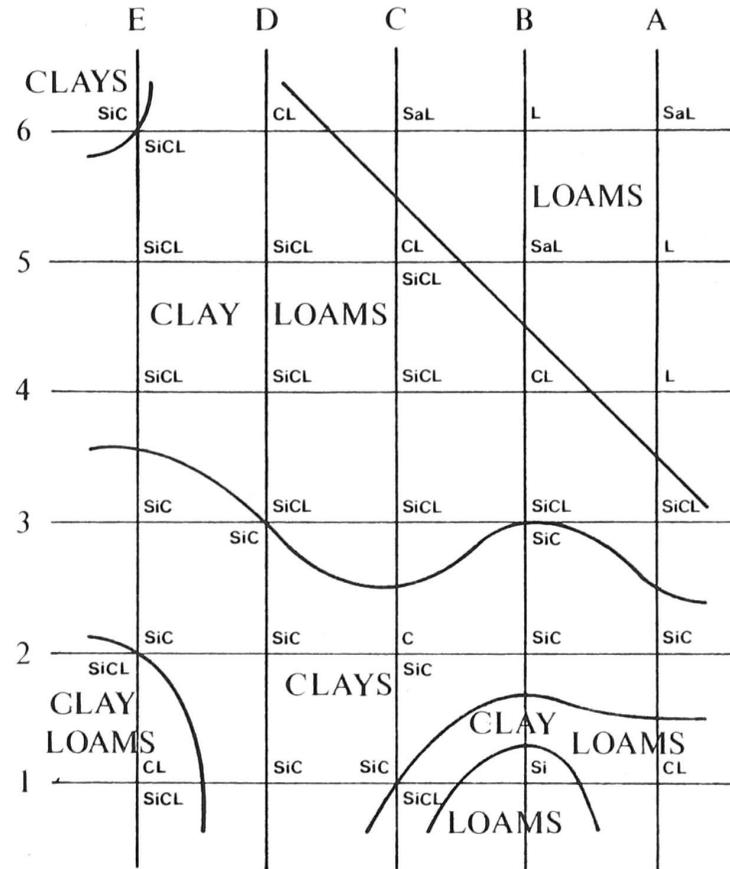


FIGURE 7. 15 cm to 30 cm DEPTH

TABLE 4. REGRESSION ANALYSIS: GRAIN SIZE VERSUS ELEVATION

| INDEPENDENT VARIABLE (X) | DEPENDENT VARIABLE (Y) | SOIL LAYER (DEPTH) | CORRELATION | |
|--------------------------------|------------------------------|-----------------------|-------------|-------------------|
| | | | (r) | (r ²) |
| ELEVATION | % SAND | 0 cm to 15 cm | +0.91 | 0.83 |
| | | 0 cm to 30 cm | +0.89 | 0.79 |
| ELEVATION | % SILT | 0 cm to 15 cm | -0.86 | 0.74 |
| | | 0 cm to 30 cm | -0.79 | 0.63 |
| ELEVATION | % CLAY | 0 cm to 15 cm | -0.88 | 0.77 |
| | | 0 cm to 30 cm | -0.78 | 0.61 |
| ELEVATION | MEAN GRAIN SIZE | 0 cm to 15 cm | -0.90 | 0.82 |
| | | 0 cm to 30 cm | -0.89 | 0.80 |
| ELEVATION | MEDIAN GRAIN SIZE | 0 cm to 15 cm | -0.90 | 0.82 |
| | | 0 cm to 30 cm | -0.90 | 0.82 |

coefficient of determination (r^2) shows that between 61% and 83% of the total variation in grain size is associated with, or explained by, the variation in elevation.

In general, there is a substantial increase in the proportion of the silt fraction and a decrease in the sand fraction with depth (Table 5). The size of the clay fraction remains relatively constant with only a small increase with depth. Some minor variations from the overall pattern were identified at individual stations. Stations A-3, A-4, A-5 and A-6 show the largest variation in the proportion of the sand fraction, both with depth and areal distribution.

5.1.2 Organic Matter Content

The distribution of organic matter was found to correspond very closely with soil type (Table 6). Soils that contain a large sand-size fraction show a strong negative relationship with the quantity of organic matter present. There also appears to be a strong positive relationship between organic content and the silt fraction. The quantity of clay by itself does not appear to have a significant influence on the organic fraction; however, the combined effect of the clay and silt fractions may be the deciding factor, since the largest quantities of organic matter were found in the silty clay, silty clay loam and silty loam soils. Similar relationships were found for both soil layers. A significant decrease in organic content with depth was observed at the majority of stations (Table 7).

The amount of organic matter found at depth is generally related to the combined effects of grain size, the rooting depth and density

TABLE 5. * GRAIN SIZE VARIATION WITH DEPTH

| STATION NUMBER | SAND % | SILT % | CLAY % | STATION NUMBER | SAND % | SILT % | CLAY % |
|-------------------|-----------|-----------|-----------|-------------------|-----------|-----------|-----------|
| A-1 | + 6.8 | -10.8 | + 4.4 | C-4 | -12.2 | +18.4 | - 0.4 |
| A-2 | + 1.2 | - 1.0 | + 5.4 | C-5 | - 7.6 | +13.0 | - 2.4 |
| A-3 | -18.2 | +14.2 | + 5.2 | C-6 | +11.6 | - 6.0 | - 5.6 |
| A-4 | -41.0 | +27.2 | +15.6 | | | | |
| A-5 | -26.6 | +21.4 | +12.6 | D-1 | + 9.8 | - 9.0 | + 4.8 |
| A-6 | -12.2 | +12.0 | + 2.6 | D-2 | + 2.2 | - 2.6 | + 3.4 |
| | | | | D-3 | + 7.4 | - 0.2 | - 2.0 |
| B-1 | +10.8 | +27.8 | -30.8 | D-4 | - 3.4 | +17.0 | - 5.4 |
| B-2 | - 2.6 | + 1.2 | + 6.8 | D-5 | - 0.6 | + 5.6 | - 1.6 |
| B-3 | - 5.8 | + 9.4 | - 0.6 | D-6 | - 2.4 | + 6.8 | - 5.4 |
| B-4 | - 1.2 | + 0.6 | - 0.6 | | | | |
| B-5 | - 2.8 | + 3.0 | + 2.8 | E-1 | -11.6 | +18.6 | - 5.4 |
| B-6 | - 8.8 | + 9.6 | + 0.2 | E-2 | + 5.2 | - 3.6 | + 0.4 |
| | | | | E-3 | - 1.4 | -13.4 | +17.2 |
| C-1 | + 6.4 | - 2.4 | - 1.0 | E-4 | 0.0 | +13.4 | - 4.4 |
| C-2 | +15.0 | -10.4 | + 0.6 | E-5 | - 6.0 | + 8.4 | + 0.8 |
| C-3 | - 3.0 | +17.4 | - 8.4 | E-6 | - 2.2 | + 3.4 | - 0.6 |

* Variation in grain size is calculated as a percentage change between the 0 cm to 15 cm and 15 cm to 30 cm soil layers. A plus (+) sign indicates an increase in the proportion of the corresponding soil fraction with depth. A minus sign (-) indicates a decrease in the proportion of the corresponding soil fraction with depth.

TABLE 6. RELATIONSHIP BETWEEN GRAIN SIZE AND ORGANIC CONTENT

| SOIL CLASSIFICATION | SOIL LAYER | ORGANIC MATTER (%) | SAND % | SILT % | CLAY % | COMBINED SILT AND CLAY (%) |
|---------------------|-------------|-----------------------|-----------|-----------|-----------|-------------------------------|
| SILTY CLAY | 0cm to 15cm | 6.5 | 10.2 | 46.4 | 42.0 | 88.4 |
| SILTY CLAY LOAM | | 6.4 | 14.1 | 48.0 | 36.8 | 84.8 |
| CLAY | | 6.2 | 14.7 | 39.1 | 42.4 | 81.5 |
| CLAY LOAM | | 5.0 | 26.3 | 37.6 | 34.8 | 72.4 |
| SANDY LOAM | | 4.0 | 62.3 | 20.6 | 35.2 | 55.8 |
| LOAMY SAND | | 3.7 | 80.2 | 8.6 | 9.8 | 18.4 |
| SILTY LOAM | 0cm to 30cm | 5.9 | 36.7 | 47.4 | 16.1 | 63.5 |
| SILTY CLAY | | 5.5 | 14.1 | 45.7 | 41.1 | 86.8 |
| SILTY CLAY LOAM | | 5.3 | 15.7 | 47.6 | 37.8 | 85.4 |
| CLAY | | 4.8 | 17.0 | 42.6 | 40.8 | 83.4 |
| CLAY LOAM | | 4.6 | 25.1 | 41.5 | 33.2 | 74.7 |
| LOAM | | 4.3 | 50.4 | 30.4 | 18.0 | 48.4 |
| SANDY LOAM | | 3.5 | 60.2 | 23.0 | 15.9 | 38.9 |

TABLE 7. VARIATION IN ORGANIC CONTENT WITH DEPTH

| STATION NUMBER | ORGANIC MATTER CONTENT (%) | | | *VARIATION IN ORGANIC CONTENT WITH DEPTH (%) |
|-------------------|----------------------------|----------------|---------------|-------------------------------------------------|
| | 0 cm to 15 cm | 15 cm to 30 cm | 0 cm to 30 cm | |
| A-1 | 6.2 | 5.4 | 5.8 | -0.8 |
| A-2 | 7.1 | 4.1 | 5.6 | -3.0 |
| A-3 | 4.3 | 5.5 | 4.9 | +1.2 |
| A-4 | 3.7 | 4.1 | 3.9 | +0.4 |
| A-5 | 3.7 | 3.1 | 3.4 | -0.6 |
| A-6 | 3.5 | 2.3 | 2.9 | -1.2 |
| B-1 | 8.4 | 4.4 | 6.4 | -4.0 |
| B-2 | 6.2 | 4.2 | 5.2 | -2.0 |
| B-3 | 5.6 | 3.2 | 4.4 | -2.4 |
| B-4 | 4.0 | 2.2 | 3.1 | -1.8 |
| B-5 | 4.7 | 6.1 | 5.4 | +1.4 |
| B-6 | 4.3 | 4.3 | 4.3 | 0.0 |
| C-1 | 5.1 | 3.9 | 4.5 | -1.2 |
| C-2 | 7.2 | 5.4 | 6.3 | -1.8 |
| C-3 | 6.5 | 8.3 | 7.4 | +1.8 |
| C-4 | 6.2 | 5.8 | 6.0 | -0.4 |
| C-5 | 4.6 | 4.6 | 4.6 | 0.0 |
| C-6 | 3.8 | 3.8 | 3.8 | 0.0 |

TABLE 7. CONT'D.

| STATION NUMBER | ORGANIC MATTER CONTENT (%) | | | * VARIATION IN ORGANIC CONTENT WITH DEPTH (%) |
|-------------------|----------------------------|----------------|---------------|--------------------------------------------------|
| | 0 cm to 15 cm | 15 cm to 30 cm | 0 cm to 30 cm | |
| D-1 | 8.9 | 6.3 | 7.6 | -2.6 |
| D-2 | 7.0 | 5.6 | 6.3 | -1.4 |
| D-3 | 6.9 | 6.9 | 6.9 | 0.0 |
| D-4 | 4.9 | 3.9 | 4.4 | -1.0 |
| D-5 | 5.0 | 4.0 | 4.5 | -1.0 |
| D-6 | 3.8 | 2.2 | 3.0 | -1.6 |
| E-1 | 4.9 | 4.7 | 4.8 | -0.2 |
| E-2 | 5.4 | 5.0 | 5.2 | -0.4 |
| E-3 | 7.3 | 1.5 | 4.4 | -5.8 |
| E-4 | 6.2 | 2.0 | 4.1 | -4.2 |
| E-5 | 5.6 | 2.4 | 4.0 | -3.2 |
| E-6 | 5.6 | 5.0 | 5.3 | -0.6 |

* Variation in organic content is calculated as a percentage change between the 0 cm to 15 cm and 15 cm to 30 cm soil layers. A plus sign (+) indicates an increase in organic matter with depth. A minus sign (-) indicates a decrease in organic content with depth.

of the vegetation cover, the supply of surface litter and the translocation of organic material by eluviation. Finer-textured soils will generally retain a larger quantity of plant nutrients, have a higher cation exchange capacity and a larger volume of moisture available for plant growth (Foth and Turk, 1972:226-227). An annual addition of organic matter may then be provided through the decomposition of the remains of the previous years' growth. Fine-textured soils also tend to restrict aeration and have slightly lower average temperatures (Foth and Turk, 1972:267; Pitty, 1979:75). This may result in a net increase in the amount of organic matter should the rate of decomposition be lower than that of supply. Poor permeability, generally associated with the fine-textured soils, will restrict the free movement of soil water and the translocation of organic matter held in either suspension or solution.

Improved cultivation practices will loosen-up the plough layer and tend to promote aeration by maintaining a homogeneous mixture of mineral grains and organic matter. Initially, improved aeration will result in increased productivity; however, there will be a decrease in organic content in the plough layer should annual cultivation practices be maintained over a prolonged period of time. The granular nature of the soil will promote the break-down of organic matter by oxidization and microbial activity, the free flow of soil water, and the translation of organic materials held in either suspension or solution.

5.1.3 Bulk Density

Within the plough layer there is a tendency for bulk density to increase as soil texture becomes coarser (Pitty, 1979:203; Foth and Turk, 1972:48). Fine-textured soils such as clays have a much higher porosity than exists in a silty or sandy soil. This higher porosity accounts for a much lower dry bulk density value as compared to an identical volume of a coarser soil (Table 8).

Bulk density will also be affected by the aggregation of soil particles and the development of soil structure (Hillel, 1980:11-12). As the individual soil particles become incorporated into larger aggregates large pore spaces and passage ways are formed. These voids contribute to lower dry bulk density values as the degree of soil aggregation increases. The majority of the soil aggregates tended to be subangular blocky to granular in nature with no evidence of a higher order of soil structure in the plough layer.

5.2 Soil Moisture Distribution

Soil moisture values showed a significant variation across the study plot in response to periods of wetting and drying. Similar variations were observed for both soil layers, however, they were less extreme for the lower layer. Tables 19, 20 and 21 (Appendix III) summarize the variation in soil moisture data obtained. The distribution of mean volumetric water contents are shown in Figures 8 and 9.

TABLE 8. RELATIONSHIP BETWEEN BULK DENSITY AND GRAIN SIZE: 0 cm to 15 cm

| STATION NUMBER | * MEAN DRY BULK DENSITY | SAND % | SILT % | CLAY % | COMBINED SAND AND SILT (%) | COMBINED SILT AND CLAY (%) |
|----------------|-------------------------|--------|--------|--------|----------------------------|----------------------------|
| C-2 | 0.69 | 6.4 | 49.3 | 42.1 | 55.7 | 91.4 |
| C-4 | 0.79 | 26.5 | 36.1 | 35.2 | 62.6 | 71.3 |
| B-3 | 0.82 | 21.7 | 37.5 | 39.8 | 59.2 | 77.3 |
| A-1 | 0.84 | 22.7 | 45.0 | 31.5 | 67.7 | 76.5 |
| A-1 | 0.88 | 22.7 | 45.0 | 31.5 | 67.7 | 76.5 |
| A-3 | 1.17 | 33.6 | 34.8 | 30.5 | 68.4 | 65.3 |
| A-3 | 1.24 | 33.6 | 34.8 | 30.5 | 68.4 | 65.3 |
| B-5 | 1.14 | 62.1 | 21.4 | 14.1 | 83.5 | 35.5 |
| B-5 | 1.26 | 62.1 | 21.4 | 14.1 | 83.5 | 35.5 |
| C-6 | 1.25 | 58.4 | 22.2 | 17.9 | 80.6 | 40.1 |
| C-6 | 1.26 | 58.4 | 22.2 | 17.9 | 80.6 | 40.1 |
| A-6 | 1.39 | 69.6 | 15.9 | 12.5 | 85.5 | 28.4 |

* Dry Bulk Density is shown as g/cm³

DISTRIBUTION OF MEAN VOLUMETRIC WATER CONTENT (%)

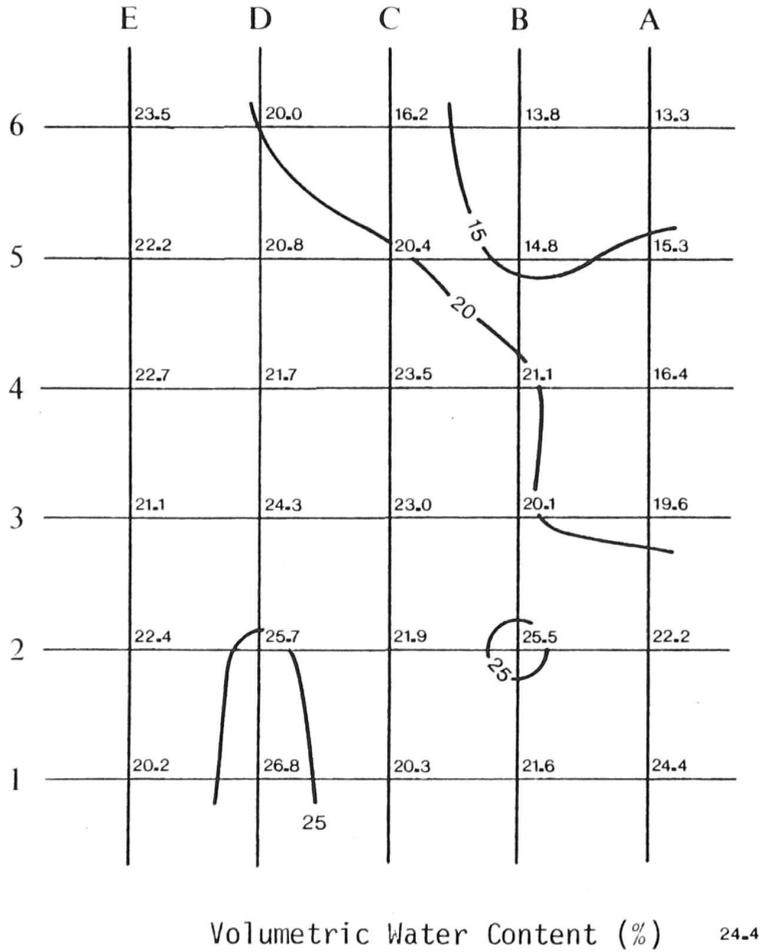


FIGURE 8. 0 cm to 15 cm DEPTH

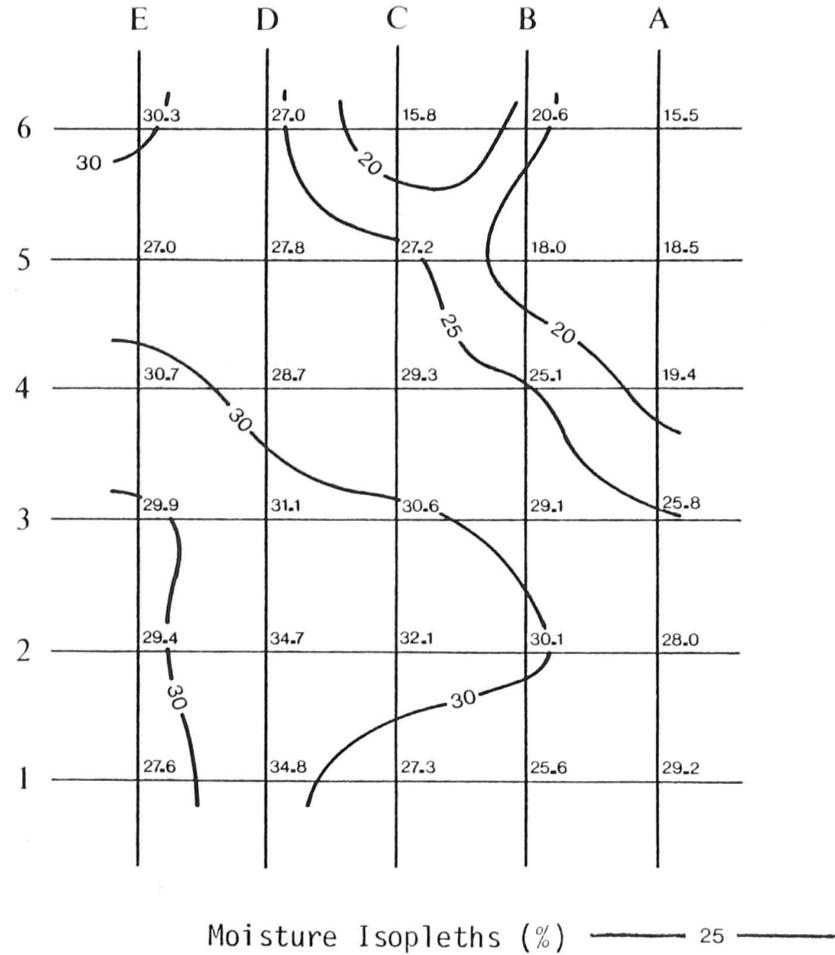


FIGURE 9. 15 cm to 30 cm DEPTH

5.2.1 Wetting and Drying Periods

During the term of field observations there were a number of wetting and drying periods of varying length. Three of the more distinct cycles were observed between July 14 and August 15, as illustrated in Figures 10 to 33 (Appendix I).

Isopleth maps constructed from the soil moisture data indicate that the lateral distribution of soil moisture is closely related to soil type and elevation. Soils classified as loams tend to be better drained with little, if any, ponding and surface runoff. The clay loam soils are transitional in characteristics and show many of the properties belonging to the loams and clays. Wetting and drying patterns show up very well where the soil contains a high percentage of sand. However, the pattern becomes more complex and less discernible as the percentages of both silt and clay increase.

Clay-rich soils are subject to ponding and show very slow drainage. Soil moisture isopleths do not follow as regular a pattern during wetting and drying periods, when compared to the more sandy soils. The complexity of the isopleth patterns reflects the high spatial variability of moisture in these soils.

Examination of the moisture data and the isopleth maps shows that the various soil types respond to wetting and drying at different rates. Both of these processes are related to permeability, which is itself, related to porosity, pore size distribution and to the number of interconnections (passages) between pores (Section 2.2). Generally, the sandy soils responded much more quickly to wetting and drying than

the silty or clayey soils.

During the time period immediately following a rainfall, the sandy soils showed relatively high infiltration (Figures: 12-17, 20-23, 28-33). Field observations indicated no evidence of surface runoff or ponding. Soils containing a large proportion of clay-size particles did not respond to initial wetting in the same manner as the more sandy soils. The initial infiltration although relatively high declined rapidly as the clay/colloidal fractions began to swell. Four additional factors had a direct influence on infiltration rates: depth of surface detention and thickness of the saturated layer, existing soil moisture content, inwash of fine soil materials and compaction due to rainfall. Each of these factors have been previously discussed in Section 2.3. Both surface runoff and ponding were observed in response to declining infiltration rates and to slope.

As the period of time between the rainfall event and the moisture readings lengthened, the sandy soils began to dry at a relatively constant rate (Figures: 18, 19, 24-27). However, the clayey soils often showed an increase in moisture content as a result of gravity flow and the lateral movement of water, including surface runoff and ponding. Distinct wetting and drying patterns were also observed between the two soil layers. Wetting was frequently observed taking place in the plough layer while the lower layer was undergoing drying (Figures: 14, 15, 20 and 21). Frequently, the opposite wetting and drying sequence was also observed (Figures: 12 and 13).

Variations in infiltration and permeability between the two layers produced a noticeable 'time lag'. It is evident that some of

this vertical variation in moisture content may be in response to a lateral movement of moisture either as surface runoff or as lateral percolation. However, not all of this vertical moisture variation can be attributed to lateral movement, since similar moisture patterns were observed at higher elevations in the sandy loams. Moisture infiltration rates were substantially reduced when the lower (underlying) soil layer contained a high moisture content. Lower permeability at depth resulted in a slower movement of water through this layer and reduced the rate of water flow originating from the plough layer.

Within the plough layer, the clay soils (27.5%) demonstrated the largest range of mean volumetric water content (θ_v), including the highest maximum and lowest minimum values (Table 9). Clay loam (17.6%) and sandy loam (17.6%) soils shared the smallest range of mean θ_v , with the clay loams demonstrating the higher maximum and minimum values. A somewhat different relationship between soil type and θ_v was observed for the overall 0 cm to 30 cm soil layer. Silty loams (23.7%) demonstrated the largest range of mean θ_v , followed closely by silty clay loam (21.1%) and clay (20.3%). Maximum mean θ_v values were associated with the silty loam soils, while minimum values corresponded with the sandy loams.

TABLE 9. SOIL MOISTURE VARIATION AND SOIL TYPE

| SOIL CLASSIFICATION | SOIL LAYER | VOLUMETRIC WATER CONTENT | | | |
|---------------------|-------------|--------------------------|--------------------|--------------------|------------------|
| | | MEAN % | MAXIMUM MEAN(%) | MINIMUM MEAN(%) | RANGE MEAN(%) |
| SILTY CLAY | 0cm to 15cm | 23.0 | 33.1 | 13.2 | 19.9 |
| SILTY CLAY LOAM | | 22.8 | 32.4 | 12.3 | 20.1 |
| CLAY | | 22.7 | 33.1 | 5.6 | 27.5 |
| CLAY LOAM | | 21.2 | 30.6 | 13.0 | 17.6 |
| LOAMY SAND | | 14.7 | 26.3 | 6.2 | 20.1 |
| SANDY LOAM | | 16.4 | 25.2 | 7.6 | 17.6 |
| SILTY CLAY | 0cm to 30cm | 26.8 | 35.8 | 15.7 | 20.1 |
| CLAY | | 26.2 | 35.1 | 14.3 | 20.8 |
| SILTY CLAY LOAM | | 26.1 | 35.6 | 14.5 | 21.1 |
| CLAY LOAM | | 24.3 | 31.4 | 14.7 | 16.7 |
| SILTY LOAM | | 23.6 | 36.0 | 12.3 | 23.7 |
| LOAM | | 17.2 | 27.0 | 9.6 | 17.4 |
| SANDY LOAM | | 16.3 | 25.0 | 8.4 | 16.6 |

5.2.2 Soil Type and Moisture Content

Variations in soil moisture content were found to correspond very closely to soil type (Table 9). High absolute volumetric water contents were generally associated with the fine-textured soils, such as clays (26.2%), silty clay (26.8%) and silty clay loam (26.1%). Over time these soils also exhibited the largest range of soil moisture content: clay (27.5%), silty clay (20.1%) and silty clay loam (21.1%). Course-textured soils (i.e., sandy loam and loamy sand) were, on average, associated with significantly lower volumetric water contents.

A series of first order regressions show a moderately strong relationship between grain size and volumetric water content (Table 10). Similar results were obtained for both soil layers, however, the correlation coefficients (r) estimated for the 15 cm to 30 cm layer were significantly higher. This may be explained by the fact that the surface layer is composed of disturbed soil while the underlying layer remained virtually undisturbed. The relationship between bulk density and water content is discussed in Section 5.2.3.

Regression analysis shows that there is an inverse relationship between the quantity of sand and the volumetric water content (Table 10). In other words, there is a direct relationship between water content and the quantity of silt and clay-size material. Both of these regressions support the major observation made in the field: low soil moisture values are generally associated with soils having a large sand-size fraction, and high soil moisture values are found in those soils having a high silt and/or clay-size content.

TABLE 10. REGRESSION ANALYSIS: GRAIN SIZE VERSUS VOLUMETRIC WATER CONTENT

| INDEPENDENT VARIABLE (X) | DEPENDENT VARIABLE (Y) | SOIL LAYER | COEFFICIENTS OF REGRESSION | | CORRELATION | |
|--------------------------------|------------------------------|---------------|----------------------------|-----------|-------------|-----------|
| | | | (b_0) | (b_1) | (r) | (r^2) |
| % SAND | % θ_v | 0 cm to 15 cm | 24.66 | -0.14 | -0.62 | 0.39 |
| | | 0 cm to 30 cm | 29.10 | -0.21 | -0.76 | 0.58 |
| % SILT | % θ_v | 0 cm to 15 cm | 11.91 | 0.23 | +0.57 | 0.33 |
| | | 0 cm to 30 cm | 11.85 | 0.29 | +0.61 | 0.38 |
| % CLAY | % θ_v | 0 cm to 15 cm | 11.34 | 0.29 | +0.61 | 0.38 |
| | | 0 cm to 30 cm | 11.61 | 0.38 | +0.75 | 0.57 |
| MEAN GRAIN SIZE | % θ_v | 0 cm to 15 cm | - 4.23 | 4.70 | +0.60 | 0.37 |
| | | 0 cm to 30 cm | -13.31 | 6.88 | +0.75 | 0.57 |
| MEDIAN GRAIN SIZE | % θ_v | 0 cm to 15 cm | 10.90 | 1.48 | +0.63 | 0.40 |
| | | 0 cm to 30 cm | 10.15 | 2.04 | +0.77 | 0.60 |

5.2.3 Bulk Density and Moisture Content

Increasing the bulk density had two major effects on the amount of water contained in the plough layer. Firstly, as the bulk density of the sandy soils increased there was a corresponding increase in the quantity (volume) of water retained in the soil (Table 22, Appendix IV). Compaction of the sandy soils placed restrictions on the free movement of water through the soil and as a result, a progressively larger volume of moisture was retained in the soil. Secondly, in the initial stages of compaction the silt and clay-rich soils also showed a corresponding increase in volumetric water content. However, this trend only continued until a 'threshold level' was attained, at which time the relationship became progressively more negative (Pitty, 1979:206). As the bulk density values continued to increase the remaining volume of voids (air spaces, macropores and passage ways), that once served as reservoirs for soil water, were substantially reduced.

5.2.4 Moisture Variability With Depth

At all stations, with the exception of C-6, the mean volumetric water content of the plough layer was substantially lower than that of the underlying layer (Table 11). Higher moisture content is in direct response to an overall decrease in permeability, resulting from a decrease in grain size, and an increase in bulk density with depth (Tables 5 and 8). The increase in bulk density is in response to compaction from the weight of overlying soil and from the fact that the lower layer has not been disturbed by cultivation. Decreasing

TABLE 11. SOIL MOISTURE VARIATION WITH DEPTH

| STATION NUMBER | MEAN VOLUMETRIC WATER CONTENT (%) | | | * VARIATION IN θ_v WITH DEPTH (%) |
|-------------------|-----------------------------------|--------------|------------|---------------------------------------------|
| | 0cm - 15 cm | 15cm - 30 cm | 0cm - 30cm | |
| A-1 | 24.4 | 29.2 | 26.8 | + 4.8 |
| A-2 | 22.2 | 28.0 | 25.1 | + 5.8 |
| A-3 | 19.6 | 25.8 | 22.7 | + 6.2 |
| A-4 | 16.4 | 19.4 | 17.9 | + 3.0 |
| A-5 | 15.3 | 18.5 | 16.9 | + 3.2 |
| A-6 | 13.3 | 15.5 | 14.4 | + 2.2 |
| B-1 | 21.6 | 25.6 | 23.6 | + 4.0 |
| B-2 | 25.5 | 30.1 | 27.8 | + 4.6 |
| B-3 | 20.1 | 29.1 | 24.6 | + 9.0 |
| B-4 | 21.1 | 25.1 | 23.1 | + 4.0 |
| B-5 | 14.8 | 18.0 | 16.4 | + 3.2 |
| B-6 | 13.8 | 20.6 | 17.2 | + 6.8 |
| C-1 | 20.3 | 27.3 | 23.8 | + 7.0 |
| C-2 | 21.9 | 32.1 | 27.0 | +10.2 |
| C-3 | 23.0 | 30.6 | 26.8 | + 7.6 |
| C-4 | 23.5 | 29.3 | 26.4 | + 5.8 |
| C-5 | 20.4 | 27.2 | 23.8 | + 6.8 |
| C-6 | 16.2 | 15.8 | 16.0 | - 0.4 |

TABLE 11. CONT'D.

| STATION NUMBER | MEAN VOLUMETRIC WATER CONTENT (%) | | | * VARIATION IN θ_V WITH DEPTH (%) |
|-------------------|-----------------------------------|--------------|------------|---------------------------------------------|
| | 0cm - 15 cm | 15cm - 30 cm | 0cm - 30cm | |
| D-1 | 26.8 | 34.8 | 30.8 | + 8.0 |
| D-2 | 25.7 | 34.7 | 30.2 | + 9.0 |
| D-3 | 24.3 | 31.1 | 27.7 | + 6.8 |
| D-4 | 21.7 | 28.7 | 25.2 | + 7.0 |
| D-5 | 20.8 | 27.8 | 24.3 | + 7.0 |
| D-6 | 20.0 | 27.0 | 23.5 | + 7.0 |
| E-1 | 20.2 | 27.6 | 23.9 | + 7.4 |
| E-2 | 22.4 | 29.4 | 25.9 | + 7.0 |
| E-3 | 21.1 | 29.9 | 25.5 | + 8.8 |
| E-4 | 22.7 | 30.7 | 26.7 | + 8.0 |
| E-5 | 22.2 | 27.0 | 24.6 | + 4.8 |
| E-6 | 23.5 | 30.3 | 26.9 | + 6.8 |

* Variation in volumetric water content (θ_V) is calculated between the 0 cm to 15 cm and 15 cm to 30 cm layers. A plus sign (+) indicates an increase in θ_V with depth. A minus sign (-) indicates a decrease in θ_V with depth.

grain size results in a tighter packing configuration between soil grains, a reduction in the size of pore spaces and subsequently, a higher moisture holding capacity. The decrease in moisture content at C-6 should be expected, since there is a significant increase (11.6%) in the amount of sand and a corresponding decrease in both the silt and clay-size fractions with depth.

Two additional factors should be mentioned in regard to the moisture content of the plough layer; evaporation rates and capillarity. It has been mentioned that the granular nature of the plough layer facilitates aeration; however, unrestricted air flow will promote higher evaporation rates. The texture (roughness) of the ground surface also affects the rate of evaporation through the development of turbulent air flow and the intermixing of air at ground level (Chang, 1977:117; Sellers, 1965:141-180). Increased capillarity may also be observed as a result of a decrease in particle size. Such an increase would have the potential for drawing moisture from the plough layer downward into the finer-textured soil layer.

5.3 Available Water Content

The available water content was estimated for each of the station locations on a gravimetric basis. This was accomplished by the use of pressure plate and pressure membrane apparatus (Section 4.5) and the application of formula (25):

$$AWC = WC_{fc} - WC_{wp}$$

Two basic assumptions are being made when applying this formula:

- 1) The quantity of water calculated from using field capacity and permanent wilting point data is equivalent to the maximum available water content.
- 2) Quantities of water in excess of field capacity are only available for plant uptake for a short period of time and are to be considered as flow through water.

Table 12 lists the percentage of residual gravimetric water contained in test soils at field capacity and at the permanent wilting point.

The quantity of available water will vary according to soil type: soils which retain the greatest quantities of soil moisture (i.e., clays) need not provide the largest amounts of available water (Foth and Turk, 1972:83). The quantity of available water is related directly to the moisture retention characteristics of the soil. Fine-grained clay soils may retain a larger quantity of moisture than a coarser soil, however, a much higher soil moisture tension may be required to extract an equal quantity of moisture. Table 13 shows the relationship between available water content and soil type.

TABLE 12. SOIL MOISTURE TENSION DETERMINATIONS

| STATION NUMBER | *FIELD CAPACITY | | *PERMANENT WILTING POINT | | *AVAILABLE WATER CONTENT | |
|-------------------|--------------------|--------------------|--------------------------|--------------------|--------------------------|--------------------|
| | 0 to 15cm DEPTH | 0 to 30cm DEPTH | 0 to 15cm DEPTH | 0 to 30cm DEPTH | 0 to 15cm DEPTH | 0 to 30cm DEPTH |
| A-1 | 28.2 | 35.1 | 12.4 | 14.7 | 15.8 | 20.4 |
| A-2 | 36.0 | 38.0 | 17.2 | 19.0 | 18.8 | 19.0 |
| A-3 | 24.2 | 30.2 | 9.9 | 13.3 | 14.3 | 16.9 |
| A-4 | 14.2 | 19.9 | 5.2 | 7.8 | 9.0 | 12.1 |
| A-5 | 18.1 | 18.8 | 6.7 | 9.1 | 11.4 | 9.7 |
| A-6 | 13.9 | 15.9 | 4.9 | 5.7 | 9.0 | 10.2 |
| B-1 | 38.8 | 43.4 | 19.3 | 20.3 | 19.5 | 23.1 |
| B-2 | 37.5 | 36.9 | 16.6 | 17.3 | 20.9 | 19.6 |
| B-3 | 29.4 | 37.3 | 14.2 | 17.6 | 15.2 | 19.7 |
| B-4 | 28.2 | 28.6 | 11.6 | 11.8 | 16.6 | 16.8 |
| B-5 | 16.8 | 19.8 | 6.0 | 7.9 | 10.8 | 11.9 |
| B-6 | 21.2 | 24.0 | 8.3 | 8.6 | 12.9 | 15.4 |
| C-1 | 34.5 | 39.0 | 17.3 | 19.3 | 17.2 | 19.7 |
| C-2 | 33.0 | 40.4 | 17.4 | 21.9 | 15.6 | 18.5 |
| C-3 | 34.3 | 37.9 | 15.8 | 17.5 | 18.5 | 20.4 |
| C-4 | 27.0 | 32.8 | 12.6 | 15.0 | 14.4 | 17.8 |
| C-5 | 29.4 | 32.4 | 12.1 | 14.2 | 17.3 | 18.2 |
| C-6 | 16.0 | 18.0 | 6.9 | 7.7 | 9.1 | 10.3 |

TABLE 12. CONT'D.

| STATION NUMBER | *FIELD CAPACITY | | *PERMANENT WILTING POINT | | *AVAILABLE WATER CONTENT | |
|-------------------|--------------------|--------------------|--------------------------|--------------------|--------------------------|--------------------|
| | 0 to 15cm DEPTH | 0 to 30cm DEPTH | 0 to 15cm DEPTH | 0 to 30cm DEPTH | 0 to 15cm DEPTH | 0 to 30cm DEPTH |
| D-1 | 44.5 | 43.8 | 22.1 | 22.0 | 22.4 | 21.8 |
| D-2 | 40.9 | 42.4 | 20.0 | 20.8 | 20.9 | 21.6 |
| D-3 | 38.5 | 42.2 | 18.0 | 18.7 | 20.5 | 23.5 |
| D-4 | 30.7 | 33.4 | 14.9 | 15.8 | 15.8 | 17.6 |
| D-5 | 30.3 | 35.0 | 14.0 | 15.1 | 16.3 | 19.9 |
| D-6 | 28.3 | 30.9 | 12.8 | 13.7 | 15.5 | 17.2 |
| E-1 | 31.3 | 35.7 | 14.3 | 16.5 | 17.0 | 19.2 |
| E-2 | 35.5 | 39.3 | 18.2 | 19.2 | 17.3 | 20.1 |
| E-3 | 39.9 | 42.5 | 17.8 | 17.6 | 22.1 | 24.9 |
| E-4 | 38.1 | 40.1 | 19.0 | 19.7 | 19.1 | 20.4 |
| E-5 | 33.0 | 35.5 | 15.0 | 16.4 | 18.0 | 19.1 |
| E-6 | 31.4 | 36.3 | 16.1 | 18.0 | 15.3 | 18.3 |

* Soil moisture content at field capacity and at the permanent wilting point are shown as a percentage based on residual gravimetric water content. Available water content is also shown as a percentage gravimetric water content.

TABLE 13. RELATIONSHIP BETWEEN AVAILABLE WATER CONTENT AND SOIL CLASSIFICATION

| SOIL CLASSIFICATION | SOIL LAYER | AVAILABLE WATER CONTENT (MEAN %) |
|---------------------|---------------|----------------------------------|
| CLAY | 0 cm to 15 cm | 19.1 |
| SILTY CLAY LOAM | | 18.7 |
| SILTY CLAY | | 18.5 |
| CLAY LOAM | | 15.8 |
| SANDY LOAM | | 10.6 |
| LOAMY SAND | | 9.0 |
| SILTY LOAM | 0 cm to 30 cm | 23.1 |
| SILTY CLAY | | 20.6 |
| CLAY | | 19.7 |
| SILTY CLAY LOAM | | 19.5 |
| CLAY LOAM | | 18.3 |
| LOAM | | 15.4 |
| SANDY LOAM | | 10.8 |

Based on mean values for the 0 cm to 30 cm depth, the silty loams (23.1%) yield the largest quantities of available water, followed by silty clay (20.6%), clay (19.7%) and silty clay loam (19.5%). The combined size of the silt and clay-size fractions would seem to be the major influencing factor in determining the quantity of available water.

The results of twenty linear regressions show a strong relationship between residual soil moisture and grain size (Tables 14 and 15). Values calculated for the Pearson correlation coefficient (r) vary between 0.83 and 0.96, suggesting a high degree of linear association between the two variables. The coefficient of determination (r^2) shows that between 68% and 93% of the total variation in residual soil moisture is associated with, or explained by, the variation in grain size. By using these linear regressions it is possible to estimate the maximum available water content for the top 30 cm of the soil and for the plough layer (0 cm - 15 cm). Soil depth 0 cm to 30 cm:

$$Y_{fc} = (62.00 - 0.43X_1 + 0.65X_2 + 0.69X_3) / 3 \quad (26)$$

$$Y_{wp} = (24.97 - 0.23X_1 + 0.35X_2 + 0.39X_3) / 3 \quad (27)$$

$$AWC = (37.03 - 0.20X_1 + 0.30X_2 + 0.30X_3) / 3 \quad (28)$$

TABLE 14. REGRESSION ANALYSIS: GRAIN SIZE VERSUS SOIL MOISTURE TENSION
0 cm to 15 cm DEPTH

| INDEPENDENT VARIABLE (X) | DEPENDENT VARIABLE (Y) | SOIL MOISTURE TENSION | COEFFICIENTS OF REGRESSION | | CORRELATION | |
|--------------------------------|------------------------------|--------------------------|----------------------------|-----------|-------------|-----------|
| | | | (b_0) | (b_1) | (r) | (r^2) |
| % SAND | SMT | 33 kilopascals | 40.50 | -0.36 | -0.93 | 0.86 |
| | | 1515 kilopascals | 19.88 | -0.21 | -0.94 | 0.88 |
| % SILT | SMT | 33 kilopascals | 6.22 | +0.62 | +0.91 | 0.82 |
| | | 1515 kilopascals | 0.23 | +0.35 | +0.91 | 0.82 |
| % CLAY | SMT | 33 kilopascals | 7.46 | +0.70 | +0.86 | 0.75 |
| | | 1515 kilopascals | 0.67 | +0.41 | +0.88 | 0.78 |
| * MEAN GRAIN SIZE | SMT | 33 kilopascals | -35.60 | +12.31 | +0.94 | 0.88 |
| | | 1515 kilopascals | -24.52 | + 7.20 | +0.96 | 0.92 |
| * MEDIAN GRAIN SIZE | SMT | 33 kilopascals | 5.92 | +3.59 | +0.91 | 0.82 |
| | | 1515 kilopascals | -0.09 | +2.08 | +0.92 | 0.84 |

TABLE 15. REGRESSION ANALYSIS: GRAIN SIZE VERSUS SOIL MOISTURE TENSION
0 cm to 30 cm DEPTH

| INDEPENDENT VARIABLE (X) | DEPENDENT VARIABLE (Y) | SOIL MOISTURE TENSION | COEFFICIENTS OF REGRESSION | | CORRELATION | |
|--------------------------------|------------------------------|--------------------------|----------------------------|-----------|-------------|-----------|
| | | | (b_0) | (b_1) | (r) | (r^2) |
| % SAND | SMT | 33 kilopascals | 44.43 | -0.43 | -0.95 | 0.91 |
| | | 1515 kilopascals | 21.41 | -0.23 | -0.94 | 0.88 |
| % SILT | SMT | 33 kilopascals | 6.55 | +0.65 | +0.86 | 0.74 |
| | | 1515 kilopascals | 0.80 | +0.35 | +0.83 | 0.68 |
| % CLAY | SMT | 33 kilopascals | 11.02 | +0.69 | +0.83 | 0.69 |
| | | 1515 kilopascals | 2.76 | +0.39 | +0.83 | 0.69 |
| *MEAN GRAIN SIZE | SMT | 33 kilopascals | -42.53 | +14.08 | +0.96 | 0.93 |
| | | 1515 kilopascals | -26.85 | + 7.82 | +0.95 | 0.91 |
| *MEDIAN GRAIN SIZE | SMT | 33 kilopascals | 6.35 | +4.06 | +0.96 | 0.92 |
| | | 1515 kilopascals | 0.42 | +2.24 | +0.94 | 0.89 |

* Mean and median grain size regressions are shown for comparison purposes. They have not been used in the derivation of the formulas presented for estimating available water content.

Soil depth 0 cm to 15 cm: plough layer

$$Y_{fc} = (54.18 - 0.36X_1 + 0.62X_2 + 0.70X_3) / 3 \quad (29)$$

$$Y_{wp} = (20.78 - 0.21X_1 + 0.35X_2 + 0.41X_3) / 3 \quad (30)$$

$$AWC = (33.40 - 0.15X_1 + 0.27X_2 + 0.29X_3) / 3 \quad (31)$$

where:

Y_{fc} = percentage of water retained in the soil at field capacity

Y_{wp} = percentage of water retained in the soil at the permanent wilting point

AWC = percentage available water content

X_1 = percent sand

X_2 = percent silt

X_3 = percent clay

Available water content may be converted to a volumetric basis by multiplying each side of the regression equations by the dry bulk density of the corresponding soil.

By using the appropriate set of formulas, it is possible to estimate available water content with a standard error of estimate of 1.89% for the plough layer and 1.79% for the top 30 cm of soil depth.

In situations where the actual water content of a soil is below that of field capacity, the available water content may be calculated in the following manner:

$$AWC = \frac{\text{existing water}}{\text{content in situ}} - WC_{wp} \quad (32)$$

This procedure requires that existing soil moisture conditions in situ must be known in addition to residual water content at the permanent wilting point. Soil moisture values estimated to be less than those corresponding to the permanent wilting point would indicate a definite water deficit and the potential for plant stress resulting from dehydration.

CHAPTER 6

CONCLUSION

6.1 Time Domain Reflectometry

The relative permittivity (K') of a soil-water system is related to the volumetric ratios of its components. Most importantly, K' is highly sensitive to the volume of water (θ_v) present in the soil. As a result of this sensitivity, the dielectric constant (K^*) of a natural soil may be used as a measure of its water content. Topp et al. (1980:580) found that the TDR technique is not significantly affected by soil texture, bulk density, mineral composition or soluble salt concentrations normally found in the soil.

Time Domain Reflectometry (TDR) is a non-destructive method for determining in situ volumetric water content. This, in itself, provides a number of advantages for its use in the field:

- 1) The use of TDR does not require the collection of soil cores for analysis in the laboratory.
- 2) Soil moisture readings can be taken in situ without disturbing the natural structure of the soil.
- 3) Repetitive measurements can be taken at specific locations.

Variations in the distribution of soil moisture do not significantly affect the use of TDR: the technique is used to determine the average volumetric water content along the transmission line. The volume of soil being tested does not vary with moisture content and the spatial

resolution offered by the TDR technique is superior to that of the neutron probe. Once the electrical characteristics have been determined for a head connector and probe, recalibration is not required, since calibration does not drift with time.

6.2 Soil Moisture Variability

The distribution of soil moisture is directly related to soil type (grain size distribution), quantity of organic matter and bulk density.

6.2.1 Grain Size Distribution

Pipette analysis was used to determine the soil classification of the two soil layers under study. From this analysis three major soil groupings were identified: clay, clay loam and loam. Regression analysis shows a strong linear relationship between grain size and elevation (r varies between 0.78 and 0.91). Sandy soils predominate at the higher elevations and grade into silty clay loam, clay loam and silty clay, in a progression down slope and with depth.

Isopleth maps show that both the areal and vertical distribution of soil moisture are closely related with soil type. Regression analysis supports this observation by showing that a moderately strong linear relationship exists between grain size and θ_v (r varies between 0.57 and 0.77). High θ_v values were found to be generally associated with the fine-textured soils, such as clay, silty clay and silty clay loam. On the average, significantly lower θ_v values were associated with loam, sandy loam and loamy sand.

6.2.2 Distribution of Organic Matter

The distribution of organic matter was found to correspond closely with the soil type. Coarse-textured loams and sandy loams showed an inverse (negative) relationship with the quantity of organic matter present. A direct (positive) relationship was observed between organic content and soils containing large silt-size fractions. As an individual factor, the proportion of the clay fraction did not appear to have a significant influence on the quantity of organic matter contained in the soil. The combined effect of the clay and silt-size fractions may be the deciding factor, since the largest amount of organic materials was found in the silty clay, silty clay loam and silty loam soils.

The addition of organic matter will modify soil structure by altering pore size distribution and bulk density. In this manner, organic matter will influence the capacity of a soil to retain available water (Salter, et al., 1966).

6.2.3 Bulk Density

There is a tendency for bulk density to increase as the soil texture becomes coarser. Fine-textured clay soils generally have a much higher porosity as compared to soils containing large sand or silt-size fractions. The higher porosity accounts for a much lower dry bulk density than for an identical volume of a coarser soil. Aggregation of soil particles and the development of soil structure will also affect bulk density values (Marshall and Holmes, 1979:10). The formation of large pore spaces and connecting passages contribute to progressively

lower bulk density values as soil aggregation continues.

Initially, as bulk density values increased (resulting from natural compaction) there was a corresponding increase in soil water content. This trend continued until a 'threshold value' was attained, at which time this relationship became negative. As the bulk density values continued to increase, the total volume of voids that once served as reservoirs for water were substantially reduced. The 'threshold value' will vary in response to soil texture, organic content and soil structure (Pitty, 1979:206).

6.3 Available Water Content

Soils that retain the greatest quantities of moisture need not necessarily yield the largest quantities of available water. Fine-textured soils will generally contain a much larger quantity of moisture in comparison to a coarser soil. However, a much higher range of soil moisture tensions will be required to extract an equivalent amount of moisture from the finer soils.

Regression analysis shows a strong linear relationship between grain size and residual moisture content (r varies between 0.83 and 0.96). The quantity of available water is related to the moisture retention characteristics of each soil.

The maximum available water content (AWC) may be estimated for both the top 30 cm of soil depth and for the plough layer.

Soil Depth 0 cm to 30 cm ($r = 0.87$): Formula (28)

$$AWC = (37.03 - 0.20X_1 + 0.30X_2 + 0.30X_3) / 3$$

Soil Depth 0 cm to 15 cm ($r = 0.90$): Formula (31)

$$AWC = (33.40 - 0.15X_1 + 0.27X_2 + 0.29X_3) / 3$$

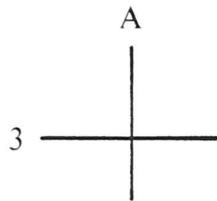
Using the appropriate formula, it is possible to estimate maximum available water content with a standard error of estimate of 1.89% for the plough layer and 1.79% for the top 30 cm of soil depth.

APPENDIX I

SOIL MOISTURE ISOPLETH MAPS

MAP LEGEND

Grid Lines



Volumetric Water Content (%)

35.5

Moisture Isopleths



Areas of Wetting



SOIL MOISTURE ISOPLETH MAPS FOR JULY 14

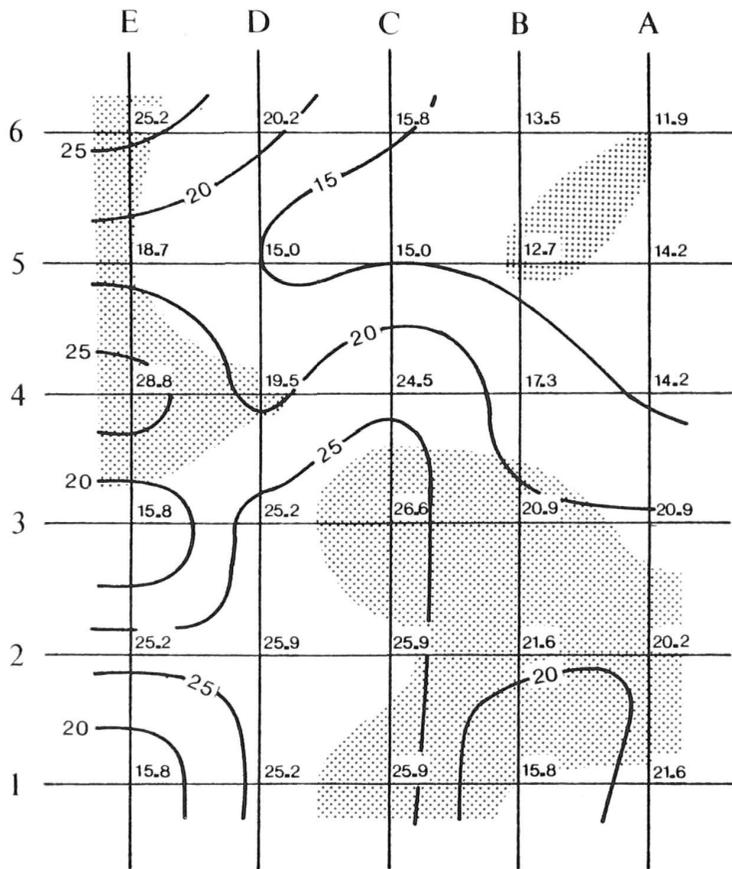


FIGURE 10. 0 cm to 15 cm DEPTH

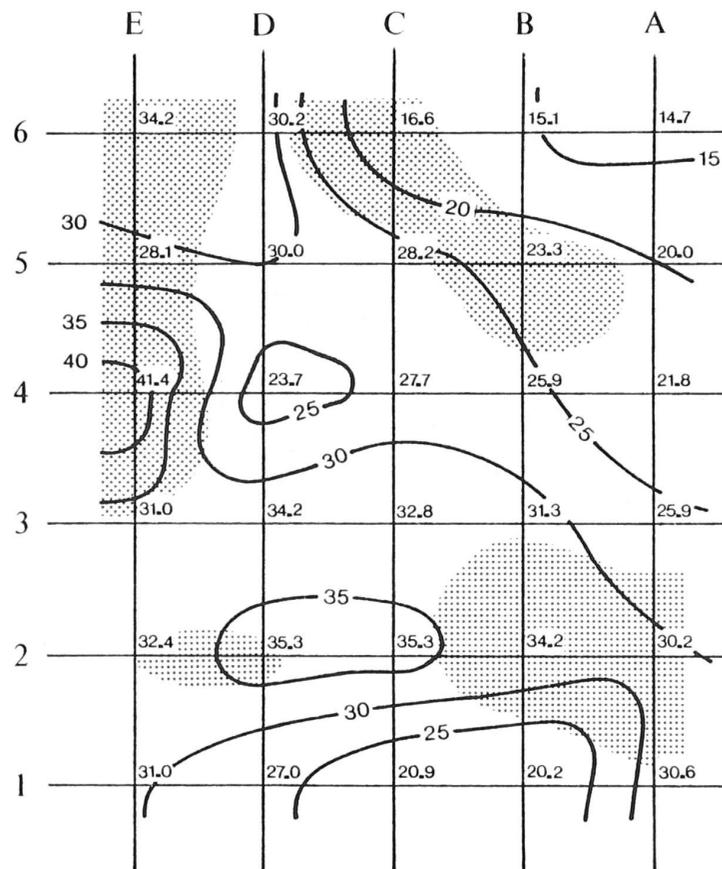


FIGURE 11. 15 cm to 30 cm DEPTH

SOIL MOISTURE ISOPLETH MAPS FOR JULY 16

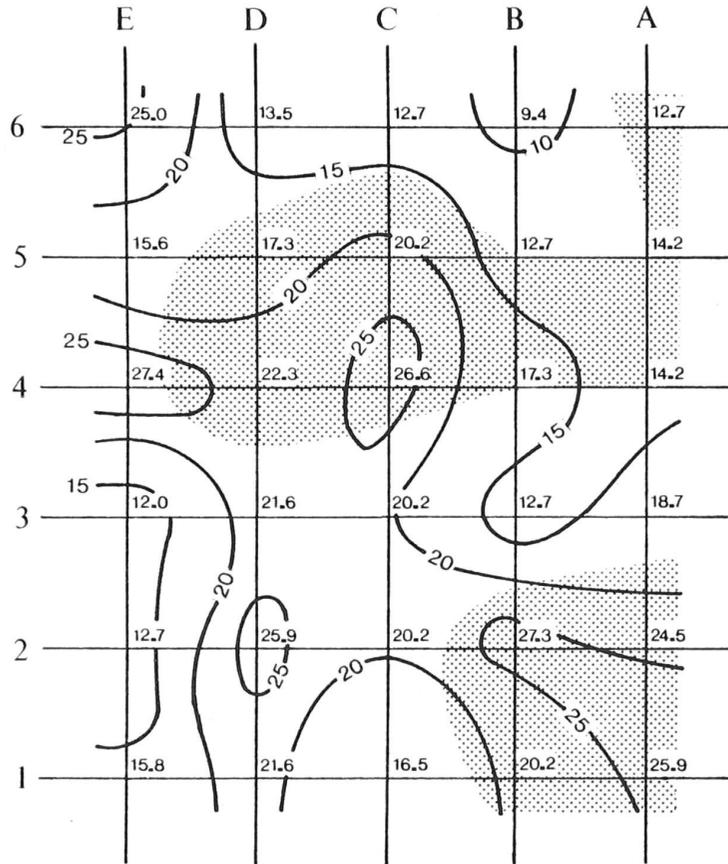


FIGURE 12. 0 cm to 15 cm DEPTH

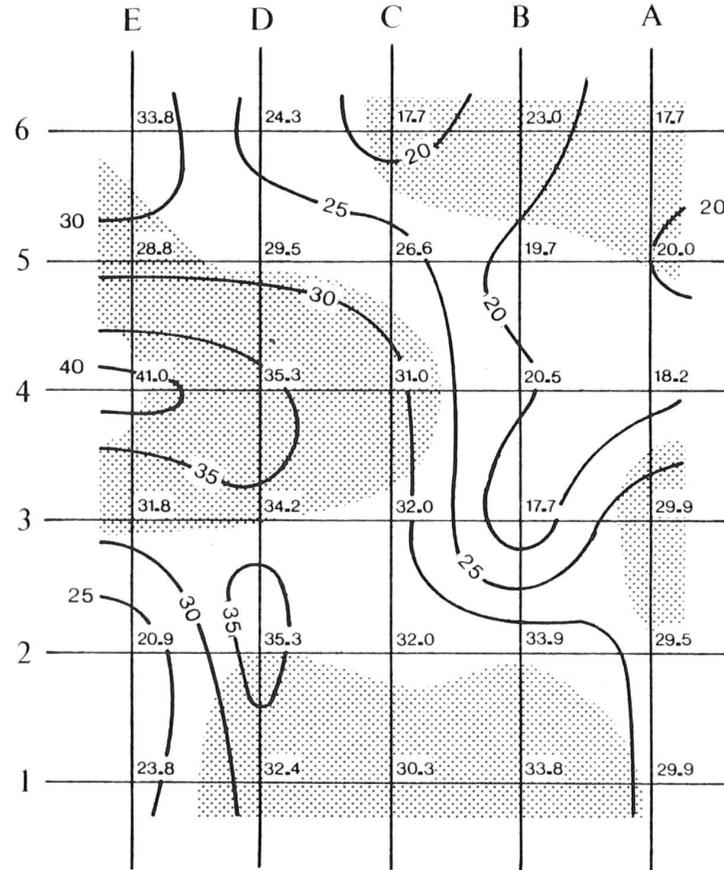


FIGURE 13. 15 cm to 30 cm DEPTH

SOIL MOISTURE ISOPLETH MAPS FOR JULY 18

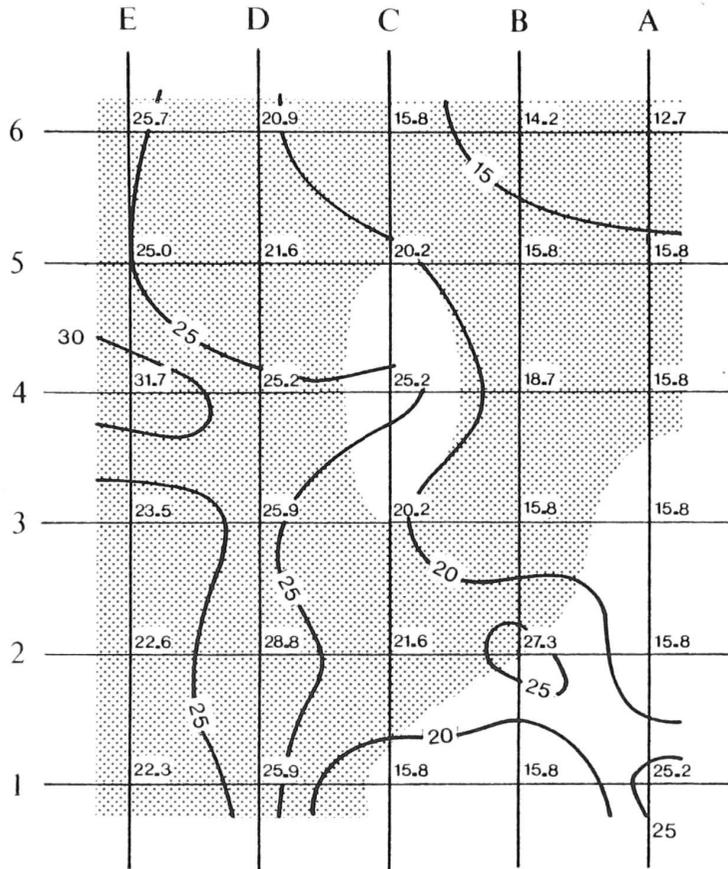


FIGURE 14. 0 cm to 15 cm DEPTH

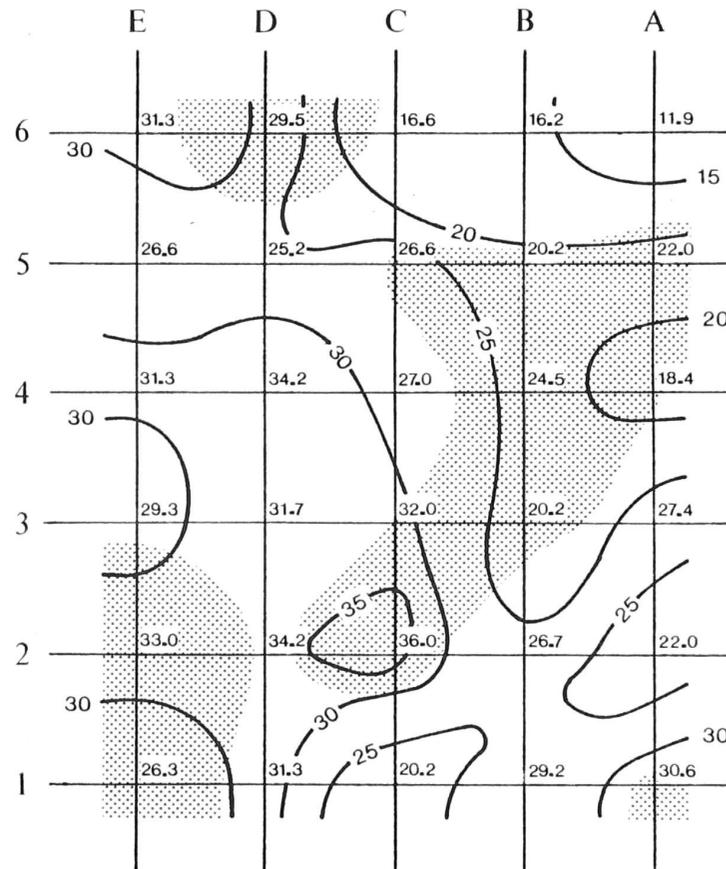


FIGURE 15. 15 cm to 30 cm DEPTH

SOIL MOISTURE ISOPLETH MAPS FOR JULY 23

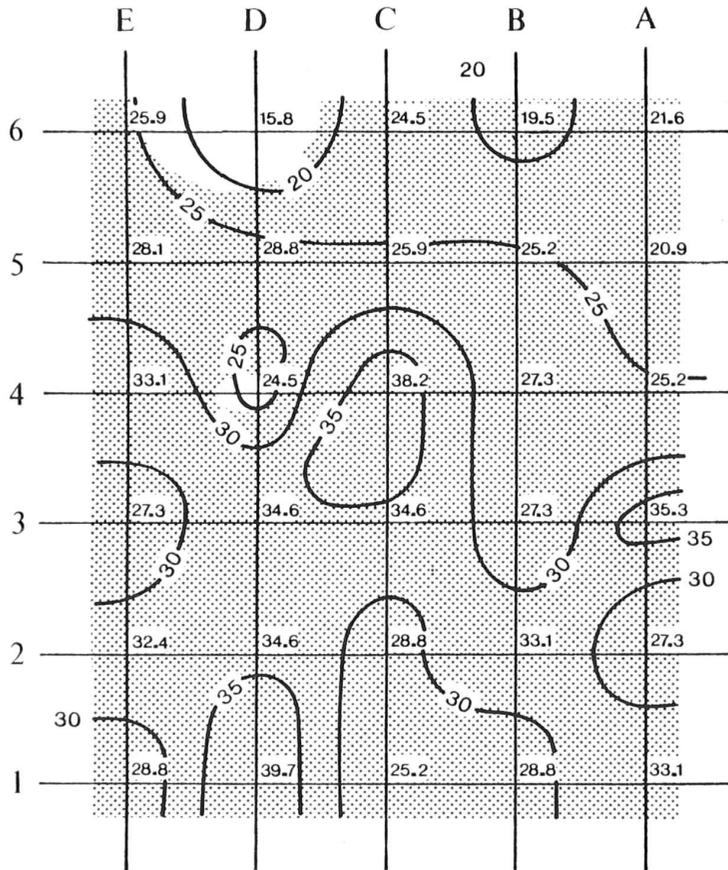


FIGURE 16. 0 cm to 15 cm DEPTH

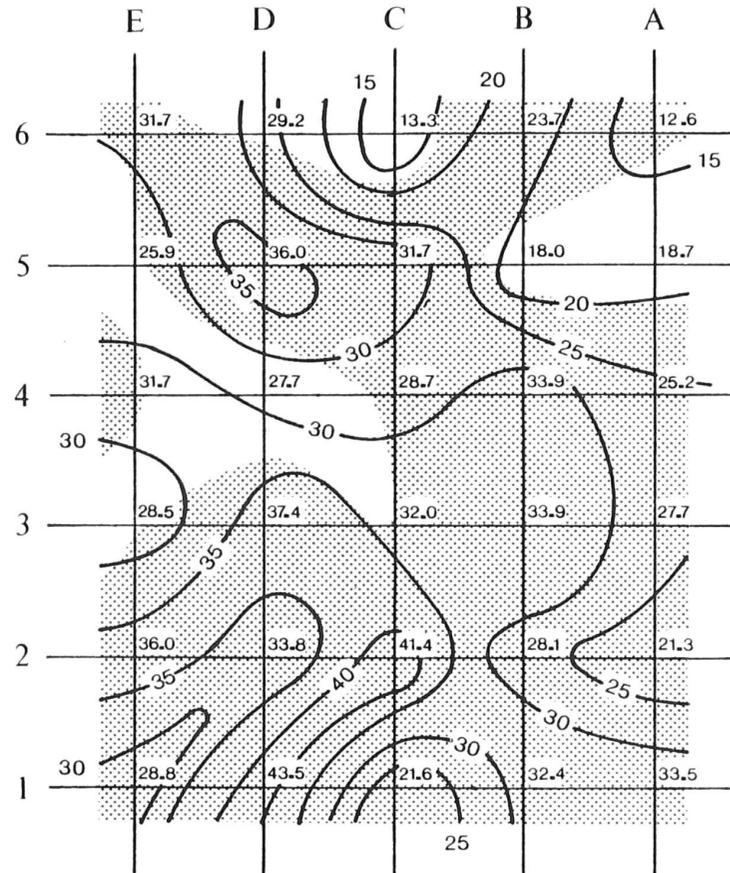


FIGURE 17. 15 cm to 30 cm DEPTH

SOIL MOISTURE ISOPLETH MAPS FOR JULY 25

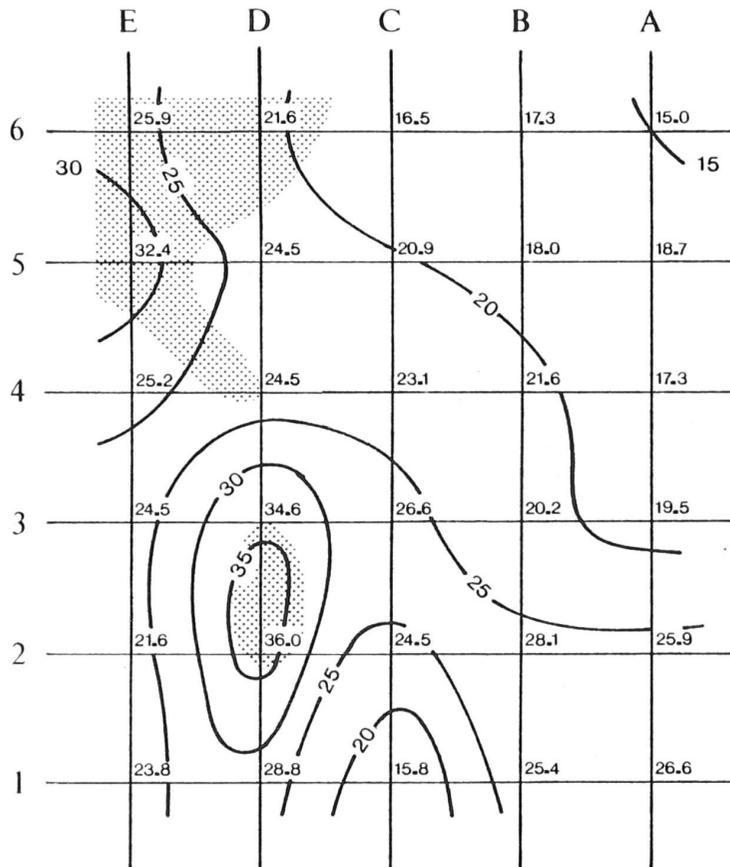


FIGURE 18. 0 cm to 15 cm DEPTH

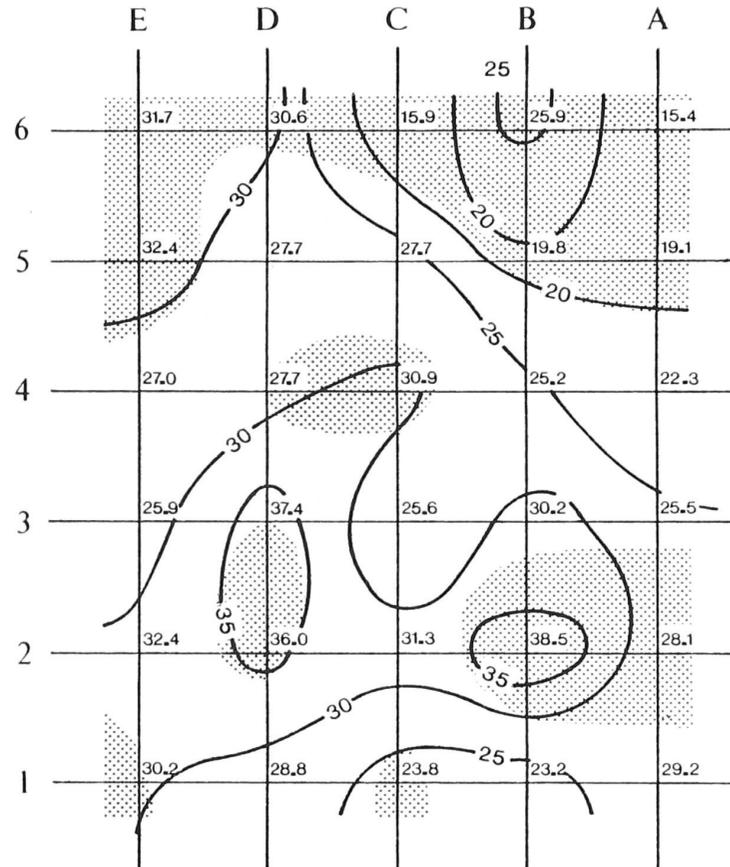


FIGURE 19. 15 cm to 30 cm DEPTH

SOIL MOISTURE ISOPLETH MAPS FOR JULY 28

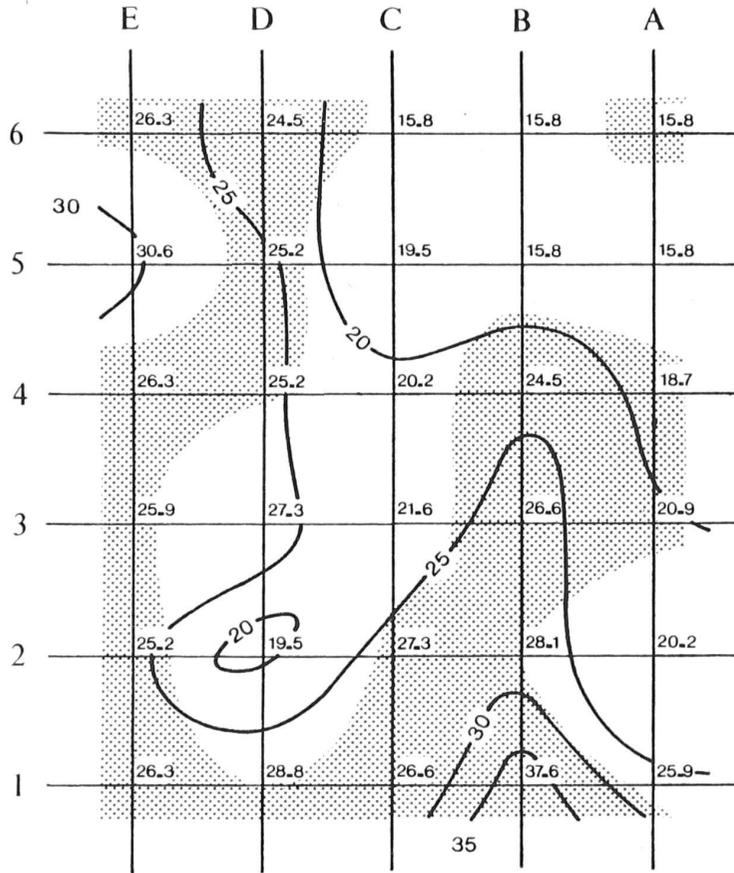


FIGURE 20. 0 cm to 15 cm DEPTH

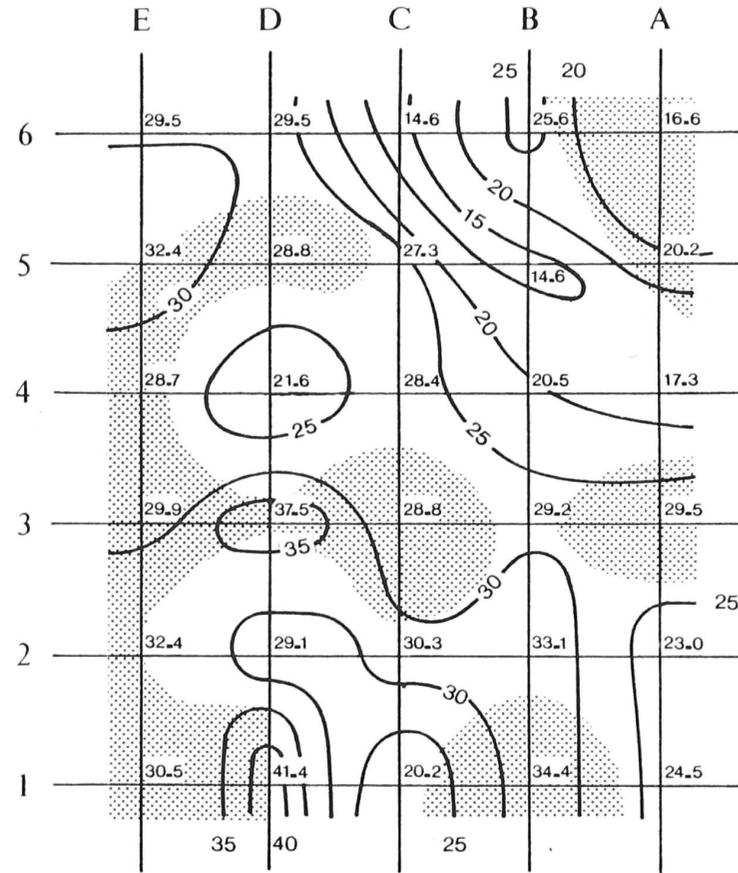


FIGURE 21. 15 cm to 30 cm DEPTH

SOIL MOISTURE ISOPLETH MAPS FOR JULY 30

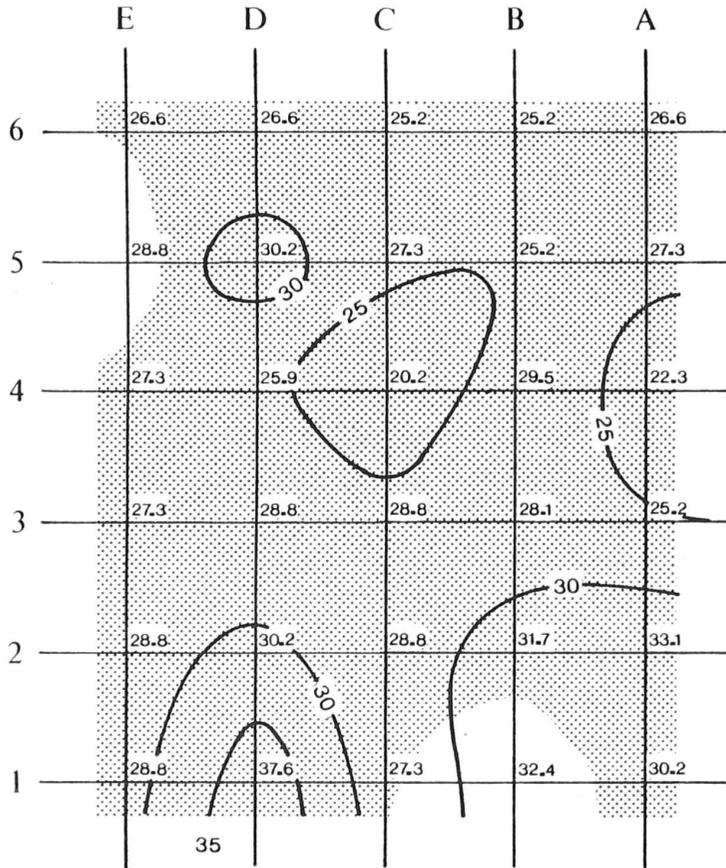


FIGURE 22. 0 cm to 15 cm DEPTH

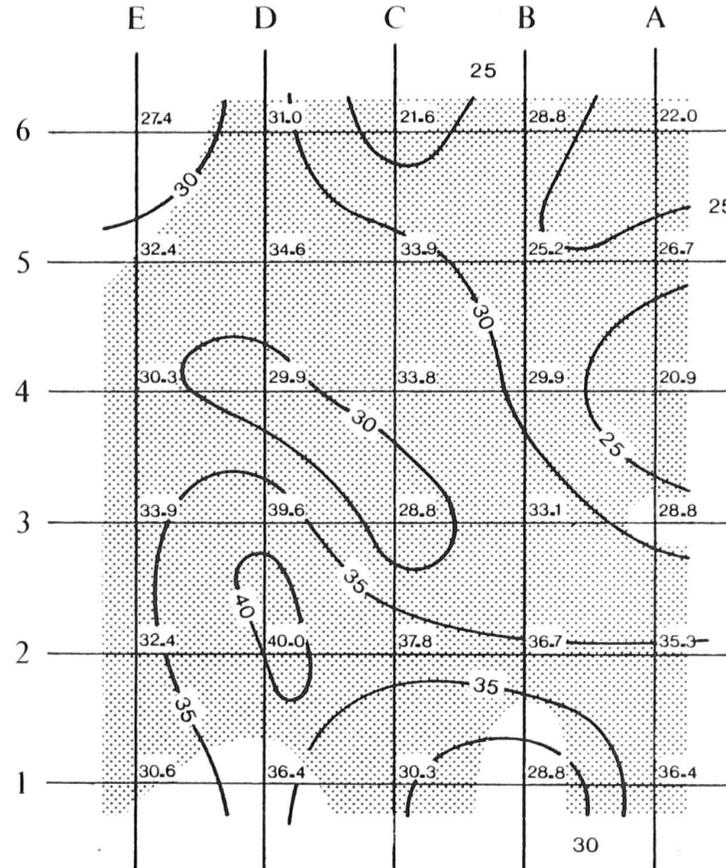


FIGURE 23. 15 cm to 30 cm DEPTH

SOIL MOISTURE ISOPLETH MAPS FOR AUGUST 1

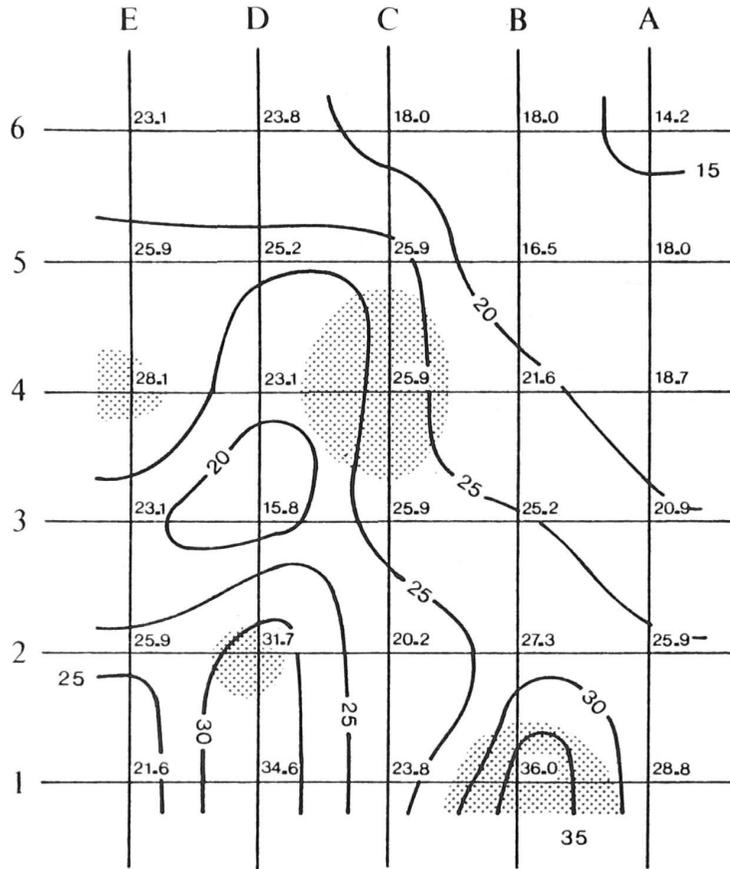


FIGURE 24. 0 cm to 15 cm DEPTH

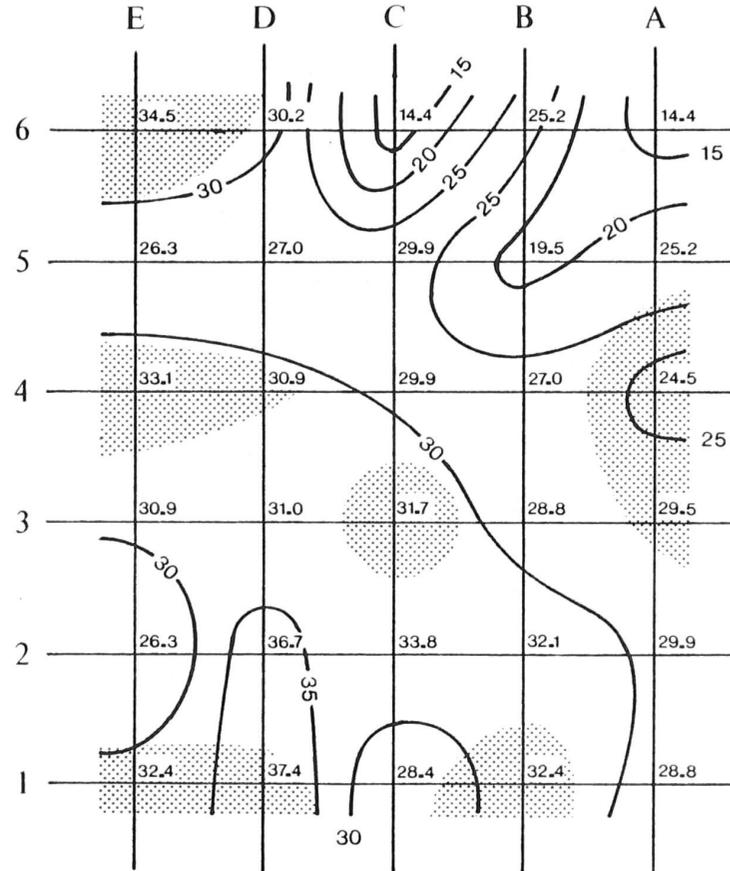


FIGURE 25. 15 cm to 30 cm DEPTH

SOIL MOISTURE ISOPLETH MAPS FOR AUGUST 6

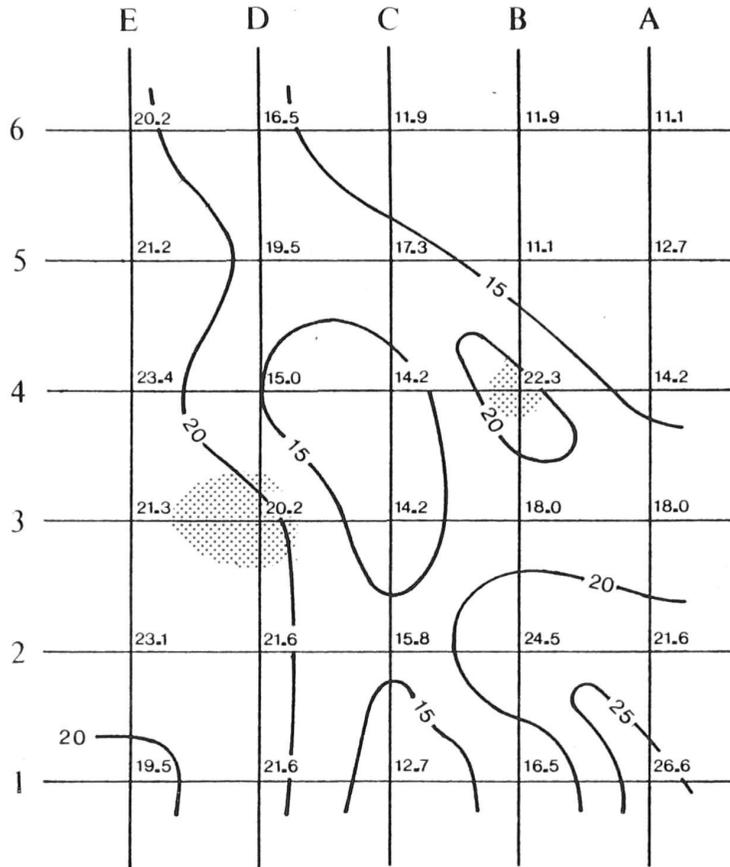


FIGURE 26. 0 cm to 15 cm DEPTH

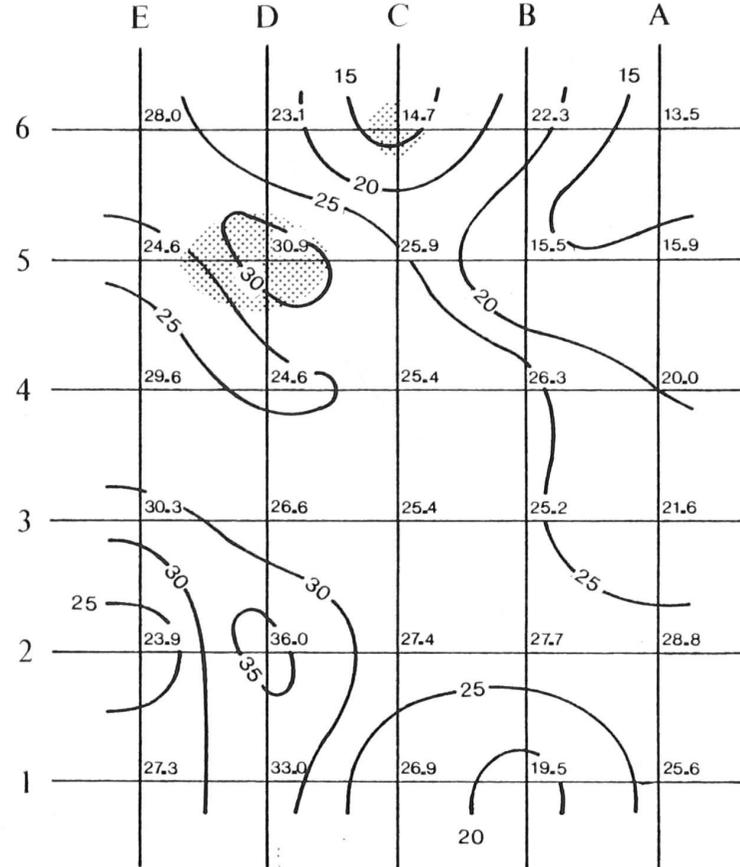


FIGURE 27. 15 cm to 30 cm DEPTH

SOIL MOISTURE ISOPLETH MAPS FOR AUGUST 11

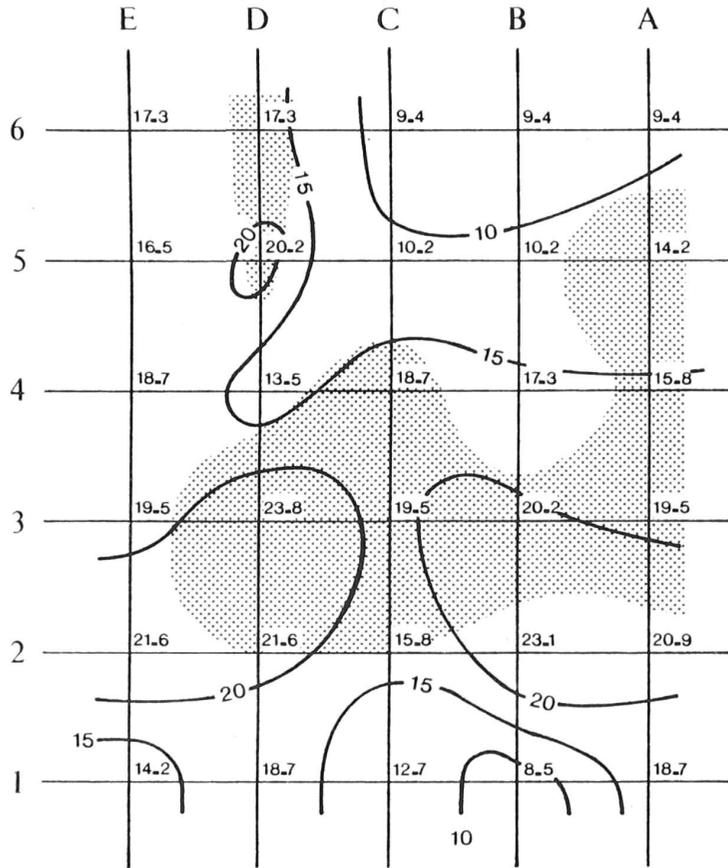


FIGURE 28. 0 cm to 15 cm DEPTH

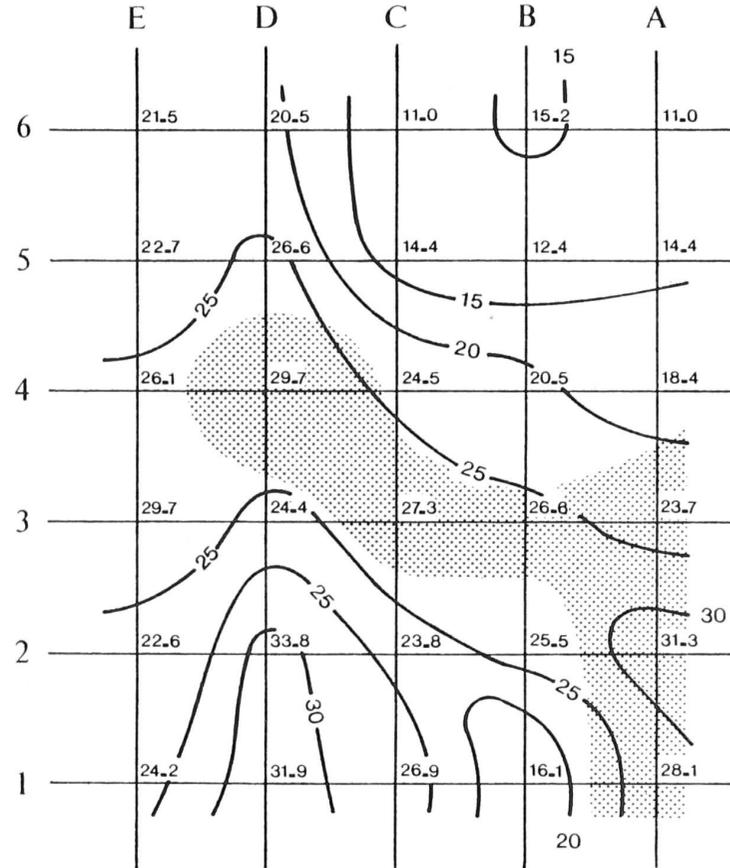


FIGURE 29. 15 cm to 30 cm DEPTH

SOIL MOISTURE ISOPLETH MAPS FOR AUGUST 13

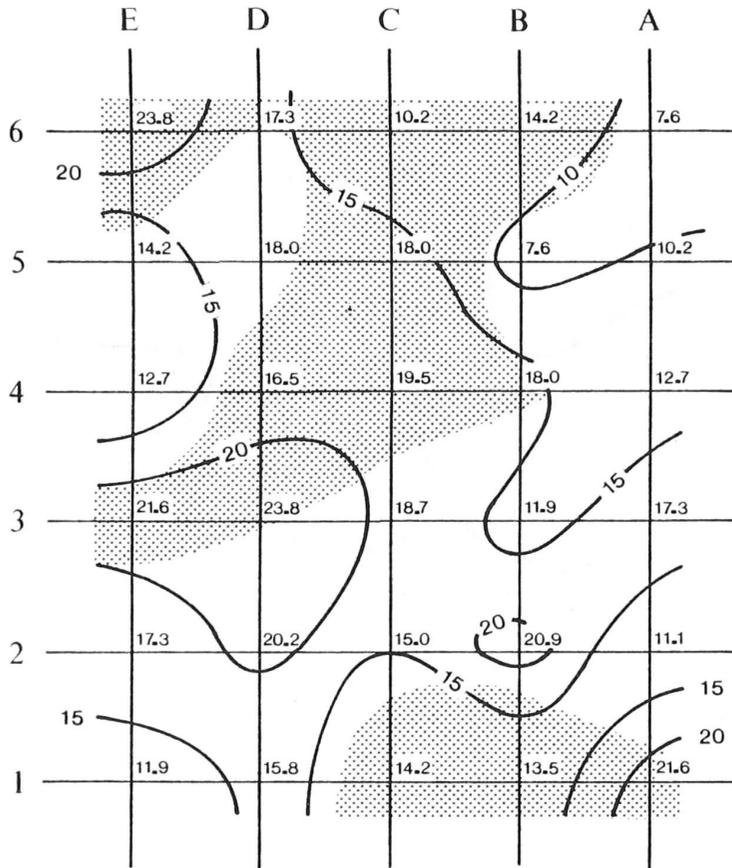


FIGURE 30. 0 cm to 15 cm DEPTH

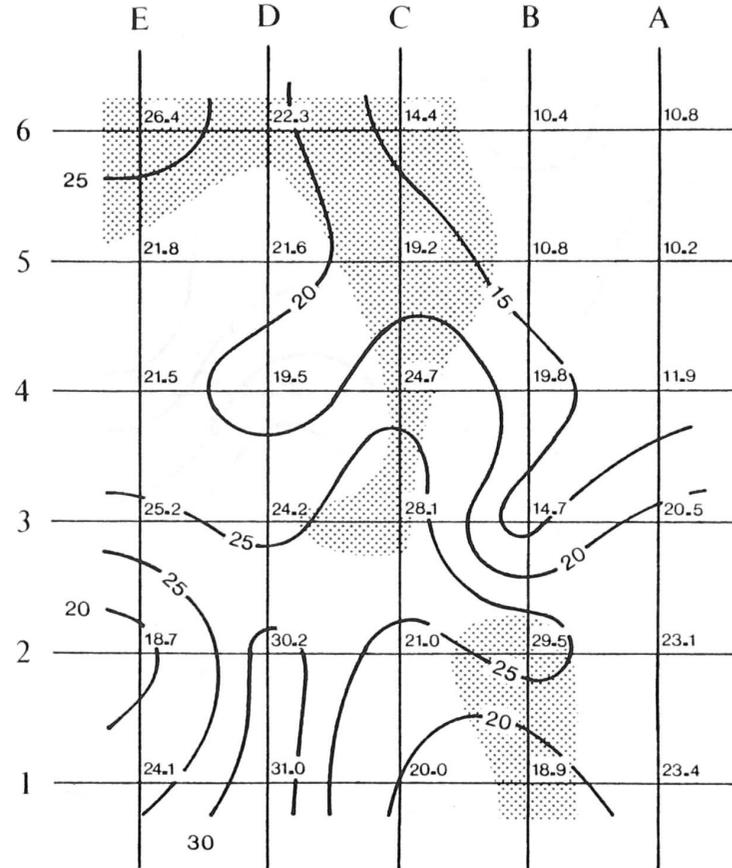


FIGURE 31. 15 cm to 30 cm DEPTH

SOIL MOISTURE ISOPLETH MAPS FOR AUGUST 15

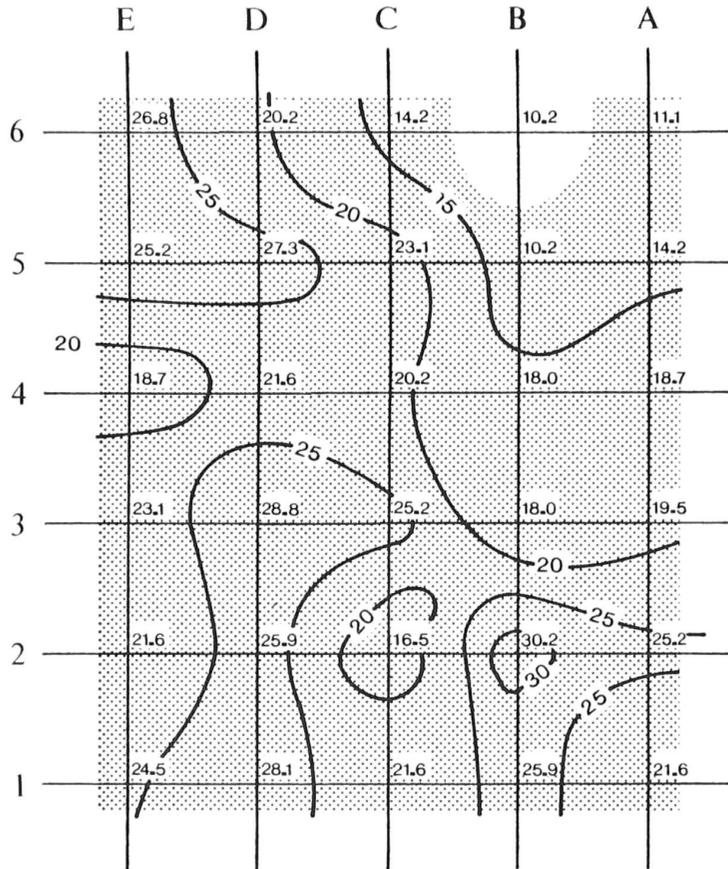


FIGURE 32. 0 cm to 15 cm DEPTH

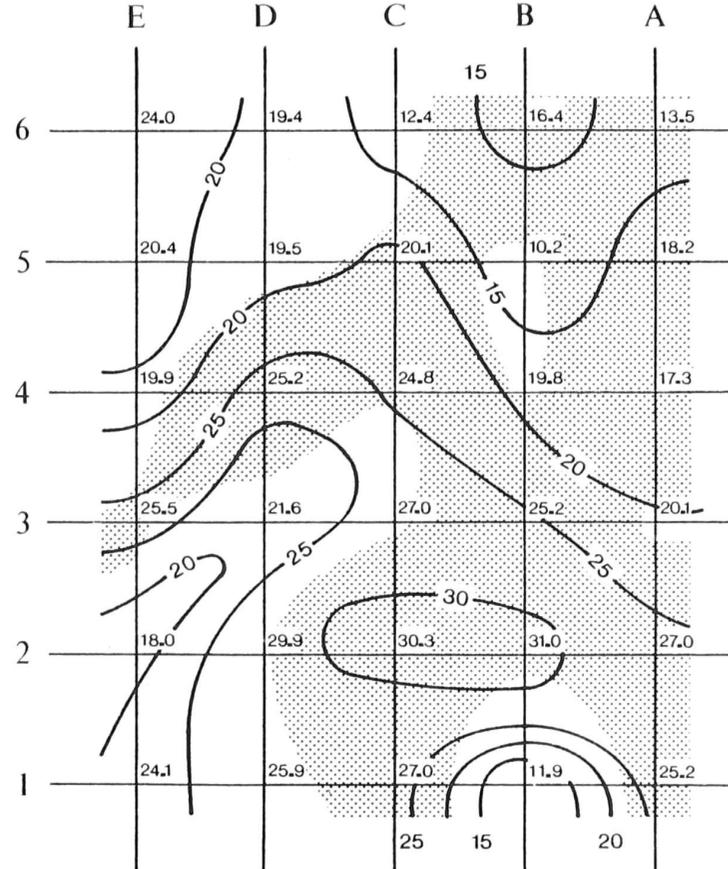


FIGURE 33. 15 cm to 30 cm DEPTH

APPENDIX II

SOIL CLASSIFICATION DATA

TABLE 16. SOIL CLASSIFICATION BY GRAIN SIZE: 0 cm to 15 cm DEPTH

| STATION NUMBER | SAND % | SILT % | CLAY % | TOTAL % | APPARENT ERROR % | SOIL TYPE/REMARKS |
|----------------|--------|--------|--------|---------|------------------|-------------------|
| A-1 | 22.7 | 45.0 | 31.5 | 99.2 | -0.8 | Clay Loam |
| A-2 | 11.1 | 50.2 | 37.6 | 98.9 | -1.1 | Silty Clay Loam |
| A-3 | 33.6 | 34.8 | 30.5 | 98.9 | -1.1 | Clay Loam |
| A-4 | 80.2 | 8.6 | 9.8 | 98.6 | -1.4 | Loamy Sand |
| A-5 | 66.8 | 18.0 | 10.7 | 95.5 | -4.5 | Sandy Loam |
| A-6 | 69.6 | 15.9 | 12.5 | 98.0 | -2.0 | Sandy Loam |
| B-1 | 7.2 | 58.0 | 32.1 | 97.3 | -2.7 | Silty Clay Loam |
| B-2 | 16.5 | 42.3 | 38.6 | 97.4 | -2.6 | Silty clay Loam |
| B-3 | 21.7 | 37.5 | 39.8 | 99.0 | -1.0 | Clay Loam |
| B-4 | 32.9 | 36.6 | 30.3 | 99.8 | -0.2 | Clay Loam |
| B-5 | 62.1 | 21.4 | 14.1 | 97.6 | -2.4 | Sandy Loam |
| B-6 | 54.8 | 25.6 | 17.9 | 98.3 | -1.7 | Sandy Loam |
| C-1 | 12.7 | 45.6 | 41.4 | 99.7 | -0.3 | Silty Clay |
| C-2 | 6.4 | 49.3 | 42.1 | 97.8 | -2.2 | Silty Clay |
| C-3 | 12.3 | 46.0 | 40.3 | 98.6 | -1.4 | Silty Clay |
| C-4 | 26.5 | 36.1 | 35.2 | 97.8 | -2.2 | Clay Loam |
| C-5 | 29.5 | 34.4 | 34.2 | 98.1 | -1.9 | Clay Loam |
| C-6 | 58.4 | 22.2 | 17.9 | 98.5 | -1.5 | Sandy Loam |

TABLE 16. CONT'D.

| STATION NUMBER | SAND % | SILT % | CLAY % | TOTAL % | APPARENT ERROR % | SOIL TYPE/REMARKS |
|-------------------|-----------|-----------|-----------|------------|---------------------|---------------------------|
| D-1 | 9.8 | 52.8 | 37.2 | 99.8 | -0.2 | Silty Clay Loam |
| D-2 | 11.0 | 44.7 | 43.7 | 99.4 | -0.6 | Silty Clay |
| D-3 | 8.8 | 46.4 | 42.6 | 97.8 | -2.2 | Silty Clay |
| D-4 | 17.6 | 39.4 | 39.1 | 96.1 | -3.9 | Clay Loam/Silty Clay Loam |
| D-5 | 20.0 | 43.5 | 35.2 | 98.7 | -1.3 | Clay Loam/Silty Clay Loam |
| D-6 | 27.3 | 37.5 | 35.2 | 100.0 | 0.0 | Clay Loam |
| E-1 | 31.5 | 31.2 | 36.7 | 99.4 | -0.6 | Clay Loam |
| E-2 | 14.3 | 46.1 | 39.4 | 99.8 | -0.2 | Silty Clay Loam |
| E-3 | 11.0 | 54.6 | 33.5 | 99.1 | -0.9 | Silty Clay Loam |
| E-4 | 14.7 | 39.1 | 42.4 | 96.2 | -3.8 | Clay |
| E-5 | 18.9 | 46.1 | 35.4 | 100.4 | +0.4 | Silty Clay Loam |
| E-6 | 14.4 | 46.8 | 39.4 | 100.6 | +0.6 | Silty Clay Loam |

TABLE 17. SOIL CLASSIFICATION BY GRAIN SIZE: 15 cm to 30 cm DEPTH

| STATION NUMBER | SAND % | SILT % | CLAY % | TOTAL % | APPARENT ERROR % | SOIL TYPE/REMARKS |
|----------------|--------|--------|--------|---------|------------------|----------------------------|
| A-1 | 29.5 | 34.2 | 35.9 | 99.6 | -0.4 | Clay Loam |
| A-2 | 12.3 | 49.2 | 43.0 | 104.5 | +4.5 | Silty Clay |
| A-3 | 15.4 | 49.0 | 35.7 | 100.1 | +0.1 | Silty Clay Loam |
| A-4 | 39.2 | 35.8 | 25.4 | 100.4 | +0.4 | Loam |
| A-5 | 40.2 | 39.4 | 23.3 | 102.9 | +2.9 | Loam |
| A-6 | 57.4 | 27.9 | 15.1 | 100.4 | +0.4 | Sandy Loam |
| B-1 | 18.0 | 85.8 | 1.3 | 105.1 | +5.1 | Silt |
| B-2 | 13.9 | 43.5 | 45.4 | 102.8 | +2.8 | Silty Clay |
| B-3 | 15.9 | 46.9 | 39.2 | 102.0 | +2.0 | Silty Clay Loam/Silty Clay |
| B-4 | 31.7 | 37.2 | 29.7 | 98.6 | -1.4 | Clay Loam |
| B-5 | 59.3 | 24.4 | 16.9 | 100.6 | +0.6 | Sandy Loam |
| B-6 | 46.0 | 35.2 | 18.1 | 99.3 | -0.7 | Loam |
| C-1 | 19.1 | 43.2 | 40.4 | 102.7 | +2.7 | Silty Clay/Silty Clay Loam |
| C-2 | 21.4 | 38.9 | 42.7 | 103.0 | +3.0 | Clay/Silty Clay |
| C-3 | 9.3 | 63.4 | 31.9 | 104.6 | +4.6 | Silty Clay Loam |
| C-4 | 14.3 | 54.5 | 34.8 | 103.6 | +3.6 | Silty Clay Loam |
| C-5 | 21.9 | 47.4 | 31.8 | 101.1 | +1.1 | Clay Loam/Silty Clay Loam |
| C-6 | 70.0 | 16.2 | 12.3 | 98.5 | -1.5 | Sandy Loam |

TABLE 17. CONT'D.

| STATION NUMBER | SAND % | SILT % | CLAY % | TOTAL % | APPARENT ERROR % | SOIL TYPE/REMARKS |
|-------------------|-----------|-----------|-----------|------------|---------------------|----------------------------|
| D-1 | 18.8 | 43.8 | 42.0 | 104.6 | +4.6 | Silty Clay |
| D-2 | 13.2 | 42.1 | 47.1 | 102.4 | +2.4 | Silty Clay |
| D-3 | 16.2 | 46.2 | 40.6 | 103.0 | +3.0 | Silty Clay/Silty Clay Loam |
| D-4 | 14.2 | 56.4 | 33.7 | 104.3 | +4.3 | Silty Clay Loam |
| D-5 | 19.4 | 49.1 | 33.6 | 102.1 | +2.1 | Silty Clay Loam |
| D-6 | 24.9 | 44.3 | 29.8 | 99.0 | -1.0 | Clay Loam |
| E-1 | 19.9 | 49.8 | 31.3 | 101.0 | +1.0 | Silty Clay Loam/Clay Loam |
| E-2 | 19.5 | 42.5 | 39.8 | 101.8 | +1.8 | Silty Clay Loam/Silty Clay |
| E-3 | 9.6 | 41.2 | 50.7 | 101.5 | +1.5 | Silty Clay |
| E-4 | 14.7 | 52.5 | 38.0 | 105.2 | +5.2 | Silty Clay Loam |
| E-5 | 12.9 | 54.5 | 36.2 | 103.6 | +3.6 | Silty Clay Loam |
| E-6 | 12.2 | 50.2 | 38.8 | 101.2 | +1.2 | Silty Clay Loam/Silty Clay |

TABLE 18. SOIL CLASSIFICATION BY GRAIN SIZE: 0 cm to 30 cm DEPTH

| STATION NUMBER | SAND % | SILT % | CLAY % | TOTAL % | APPARENT ERROR % | SOIL TYPE/REMARKS |
|----------------|--------|--------|--------|---------|------------------|---------------------------------|
| A-1 | 26.1 | 39.6 | 33.7 | 99.4 | -0.6 | Clay Loam |
| A-2 | 11.7 | 49.7 | 40.3 | 101.7 | +1.7 | Silty Clay/Silty Clay Loam |
| A-3 | 24.5 | 41.9 | 33.1 | 99.5 | -0.5 | Clay Loam |
| A-4 | 59.7 | 22.2 | 17.6 | 99.5 | -0.5 | Sandy Loam |
| A-5 | 53.5 | 28.7 | 17.0 | 99.2 | -0.8 | Sandy Loam |
| A-6 | 63.5 | 21.9 | 13.8 | 99.2 | -0.8 | Sandy Loam |
| B-1 | 12.6 | 71.9 | 16.7 | 101.2 | +1.2 | Silt Loam |
| B-2 | 15.2 | 42.9 | 42.0 | 100.1 | +0.1 | Silty Clay/Clay |
| B-3 | 18.8 | 42.2 | 39.5 | 100.5 | +0.5 | Silty Clay Loam/Silty Clay/Clay |
| B-4 | 32.3 | 36.9 | 30.0 | 99.2 | -0.8 | Clay Loam |
| B-5 | 60.7 | 22.9 | 15.5 | 99.1 | -0.9 | Sandy Loam |
| B-6 | 50.4 | 30.4 | 18.0 | 98.8 | -1.2 | Loam |
| C-1 | 15.9 | 44.4 | 40.9 | 101.2 | +1.2 | Silty Clay |
| C-2 | 13.9 | 44.1 | 42.4 | 100.4 | +0.4 | Silty Clay |
| C-3 | 10.8 | 54.7 | 36.1 | 101.6 | +1.6 | Silty Clay Loam |
| C-4 | 20.4 | 45.3 | 35.0 | 100.7 | +0.7 | Silty Clay Loam/Clay Loam |
| C-5 | 25.7 | 40.9 | 33.0 | 99.6 | -0.4 | Clay Loam |
| C-6 | 64.2 | 19.2 | 15.1 | 98.5 | -1.5 | Sandy Loam |

TABLE 18. CONT'D.

| STATION NUMBER | SAND % | SILT % | CLAY % | TOTAL % | APPARENT ERROR % | SOIL TYPE/REMARKS |
|-------------------|-----------|-----------|-----------|------------|---------------------|----------------------------|
| D-1 | 14.3 | 48.3 | 39.6 | 102.2 | +2.2 | Silty Clay Loam/Silty Clay |
| D-2 | 12.1 | 43.4 | 45.4 | 100.9 | +0.9 | Silty Clay |
| D-3 | 12.5 | 46.3 | 41.6 | 100.4 | +0.4 | Silty Clay |
| D-4 | 15.9 | 47.9 | 36.4 | 100.2 | +0.2 | Silty Clay Loam |
| D-5 | 19.7 | 46.3 | 34.4 | 100.4 | +0.4 | Silty Clay Loam/Clay Loam |
| D-6 | 26.1 | 40.9 | 32.5 | 99.5 | -0.5 | Clay Loam |
| E-1 | 25.7 | 40.5 | 34.0 | 100.2 | +0.2 | Clay Loam |
| E-2 | 16.9 | 44.3 | 39.6 | 100.8 | +0.8 | Silty Clay Loam/Silty Clay |
| E-3 | 10.3 | 47.9 | 42.1 | 100.3 | +0.3 | Silty Clay |
| E-4 | 14.7 | 45.8 | 40.2 | 100.7 | +0.7 | Silty Clay/Silty Clay Loam |
| E-5 | 15.9 | 50.3 | 35.8 | 102.0 | +2.0 | Silty Clay Loam |
| E-6 | 13.3 | 48.5 | 39.1 | 100.9 | +0.9 | Silty Clay Loam/Silty Clay |

APPENDIX III

SOIL MOISTURE DATA

TABLE 19. SOIL MOISTURE VARIATION: 0 cm to 15 cm DEPTH

| STATION NUMBER | MEAN VOLUMETRIC WATER CONTENT (%) | VARIATION FROM MEAN (%) | VARIATION (%) | | RANGE (%) |
|-------------------|--------------------------------------|----------------------------|---------------|---------|--------------|
| | | | MAXIMUM | MINIMUM | |
| A-1 | 24.4 | + 8.7 / -10.2 | 33.1 | 14.2 | 18.9 |
| A-2 | 22.2 | +10.9 / -11.1 | 33.1 | 11.1 | 22.0 |
| A-3 | 19.6 | +15.6 / - 5.5 | 35.2 | 14.1 | 21.1 |
| A-4 | 16.4 | + 8.8 / - 8.8 | 25.2 | 7.6 | 17.6 |
| A-5 | 15.3 | +12.0 / - 9.7 | 27.3 | 5.6 | 21.7 |
| A-6 | 13.3 | +13.3 / - 7.7 | 26.6 | 5.6 | 21.0 |
| B-1 | 21.6 | +16.0 / -13.1 | 37.6 | 8.5 | 29.1 |
| B-2 | 25.5 | +10.5 / -10.5 | 36.0 | 15.0 | 21.0 |
| B-3 | 20.1 | + 8.7 / - 9.0 | 28.8 | 11.1 | 17.7 |
| B-4 | 21.1 | + 8.4 / - 4.6 | 29.5 | 16.5 | 13.0 |
| B-5 | 14.8 | +10.4 / - 9.2 | 25.2 | 5.6 | 19.6 |
| B-6 | 13.8 | +11.4 / - 7.2 | 25.2 | 6.6 | 18.6 |
| C-1 | 20.3 | + 8.5 / - 8.4 | 28.8 | 11.9 | 16.9 |
| C-2 | 21.9 | + 9.8 / - 9.2 | 31.7 | 12.7 | 19.0 |
| C-3 | 23.0 | +11.6 / -10.3 | 34.6 | 12.7 | 21.9 |
| C-4 | 23.5 | +14.7 / - 9.3 | 38.2 | 14.2 | 24.0 |
| C-5 | 20.4 | + 8.4 / -10.2 | 28.8 | 10.2 | 18.6 |
| C-6 | 16.2 | +11.1 / - 8.6 | 27.3 | 7.6 | 19.7 |

TABLE 19. CONT'D.

| STATION NUMBER | MEAN VOLUMETRIC WATER CONTENT (%) | VARIATION FROM MEAN (%) | VARIATION (%) | | RANGE (%) |
|-------------------|--------------------------------------|----------------------------|---------------|---------|--------------|
| | | | MAXIMUM | MINIMUM | |
| D-1 | 26.8 | +12.9 / -12.6 | 39.7 | 14.2 | 25.5 |
| D-2 | 25.7 | +10.3 / - 7.2 | 36.0 | 18.5 | 17.5 |
| D-3 | 24.3 | +10.3 / -14.1 | 34.6 | 10.2 | 24.4 |
| D-4 | 21.7 | + 4.2 / - 8.2 | 25.9 | 13.5 | 12.4 |
| D-5 | 20.8 | + 9.4 / - 8.1 | 30.2 | 12.7 | 17.5 |
| D-6 | 20.0 | + 7.3 / - 8.9 | 27.3 | 11.1 | 16.2 |
| E-1 | 20.2 | + 8.6 / - 8.3 | 28.8 | 11.9 | 16.9 |
| E-2 | 22.4 | +10.0 / - 9.7 | 32.4 | 12.7 | 19.7 |
| E-3 | 21.1 | + 6.2 / - 9.1 | 27.3 | 12.0 | 15.3 |
| E-4 | 22.7 | +10.4 / -17.1 | 33.1 | 5.6 | 27.5 |
| E-5 | 22.2 | +12.4 / -12.0 | 34.6 | 10.2 | 24.4 |
| E-6 | 23.5 | + 3.8 / -10.8 | 27.3 | 12.7 | 14.6 |

TABLE 20. SOIL MOISTURE VARIATION: 15 cm to 30 cm DEPTH

| STATION NUMBER | MEAN VOLUMETRIC WATER CONTENT (%) | VARIATION FROM MEAN (%) | VARIATION (%) | | RANGE (%) |
|-------------------|--------------------------------------|----------------------------|---------------|---------|--------------|
| | | | MAXIMUM | MINIMUM | |
| A-1 | 29.2 | + 7.2 / -11.8 | 36.4 | 17.4 | 19.0 |
| A-2 | 28.0 | + 9.5 / -13.7 | 37.5 | 14.3 | 23.2 |
| A-3 | 25.8 | + 4.8 / - 9.0 | 30.6 | 16.8 | 13.8 |
| A-4 | 19.4 | + 5.8 / - 8.6 | 25.2 | 10.8 | 14.4 |
| A-5 | 18.5 | + 8.2 / - 8.3 | 26.7 | 10.2 | 16.5 |
| A-6 | 15.5 | +11.9 / - 4.9 | 27.4 | 10.6 | 16.8 |
| B-1 | 25.6 | +12.2 / -13.7 | 37.8 | 11.9 | 25.9 |
| B-2 | 30.1 | + 8.4 / -12.7 | 38.5 | 17.4 | 21.1 |
| B-3 | 29.1 | +10.5 / -15.6 | 39.6 | 13.5 | 26.1 |
| B-4 | 25.1 | + 8.8 / - 5.6 | 33.9 | 19.5 | 14.4 |
| B-5 | 18.0 | + 7.2 / - 8.7 | 25.2 | 9.3 | 15.9 |
| B-6 | 20.6 | + 8.2 / -10.2 | 28.8 | 10.4 | 18.4 |
| C-1 | 27.3 | +12.3 / - 8.1 | 39.6 | 19.2 | 20.4 |
| C-2 | 32.1 | + 9.3 / -11.1 | 41.4 | 21.0 | 20.4 |
| C-3 | 30.6 | + 9.0 / -10.9 | 39.6 | 19.7 | 19.9 |
| C-4 | 29.3 | + 6.0 / -14.2 | 35.3 | 15.1 | 20.2 |
| C-5 | 27.2 | +12.8 / -13.5 | 40.0 | 13.7 | 26.3 |
| C-6 | 15.8 | + 9.4 / - 8.9 | 25.2 | 6.9 | 18.3 |

TABLE 20. CONT'D.

| STATION NUMBER | MEAN VOLUMETRIC WATER CONTENT (%) | VARIATION FROM MEAN (%) | VARIATION (%) | | RANGE (%) |
|-------------------|--------------------------------------|----------------------------|---------------|---------|--------------|
| | | | MAXIMUM | MINIMUM | |
| D-1 | 34.8 | + 8.7 / -17.8 | 43.5 | 17.0 | 26.5 |
| D-2 | 34.7 | + 8.5 / -16.2 | 43.2 | 18.5 | 24.7 |
| D-3 | 31.1 | + 8.5 / -12.7 | 39.6 | 18.4 | 21.2 |
| D-4 | 28.7 | +13.8 / - 9.2 | 42.5 | 19.5 | 23.0 |
| D-5 | 27.8 | + 8.2 / -15.3 | 36.0 | 12.5 | 23.5 |
| D-6 | 27.0 | + 6.8 / -15.9 | 33.8 | 11.1 | 22.7 |
| E-1 | 27.6 | + 5.5 / -10.8 | 33.1 | 16.8 | 16.3 |
| E-2 | 29.4 | +13.1 / -11.4 | 42.5 | 18.0 | 24.5 |
| E-3 | 29.9 | + 5.0 / - 4.7 | 34.9 | 25.2 | 9.7 |
| E-4 | 30.7 | +12.2 / -15.9 | 42.9 | 14.8 | 28.1 |
| E-5 | 27.0 | + 8.6 / - 8.6 | 35.6 | 18.4 | 17.2 |
| E-6 | 30.3 | +10.8 / -11.2 | 41.1 | 19.1 | 22.0 |

TABLE 21. SOIL MOISTURE VARIATION: 0 cm to 30 cm DEPTH

| STATION NUMBER | MEAN VOLUMETRIC WATER CONTENT (%) | VARIATION FROM MEAN (%) | VARIATION (%) | | RANGE (%) |
|-------------------|--------------------------------------|----------------------------|---------------|---------|--------------|
| | | | MAXIMUM | MINIMUM | |
| A-1 | 26.8 | + 6.5 / -11.0 | 33.3 | 15.8 | 17.5 |
| A-2 | 25.1 | + 9.1 / -12.4 | 34.2 | 12.7 | 21.5 |
| A-3 | 22.7 | + 8.8 / - 7.2 | 31.5 | 15.5 | 16.0 |
| A-4 | 17.9 | + 7.3 / - 8.7 | 25.2 | 9.2 | 16.0 |
| A-5 | 16.9 | +10.1 / - 8.8 | 27.0 | 8.1 | 18.9 |
| A-6 | 14.4 | + 9.9 / - 6.3 | 24.3 | 8.1 | 16.2 |
| B-1 | 23.6 | +12.4 / -11.3 | 36.0 | 12.3 | 23.7 |
| B-2 | 27.8 | + 8.2 / -11.6 | 36.0 | 16.2 | 19.8 |
| B-3 | 24.6 | + 9.6 / -12.3 | 34.2 | 12.3 | 21.9 |
| B-4 | 23.1 | + 7.5 / - 5.1 | 30.6 | 18.0 | 12.6 |
| B-5 | 16.4 | + 8.8 / - 8.3 | 25.2 | 8.1 | 17.1 |
| B-6 | 17.2 | + 9.8 / - 7.6 | 27.0 | 9.6 | 17.4 |
| C-1 | 23.8 | +10.4 / - 6.7 | 34.2 | 17.1 | 17.1 |
| C-2 | 27.0 | + 8.1 / - 9.0 | 35.1 | 18.0 | 17.1 |
| C-3 | 26.8 | + 7.4 / -10.6 | 34.2 | 16.2 | 18.0 |
| C-4 | 26.4 | + 6.9 / -10.2 | 33.3 | 16.2 | 17.1 |
| C-5 | 23.8 | + 6.8 / -11.5 | 30.6 | 12.3 | 18.3 |
| C-6 | 16.0 | + 7.4 / - 7.4 | 23.4 | 8.6 | 14.8 |

TABLE 21. CONT'D.

| STATION NUMBER | MEAN VOLUMETRIC WATER CONTENT (%) | VARIATION FROM MEAN (%) | VARIATION (%) | | RANGE (%) |
|-------------------|--------------------------------------|----------------------------|---------------|---------|--------------|
| | | | MAXIMUM | MINIMUM | |
| D-1 | 30.8 | +18.5 / -15.2 | 49.3 | 15.6 | 33.7 |
| D-2 | 30.2 | + 5.8 / -11.7 | 36.0 | 18.5 | 17.5 |
| D-3 | 27.7 | + 8.3 / -13.4 | 36.0 | 14.3 | 21.7 |
| D-4 | 25.2 | + 9.0 / - 7.8 | 34.2 | 17.4 | 16.8 |
| D-5 | 24.3 | + 8.1 / -11.7 | 32.4 | 12.6 | 19.8 |
| D-6 | 23.5 | + 6.2 / -12.4 | 29.7 | 11.1 | 18.6 |
| E-1 | 23.9 | + 5.8 / - 7.7 | 29.7 | 16.2 | 13.5 |
| E-2 | 25.9 | + 9.2 / - 9.7 | 35.1 | 16.2 | 18.9 |
| E-3 | 25.5 | + 5.1 / - 3.9 | 30.6 | 21.6 | 9.0 |
| E-4 | 26.7 | + 8.4 / -16.5 | 35.1 | 10.2 | 24.9 |
| E-5 | 24.6 | +10.5 / -10.3 | 35.1 | 14.3 | 20.8 |
| E-6 | 26.9 | + 7.3 / -10.7 | 34.2 | 16.2 | 18.0 |

APPENDIX IV

BULK DENSITY AND VOLUMETRIC WATER CONTENT: DATA

TABLE 22. RELATIONSHIP BETWEEN BULK DENSITY AND VOLUMETRIC WATER CONTENT
0 cm to 15 cm DEPTH

| STATION** | DRY BULK DENSITY | VOLUMETRIC WATER CONTENT (%) | STATION | **DRY BULK DENSITY | VOLUMETRIC WATER CONTENT (%) |
|-----------|------------------|------------------------------|---------|--------------------|------------------------------|
| A-1 | 0.78 | 31.7 | A-3 | 1.07 | 27.4 |
| | 0.79 | 36.1 | | 1.09 | 21.6 |
| | 0.81 | 25.3 | | 1.11 | 20.9 |
| | 0.83 | 15.8 | | 1.12 | 21.6 |
| | * 0.88 | 34.6 | | 1.14 | 30.3 |
| | 0.91 | 25.3 | | * 1.19 | 27.4 |
| | 0.97 | 27.4 | | 1.23 | 18.1 |
| | 0.97 | 27.4 | | 1.23 | 26.0 |
| | 0.98 | 26.0 | | 1.31 | 25.3 |
| A-1 | 0.65 | 27.4 | A-3 | 1.13 | 21.6 |
| | 0.78 | 14.2 | | 1.17 | 21.6 |
| | 0.80 | 24.6 | | 1.21 | 18.1 |
| | 0.81 | 27.4 | | 1.22 | 27.4 |
| | * 0.83 | 39.7 | | * 1.23 | 30.3 |
| | * 0.84 | 36.1 | | 1.25 | 27.4 |
| | 0.90 | 21.6 | | 1.27 | 20.9 |
| | 0.95 | 26.0 | | 1.35 | 26.0 |
| | 1.01 | 27.4 | | 1.37 | 25.3 |

* Maximum Dry Bulk Density and Volumetric Water Content Value(s)

** Dry Bulk Density shown as g/cm³

TABLE 22. CONT'D.

| STATION NUMBER | **DRY BULK DENSITY | VOLUMETRIC WATER CONTENT (%) | STATION NUMBER | **DRY BULK DENSITY | VOLUMETRIC WATER CONTENT (%) |
|-------------------|-----------------------|------------------------------------|-------------------|-----------------------|------------------------------------|
| A-6 | 1.28 | 15.8 | B-5 | 1.05 | 14.2 |
| | 1.33 | 16.6 | | 1.15 | 12.7 |
| | * 1.37 | 25.3 | | 1.23 | 15.8 |
| | 1.38 | 18.8 | | 1.24 | 16.6 |
| | 1.39 | 17.3 | | 1.29 | 20.2 |
| | 1.40 | 18.1 | | 1.30 | 18.8 |
| | 1.41 | 18.1 | | * 1.35 | 21.6 |
| | 1.46 | 21.6 | | 1.38 | 21.6 |
| | 1.48 | 18.8 | | 1.38 | 20.2 |
| B-3 | 0.66 | 23.8 | B-5 | 1.02 | 12.7 |
| | 0.71 | 25.9 | | 1.08 | 20.2 |
| | 0.77 | 23.1 | | 1.09 | 14.2 |
| | 0.79 | 28.1 | | 1.10 | 15.8 |
| | 0.81 | 20.2 | | 1.12 | 18.8 |
| | 0.84 | 21.6 | | 1.19 | 21.6 |
| | 0.88 | 20.2 | | 1.20 | 16.6 |
| | * 0.91 | 31.7 | | * 1.22 | 20.2 |
| | 1.05 | 25.2 | | 1.22 | 21.6 |

* Maximum Dry Bulk Density and Volumetric Water Content Value(s)

** Dry Bulk Density shown as g/cm³

TABLE 22. CONT'D.

| STATION NUMBER | **DRY BULK DENSITY | VOLUMETRIC WATER CONTENT (%) | STATION NUMBER | **DRY BULK DENSITY | VOLUMETRIC WATER CONTENT (%) |
|----------------|--------------------|------------------------------|----------------|--------------------|------------------------------|
| C-2 | 0.51 | 33.1 | C-6 | 1.07 | 18.7 |
| | 0.57 | 18.0 | | 1.18 | 19.5 |
| | 0.66 | 27.3 | | 1.19 | 25.2 |
| | 0.69 | 27.3 | | 1.23 | 16.5 |
| | 0.70 | 21.6 | | * 1.28 | 27.3 |
| | 0.71 | 15.8 | | 1.29 | 27.3 |
| | 0.72 | 15.8 | | 1.33 | 21.6 |
| | 0.73 | 33.1 | | 1.34 | 23.8 |
| | * 0.89 | 33.8 | | 1.41 | 24.5 |
| C-4 | 0.58 | 27.3 | C-6 | 1.07 | 24.5 |
| | 0.67 | 32.4 | | 1.08 | 18.7 |
| | 0.75 | 34.6 | | 1.12 | 16.5 |
| | 0.78 | 21.6 | | 1.21 | 19.5 |
| | 0.82 | 32.4 | | 1.28 | 25.2 |
| | 0.86 | 34.6 | | 1.34 | 27.3 |
| | * 0.86 | 27.3 | | 1.35 | 23.8 |
| | 0.87 | 34.6 | | * 1.41 | 27.3 |
| | 0.90 | 27.3 | | 1.43 | 21.6 |

* Maximum Dry Bulk Density and Volumetric Water Content Value(s)

** Dry Bulk Density shown as g/cm³

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