SPATIAL VARIABILITY OF UNSATURATED HYDRAULIC CONDUCTIVITY OF TIPTON SOIL SERIES

By

JOSEPH ROBERT WILLIAMS

Bachelor of Science

University of Tennessee, Martin

Martin, Tennessee

1978

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 1980

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Thesis Approved:

Thesis Adviser

Dean of Graduate College

PREFACE

This study was made to evaluate the spatial variability of Tipton soil series; and to evaluate four methods of calculation of the unsaturated hydraulic conductivity. Measurements were taken *in situ* and in the laboratory utilizing a basic instantaneous profile method of calculation.

I wish to express my gratitude to my major adviser, Dr. D. L. Nofziger, for his suggestions and helpful advice in the course of this study. I also wish to express my appreciation to Drs. J. E. Garton, L. G. Morrill, and D. S. Murray for their suggestions in the preparation of the final manuscript. I wish to express gratitude to Mr. Harold Gray, Mr. Sarmad Mishu, and Mr. Tom Acre for their assistance in this study.

Special gratitude is expressed to my father and mother, Walter and Ruth, and my brother and sister, Walter and Eulalia, for their encouragement, support, and many sacrifices.

I wish to express a very special appreciation to my wife, Melinda, for understanding, encouragement, and many sacrifices in this study and preparation of this manuscript.

Finally, all praises and honors for these accomplishments go to Jesus Christ, our Lord for His guidance in my life.

Partial support for this research was provided by Regional Research Task Group S-124 and Oklahoma State University Water Research Center Project 4069.

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CHAPTER I

INTRODUCTION

Each year new information becomes available to assess soils for their hydraulic properties. Current taxonomic classification systems do not require thorough analysis of a soils ability to conduct water. The importance of this ability to conduct water has begun to attract considerable attention in many regions. Soils have generally been placed in drainage classes according to morphological characteristics. Therefore, if a soil is classified, morphologically, as being a certain soil series, it is automatically placed in the same drainage class as the representative profile. The validity of assigning a soil site to a particular drainage class through its morphological classification is becoming the subject of much research.

A major factor in a soil's ability to conduct water is its unsaturated hydraulic conductivity, $K(\theta)$. This study is an analysis of the unsaturated hydraulic conductivity and its variability for three sites of the Tipton soil series. Knowledge of the hydraulic conductivity and its variability, or spatial variability, for a soil series can aid in deciding appropriate uses of the land. (Spatial variability refers to the amount of variation in a soil property between sites.) Stockton and Warrick (1971) stated that if the spatial variability is not included in planning soil useage, wrong choices of land use could be made.

A great many studies are needed with various soils to gain a better knowledge of the hydraulic conductivity and its variability. In keeping with this idea, the first objective of this study was to obtain unsaturated hydraulic conductivity curves for Tipton soil series and compare these values for three sites.

Time and expense considerations have played and will continue to play a big part in research. Due to this, a secondary objective was formulated. This objective was to obtain unsaturated hydraulic conductivity values using four methods of calculation. These methods require different amounts of time and expense for collecting the experimental data. The results should assist scientists in evaluating simple methods for measuring conductivity. If the results are in good agreement with the more detailed measurements, the simpler approach could be used in future studies.

CHAPTER II

LITERATURE REVIEW

Hydraulic properties that vary within soil series are the subject of considerable research in the field of soil science. Understanding the variability of these properties will aid in the decision process of land-use planning. The primary concern of this research is the movement of water through the soil. The importance of this is seen when considering:

1. Movement of chemicals from landfills.
2. Movement of fertilizers and other chemicals from agricultural lands.
3. The need to remove excessive salts from saline areas.

To approach these and other problems, a knowledge of the soil's ability to conduct water must be gained. This ability to conduct water is dependent on the water content of the soil (Rose *et al.*, 1965). Other factors that may be involved in the conductivity are texture, bulk density, and structure.

For the conductivity of a soil to be considered in land-use planning, variability of the conductivity within a soil series must be investigated (Cassel, 1975).

Reliable estimates of the conductivity must be available to understand what the soil will do at different water contents.

Soils have been assigned to drainage classes in the morphological classification processes. Researchers have found that some soils which have been placed in different drainage classes may exhibit similar hydraulic properties (Bouma, 1973; Baker and Bouma, 1976). An earlier study (Stockton and Warrick, 1971) indicated that soils could have been placed in incorrect drainage classes. Bouma and Hole (1971) recognized that soil hydraulic properties should be considered when reviewing established soil series. Their study dealt with management-induced structural changes in soil hydraulic properties.

Stockton and Warrick (1971), using a Cumulic Haplustoll (Prima clay loam), found that if water contents used in conductivity calculations were greater than one standard deviation from the average moisture release curve, variabilities of 20 to 30 percent could occur in the hydraulic conductivity. Their moisture release curve was the average of 36 cores. They proposed that the variation in conductivity could be due to variability of the pore size distribution, depth, and spatial position.

Coefficients of variations in the unsaturated hydraulic conductivity of about 100 percent at saturation to about 400 percent at 54 percent of saturation were found by Nielsen et al. (1973) for the spatial variability of

Panoche soil series. These coefficients are large when compared to the coefficient of variation for the bulk density, which was about 7 percent. These values were obtained for 20 sites in a 150 hectare field.

Significant variability of the unsaturated hydraulic conductivity at the one percent level was found by Carvallo et al. (1976). Using an Aeric Calciaquoll (Maddock sandy loam), they indicate that the conductivity had a significant spatial variability, although they did not report statistical variances. They found that the conductivity variability generally increased with depth due to the heterogeneous nature of the soil.

Keisling (1974) found that by restricting the sampling to within the morphological horizons the variability of the conductivity could be reduced. He found that variability for the upper depths could also be reduced by restricting the sampling area to within an area of 0.15 km radius. Although, for sampling in the lower depths, areas as small as 0.15 km in radius did not reduce variation of the conductivity. It was pointed out that valid predictions of conductivity of a soil cannot be made from prediction models of other soils.

All examples given above show variability to be considerable for the soils studied. It must be realized that the amount of variability within one soil series may differ considerably from the amount of variability in another series. This was indicated by Baker (1978) in studies using nine Wisconsin soil series. It was pointed out that if a series has a low variability of the hydraulic conductivity, more accurate estimates could be made of the conductivity at specific water contents.

An *in situ* drainage method of obtaining measurements for conductivity calculations has been commonly used (Davidson *et al*., 1969; Hillel *et al*., 1972; Nielsen *et al*., 1973; Dane, 1980). In this method water is ponded on a plot until the profile is approximately saturated. When a steady infiltration rate is obtained and changes in the negative pressure heads in the profile become zero, the plot's surface is drained and covered. Covering the surface prevents upward movement of water and evaporation during the drying phase. Measurements to evaluate the hydraulic gradient and flux at specific times are taken during the drying process.

Hydraulic gradients have normally been calculated using data from tensiometers which utilize a mercury manometer. These are referred to as measured gradients. Suggestions have been made which could discontinue tensiometer use in conductivity studies. Hydraulic gradients may be equal to one or so close to one that conductivity calculations using the gradient of one assumption may describe conductivity values calculated with measured gradients (Davidson *et al*., 1969; Hillel *et al*., 1972; Nielsen *et al*., 1973; Simmons *et al*., 1979).

Flux calculations involve the use of water content values obtained *in situ* or in the laboratory. *In situ* values are obtained with a neutron moisture probe. Hillel *et al*. (1972) and Dane (1980) used probes in their studies to obtain water contents. A neutron access tube is located in the center of each site for taking neutron probe readings. If a probe is calibrated adequately, it will estimate *in situ* water contents very well (Grant, 1975; Parkes and Sian, 1979). McCauley and Stone (1972) have shown that more accurate water content measurements can be obtained by locating the source centrally in the probe and very close to the detector.

Laboratory analysis, using undisturbed soil core samples, can also be used to obtain water contents at specific negative pressure heads. LaRue *et al*. (1968) showed that two-thirds of their field measurements (using a gravimetric method) fell within one standard deviation of the soil core data. This observation was reiterated by Davidson *et al*. (1969) and later by Dane (1980). Dane (1980) specifically stated that it may be possible to eliminate field measurements for determining unsaturated hydraulic conductivity if undisturbed core samples can be analyzed.

These trends toward the complete use of core data for water content values and the unit gradient assumption could lead to some very economical and time-saving methods of obtaining conductivity curves. It may become more feasible to increase the number of sampling sites to increase realiability of characterizing a soil's hydraulic conductivity and its variability.

CHAPTER III

MATERIALS AND METHODS

Theory

The instantaneous profile method described by Hillel _et al_. (1972) was used for this study. The method is a derivation of a similiarly named method by Watson (1966). For this method Darcy's equation is used in the form

$$q = -K(\theta)\ \frac{\partial H}{\partial z} \qquad (1)$$

where q is the flux of water passing through the soil at depth z. The flux is the product of the unsaturated hydraulic conductivity, $K(\theta)$, and the total head gradient, $\partial H/\partial z$. Rearranging equation (1) to form

$$K(\theta) = -\ \frac{q}{\partial H/\partial z} \qquad (2)$$

allows for direct calculation of the conductivity from independent determinations of the flux and gradient.

Calculation of flux was done as described by Hillel _et al_. (1972). The continuity equation for one-dimensional flow implies

$$q = \int_0^z \frac{\partial\theta}{\partial t} dz \qquad (3)$$

where q is the flux (cm/day), θ is the volumetric water content (cm^3/cm^3), t is time (day), and z is depth (cm). The flux, q_i, at any depth, z_i, can be described by

$$q_i = q_{i-1} + \int_{z_{i-1}}^{z_i} \frac{\partial\theta}{\partial t}dz \quad \text{for } i=2,3,... \tag{4a}$$

and

$$q_1 = \int_0^{z_1} \frac{\partial\theta}{\partial t}dz \tag{4b}$$

These equations assume a flux of zero at the soil surface. In this study the integrals in equation (4) were evaluated using the trapezoidal rule in the form

$$\int_{x_1}^{x_2} f(x)dz \approx \frac{f(x_1)+f(x_2)}{2}(x_2-x_1) \tag{5}$$

In this study water content measurements were made at 15 cm intervals from 15 to 120 cm depths. It was assumed that the water content at the soil surface, z=0 cm, was the same as that at z=15 cm. Therefore,

$$\left.\frac{\partial\theta}{\partial t}\right|_{z=0} = \left.\frac{\partial\theta}{\partial t}\right|_{z=15} \tag{6}$$

This implies that the flux, q_1, across the first interval is

$$q_1 = 15 \cdot \left.\frac{\partial\theta}{\partial t}\right|_{z=15} \tag{7}$$

Equation (7) was always used to describe the first interval each time the flux was calculated.

The gradients can be calculated using the equation

$$\frac{\partial H}{\partial z} = \frac{\partial \phi}{\partial z} - 1 \qquad (8)$$

where ϕ is the soil-water pressure head. The pressure head was calculated from tensiometer data.

Using equation (2) as the basic expression of calculation of conductivity, four methods were used to calculate the conductivity. The first method (neutron-tensiometer method) used the neutron moisture probe data to obtain water contents for flux calculations and tensiometer data for gradient calculations. The second method (neutron-unity method) also used neutron moisture probe data, but used the unit gradient assumption as proposed by Simmons et al. (1979). The third method (core-tensiometer method) used undisturbed core samples for water content data and tensiometers for the gradient measurements. The fourth method (core-unity method) used undisturbed core samples and the unit gradient assumption for the calculation of the unsaturated hydraulic conductivity values.

Both field and lab water contents were fit by least squares to an equation of the form

$$\theta(z,t) = A(z) + B(z) \cdot \ln(t) \qquad (9)$$

The A(z) and B(z) terms are constants for each depth. Figure 1 shows the water content as a function of time along with the fitted function for two depths using core data for site 1. The neutron data can also be described by equation (9). The water contents obtained by the

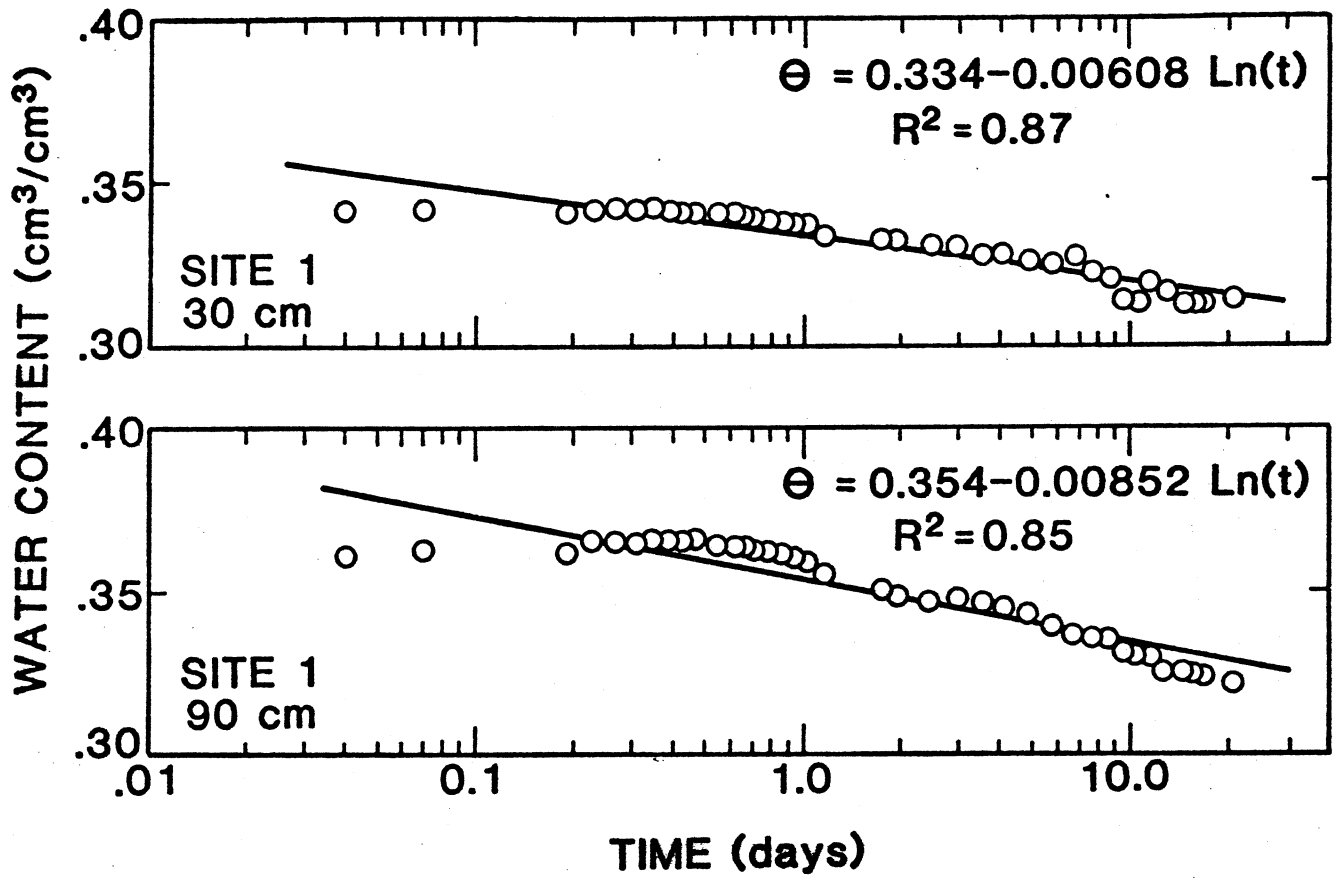

Figure 1. Water Content as a Function of Time Showing Raw Data in Relation to the Fitted Function

neutron method showed more scatter than those obtained from the core data. This function does overestimate the water content at small times by as much as 0.02 cm^3/cm^3, but the agreement is excellent for times greater than 0.2 day. From 0.2 to 12.0 days the function estimates the water content to within 0.005 cm^3/cm^3. Correlation index values (Ostle, 1963) were determined for each fitted function. Correlation values for neutron obtained data ranged from 0.81 to 0.92 for all depths except the 15 and 120 cm depths in site 2 and the 120 cm depth in site 3 which had values of 0.66, 0.49, and 0.70, respectively. For core obtained data, the correlation values ranged from 0.82 to 0.96 for all depths except the 30 and 120 cm depths in site 2 and the 45 cm depth in site 3 which had values of 0.79, 0.66, and 0.78, respectively.

Field Work

During the summer of 1979, three sites of Tipton soil series were chosen in Tillman County of Oklahoma. The sites were located within a distance of 2 km. The soils were classified by Mr. Earl Nance and Mr. Tom Reinsch (Soil Scientists, Agronomy Department, Oklahoma State University) to be representative of the series. (For discussion, the sites will be identified as sites 1, 2, and 3.) Detailed profile descriptions for the sites can be found in the Appendix.

Equipment was installed during a period of 04 June to 16 June. The ponding surface was laid out to be 3 m by 3 m at each site. Border boards (20 cm wide) bounded the site with 10 cm below and 10 cm above the soil surface. Black plastic (3-mil) was placed vertically below the boards to a depth of 60 cm. This vertical barrier was used to minimize horizontal water movement. Tensiometers were placed at 15 cm depth increments to 90 cm and at 30 cm increments from 90 cm to 150 cm. Three tensiometers were placed at each depth in each site. The tensiometers were located in a 1.5 by 1.5 meter square in the center of each site. A similar design is described by Davidson et al. (1969).

A single neutron access tube was located in the center of each site as described by Dane (1980). A neutron moisture probe similar to that of McCauley and Stone (1972) was used to obtain volumetric water contents. Roofs were built to cover the sites. During the drying process, black plastic (3-mil) and R-13 fiberglass insulation was placed on the soil's surface. The plastic, insulation, and roofs reduced soil temperature fluctuations and prevented evaporation from the soil surface.

Water was ponded on site 1 from 13 June to 18 June, on site 2 from 18 June to 21 June, and on site 3 from 14 June to 20 June. The sites were drained and the drying process began when infiltration rates became constant (approximately 6.0 cm/day for site 1, 17.8 cm/day for site 2, and 7.5 cm/day for site 3) and changes in tensiometer readings were approximately zero for a 24 hour period.

During the drying process, tensiometer readings were taken at 1 hour to 3 hour intervals for the first 24 hours. Neutron moisture probe readings were taken every two hours initially and at each time tensiometer readings were taken at later times. The frequency of tensiometer readings were gradually reduced until only one reading was taken each day. Two minute counts were taken with the neutron moisture probe at each depth. The drying process was considered complete when changes in tensiometer readings became less than 0.5 cm of mercury in 48 hours. This generally occurred 3-4 weeks after the time the drying process began.

Laboratory Work

In September, 1979, six 7.6 cm core samples were taken from each site at each tensiometer depth, except the 60 cm and 150 cm depths. The 60 cm and 150 cm depths were not selected due to the close proximity to horizon boundaries. The cores were used for laboratory measurements of soil-water characteristic curves, bulk density, and particle size analysis.

Core analysis began 16 September 1979 and extended through 22 September 1980. The work was done in the soil physics laboratory in the Agronomy Department, Agriculture

Hall, on the Oklahoma State University campus, Stillwater. Water release equipment was located in a constant temperature room maintained at 21°C ± 2°C.

All cores were exposed to a 0-152 cm range of pressure in increments of approximately 20 cm. Four of the six cores from each depth and each site were exposed to 510 cm of pressure. Volumetric water contents were obtained at each pressure to construct soil-water retention curves.

Particle size analysis was performed on three cores from each depth. The procedure was that described by Black (1965). Bulk densities were calculated for all cores.

CHAPTER IV

RESULTS AND DISCUSSION

Profile Descriptions

Detailed profile descriptions are included in the Appendix. The three sites were classified to have fine-loamy control sections and moderately slow permeability which would indicate that the three sites would have similar hydraulic properties. (The control section in this soil is designated as the surface 50 cm, due to an argillic horizon being present.)

Obvious differences in horizon positions can be seen in Figure 2. This figure also shows the position of tensiometers in the profile. Sites 1 and 2 had an A12 horizon from 22 cm ± 3 cm to 60 cm ± 3 cm, while site 3 had an A12 from 21 cm ± 3 cm to 46 cm ± 6 cm. (The plus or minus terms are used to represent the type horizon boundary. Abrupt-- ± 1 cm; clear-- ± 3 cm; gradual-- ± 6 cm; and diffuse--greater than ± 6 cm (Buol *et al.*, 1973).) This is the major difference in the surface horizons. The subsurface horizons differ considerably more. Site 1 had a B21t horizon from 59 cm ± 3 cm to

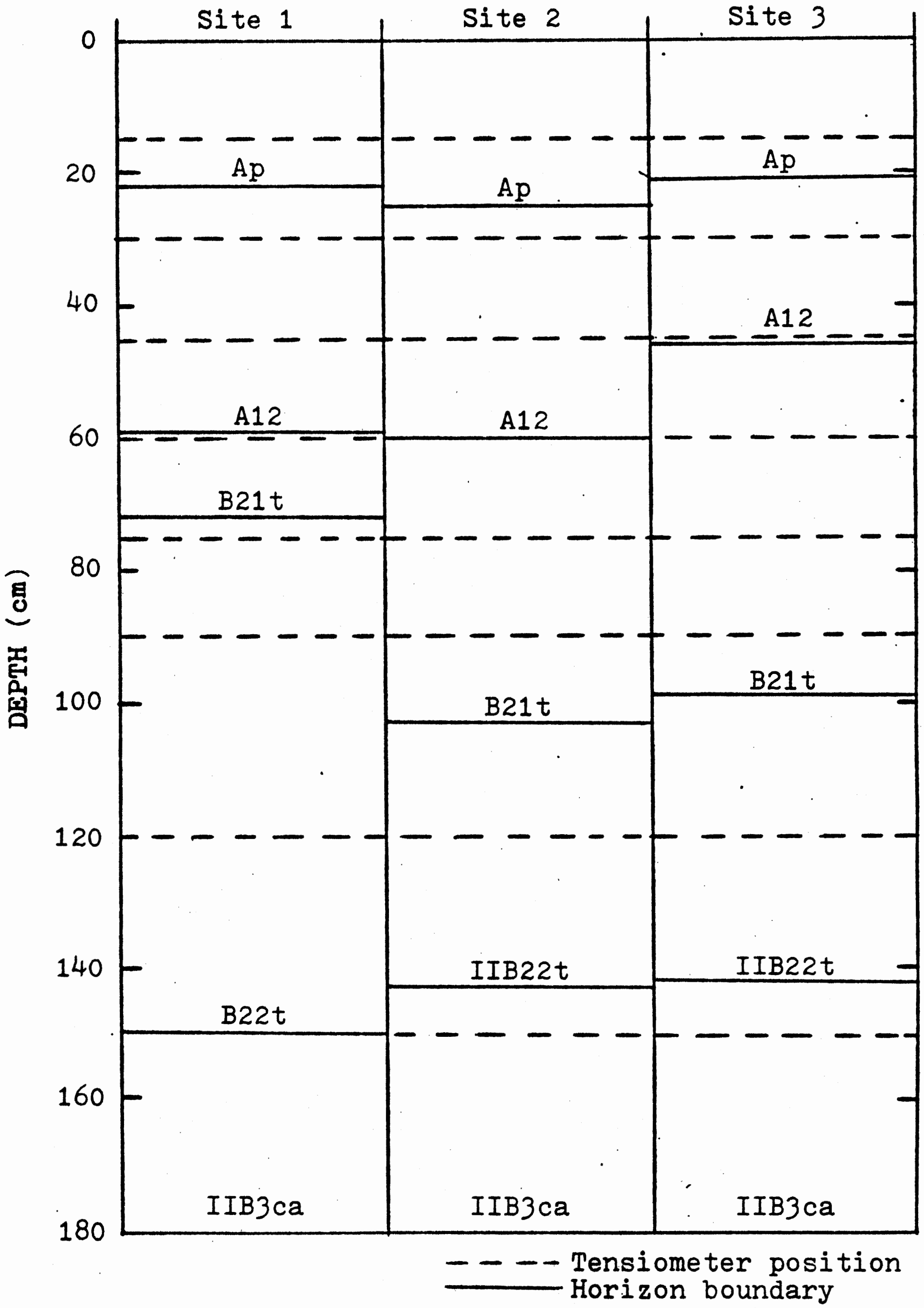

Figure 2. Position of Tensiometers and Horizons in the Three Profiles Studied

72 cm ± 6 cm, while the B21t in sites 2 and 3 extended to 103 cm ± 3 cm and 99 cm ± 6 cm, respectively.

Below the B21t horizon in site 1 was a B22t horizon. In sites 2 and 3 the horizon below the B21t was a IIB22t. The "II" prefix indicates a change in geologic processes. When no Roman numeral prefix is attached, the changes in the horizons are due to pedologic processes (Buol et al., 1973). The including of the "II" is probably due to the location of the sites. Sites 2 and 3 were within 0.4 km of each other, while site 1 was approximately 1.6 km from either of the other two sites.

The bottom horizon in all three sites was a IIB3ca horizon. This horizon began in the three sites at approximately 145 cm, with a diffuse boundary.

Table I shows the results of the particle size analysis. Textures were determined using the percentages of sand, silt, and clay and the textural triangle. The U.S.D.A. (United States Department of Agriculture) criteria for sand, silt, and clay were used. The results shown represent the mean of three measurements at each depth for each site. The standard deviation for these means ranged from 0.01 to 7.3 percent sand, silt, or clay. Considerable differences between sites were found in the subsurface. Sites 1 and 3 agreed well, being sandy loam, but site 2 was primarily loam. The three sites had differing textures at the 120 cm depth.

TABLE I

PARTICLE SIZE ANALYSIS RESULTS

Site-Depth (#) (cm)	% Sand	% Silt	% Clay	Texture
1-15	53.4	28.4	18.2	Sandy Loam
2-15	53.2	31.4	15.4	Sandy Loam
3-15	57.3	26.1	16.6	Sandy Loam
1-30	52.6	29.2	18.2	Sandy Loam
2-30	46.7	34.2	19.1	Loam
3-30	56.3	25.0	18.7	Sandy Loam
1-45	53.2	27.5	19.3	Sandy Loam
2-45	45.3	32.4	22.3	Loam
3-45	58.8	21.3	19.9	Sandy Loam
1-75	54.3	24.5	21.2	Sandy Clay Loam
2-75	43.7	33.4	22.9	Loam
3-75	59.5	21.0	19.5	Sandy Loam
1-90	55.7	25.6	18.7	Sandy Loam
2-90	44.4	31.4	24.2	Loam
3-90	64.2	17.9	17.9	Sandy Loam
1-120	56.0	23.7	20.3	Sandy Clay Loam
2-120	29.5	38.1	32.4	Clay Loam
3-120	40.9	33.0	26.1	Loam

Bulk density results are given in Table II. The values given are the average of the six cores taken from each depth. The average of samples from all depths and all sites was 1.64 g/cm^3, with a standard deviation of 0.08 g/cm^3. This standard deviation is 0.01 g/cm^3 less than the maximum standard deviation for any depth for any site, indicating that the variation between sites was about the same as the variation between samples representing the same depth and site.

TABLE II

AVERAGE BULK DENSITIES (g/cm^3) OF SOIL CORES

	Depth (cm)					
	15	30	45	75	90	120
Site 1	1.78	1.72	1.59	1.62	1.69	1.71
s	.03	.02	.06	.02	.06	.04
Site 2	1.68	1.66	1.52	1.60	1.61	1.58
s	.02	.04	.02	.06	.04	.04
Site 3	1.75	1.66	1.55	1.59	1.61	1.52
s	.04	.06	.04	.02	.09	.05

Average bulk densities and standard deviations (s) were calculated for six cores at each depth in each site.

Spatial Variability of $K(\theta)$

The hydraulic conductivity values of the three sites are shown as functions of volumetric water content in Figures 3-7 for the core-tensiometer method. This method was chosen due to the general acceptance of core-obtained water contents. Comparisons among sites for the other three methods gave similar results.

The conductivity curves for the three sites at the 15-30 cm depth agree very well. Below 30 cm the curves for the different depths begin to separate from one another. For the 30-45 cm, 45-75 cm, and 75-90 cm depths, the curves for sites 1 and 3 tend to coincide. The curves for site 2, for the same depths, shift to the right. That is, site 2 had a lower conductivity at the same water content. The conductivities, at the same water contents, for sites 1 and 3 are approximately 10 times greater than site 2 at the 30-45 cm depth. Conductivities at sites 1 and 3 are 100 times greater at the 45-75 cm and 75-90 cm depths. These results are consistent with results in Table I. Sites 1 and 3 had sandy loam textures at the 15, 30, 45, 75, and 90 cm depths, except for site 1, which had a sandy clay loam texture at the 75 cm depth. In contrast, site 2 was sandy loam at 15 cm and loam at the other depths.

At the 90-120 cm depth the conductivity curves separated to a degree that curves for each site could easily

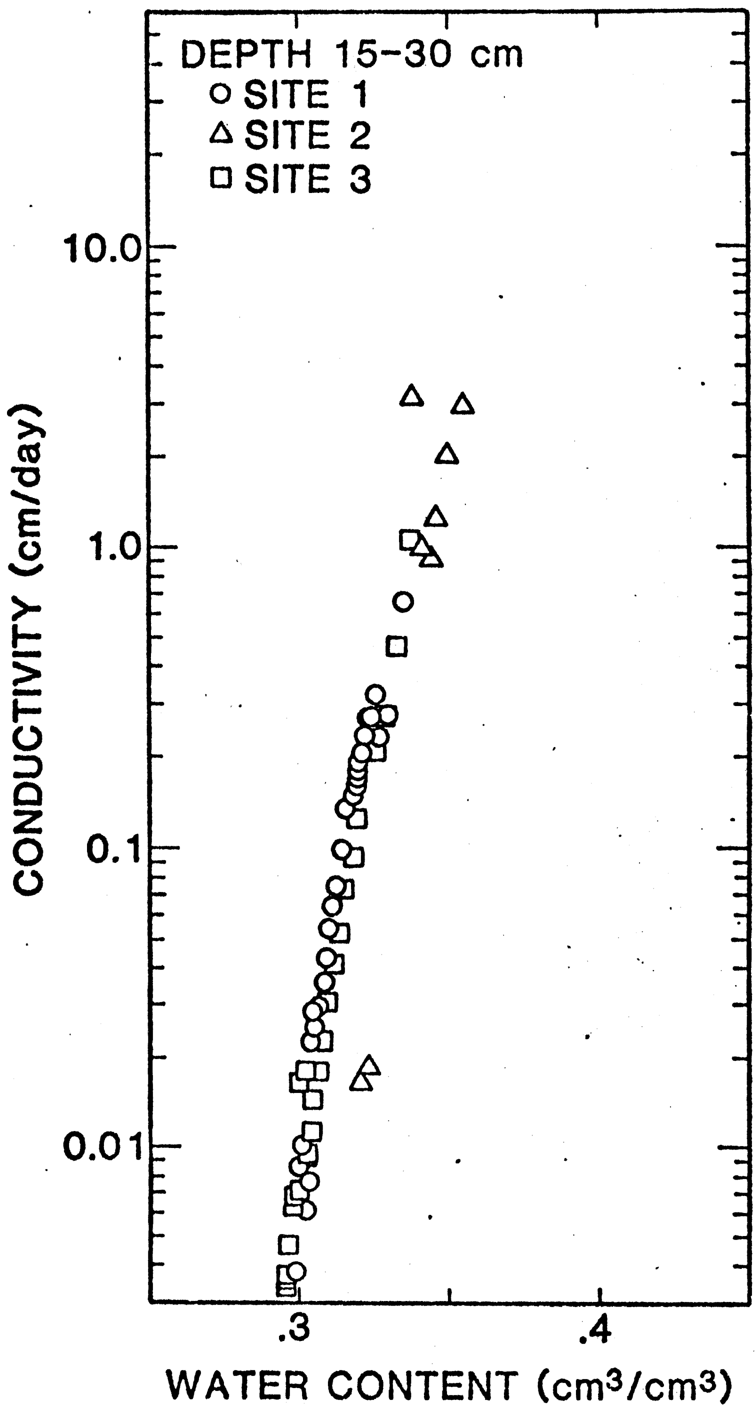

Figure 3. Conductivity as a Function of Water Content for the 15-30 cm Depth at Three Sites

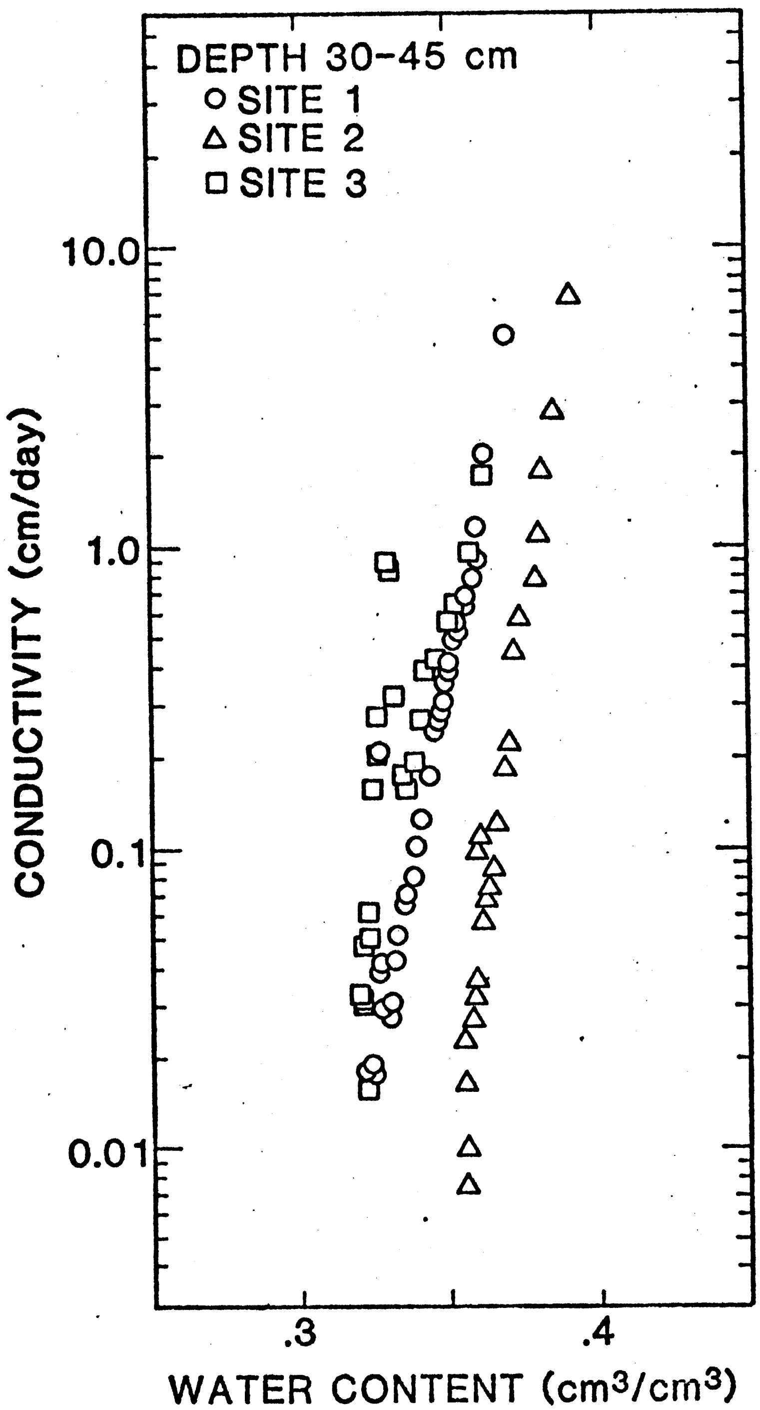

Figure 4. Conductivity as a Function of Water Content for the 30-45 cm Depth at Three Sites

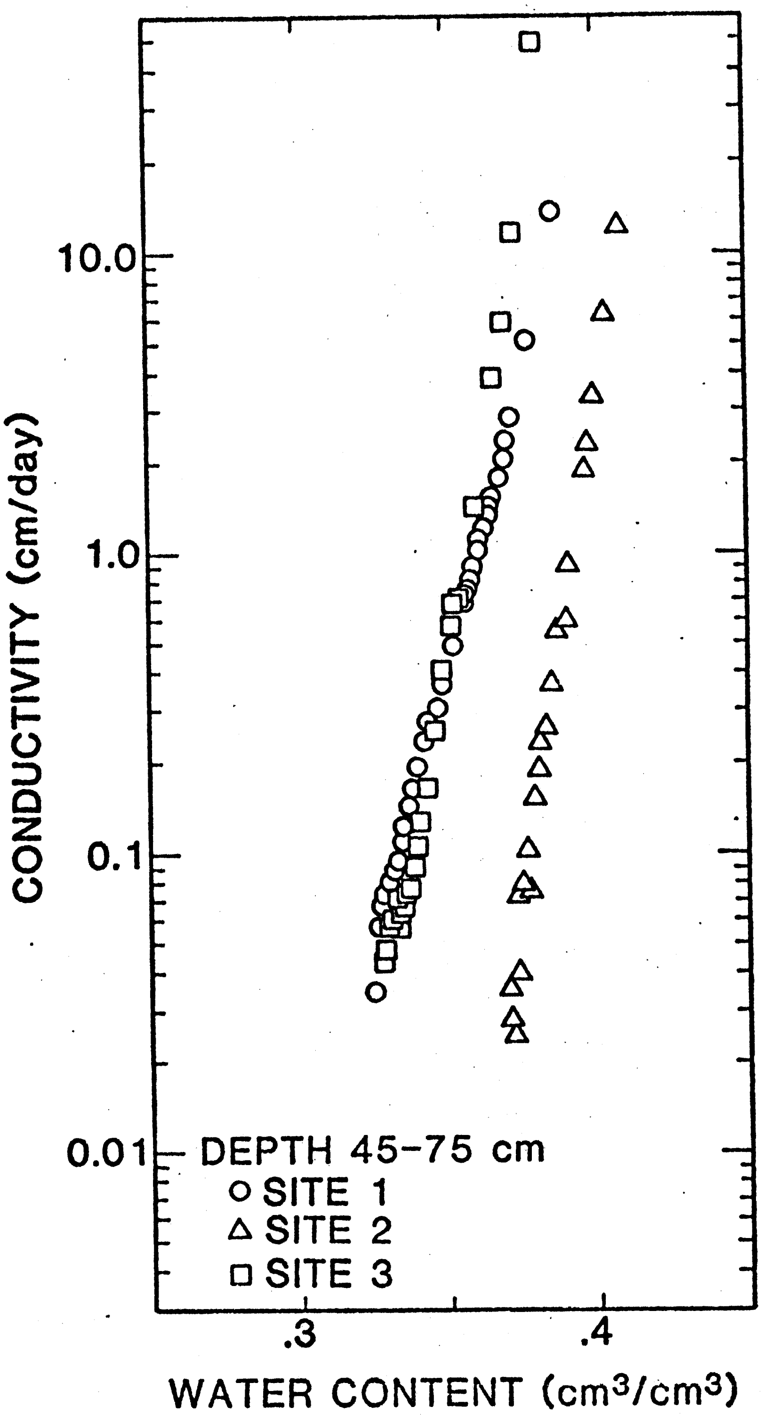

Figure 5. Conductivity as a Function of Water Content for the 45-75 cm Depth at Three Sites

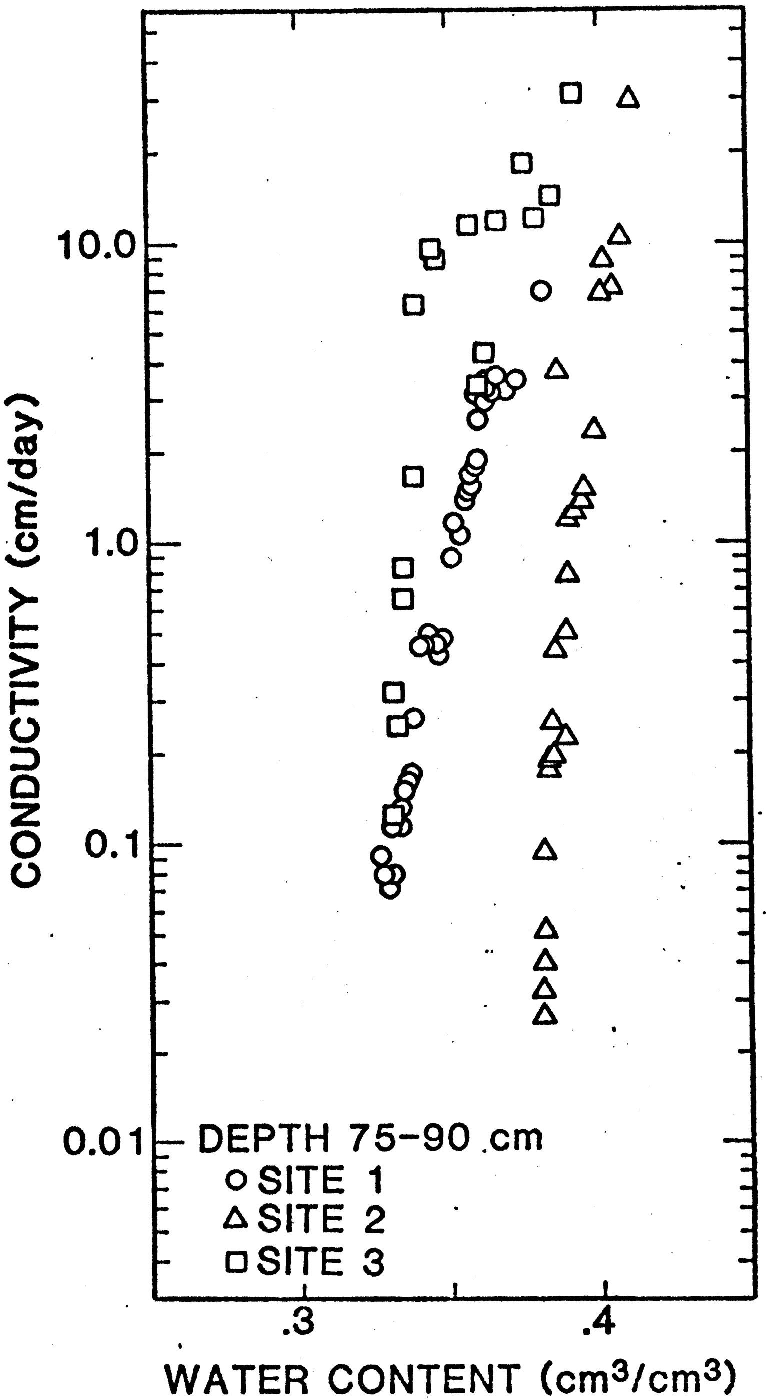

Figure 6. Conductivity as a Function of Water Content for the 75-90 cm Depth at Three Sites

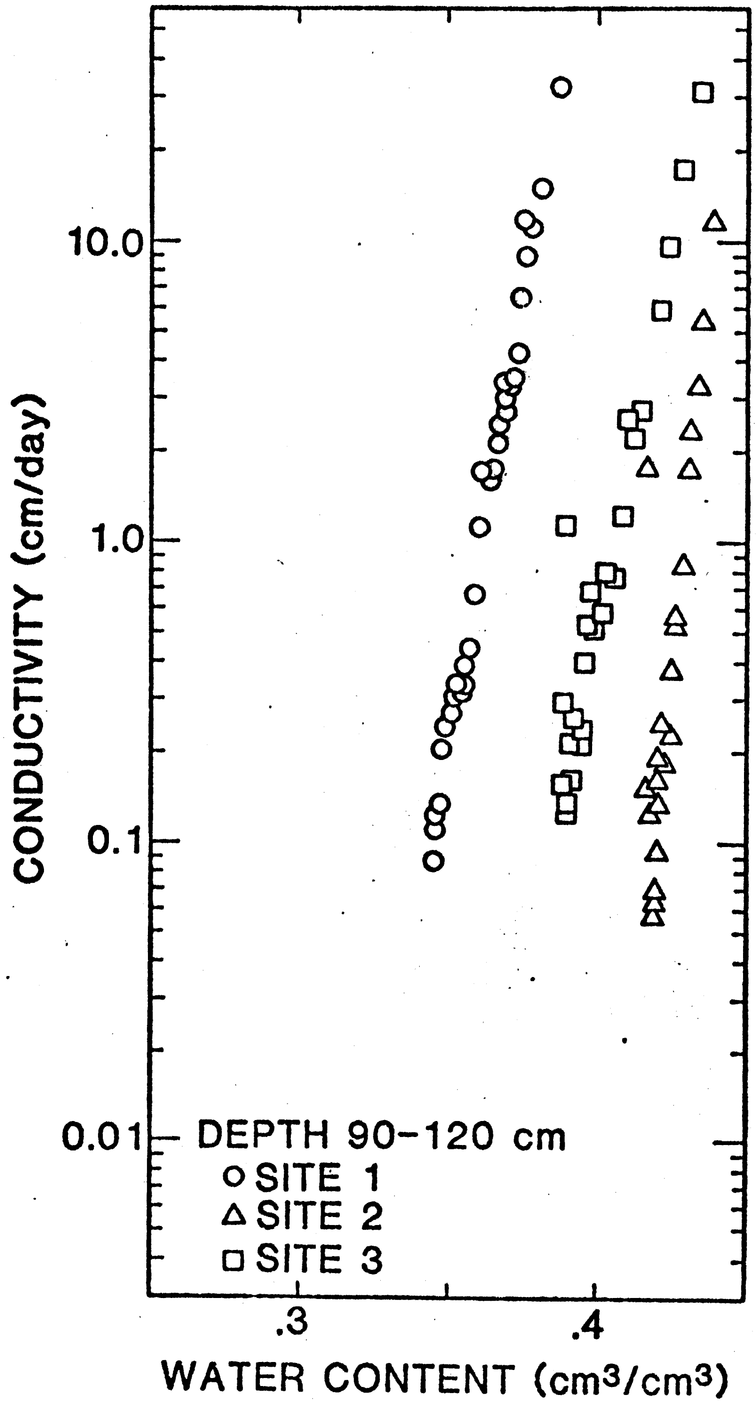

Figure 7. Conductivity as a Function of Water Content for the 90-120 cm Depth at Three Sites

be distinguished. Site 1 had conductivities as much as 100 times greater than site 3 at the same water contents. Site 3 had conductivities 10 times greater than site 2. The three curves were nearly parallel. The differences in the three sites were also seen in the textural analysis. Site 1 was a sandy clay loam, site 2 was a clay loam, and site 3 was a loam. In terms of coarseness, site 1 would be expected to have the greatest conductivity, site 3 the intermediate value, and site 2 the lowest value at a specific water content.

Variability of Methods of $K(\theta)$-Calculation

Figures 8-14 illustrate the results for the four methods of hydraulic conductivity calculation. These figures are for site 3. Similar results were obtained for sites 1 and 2. It was found that neutron-derived curves yielded consistently higher conductivities at the same water content and that the unit gradient assumption is a valid assumption for Tipton soil series.

Figures 8, 9, 13, and 14 show the consistently higher conductivities for the neutron-derived curves. No comparisons of this nature were made for the 45-75 cm depth, since no cores were taken at the 60 cm depth. For the two methods of obtaining water content, the 15-30 cm depth curves appear to intersect at the higher conductivities. Comparing the curves to those for the lower depths, the differences in water contents at the lower conductivities

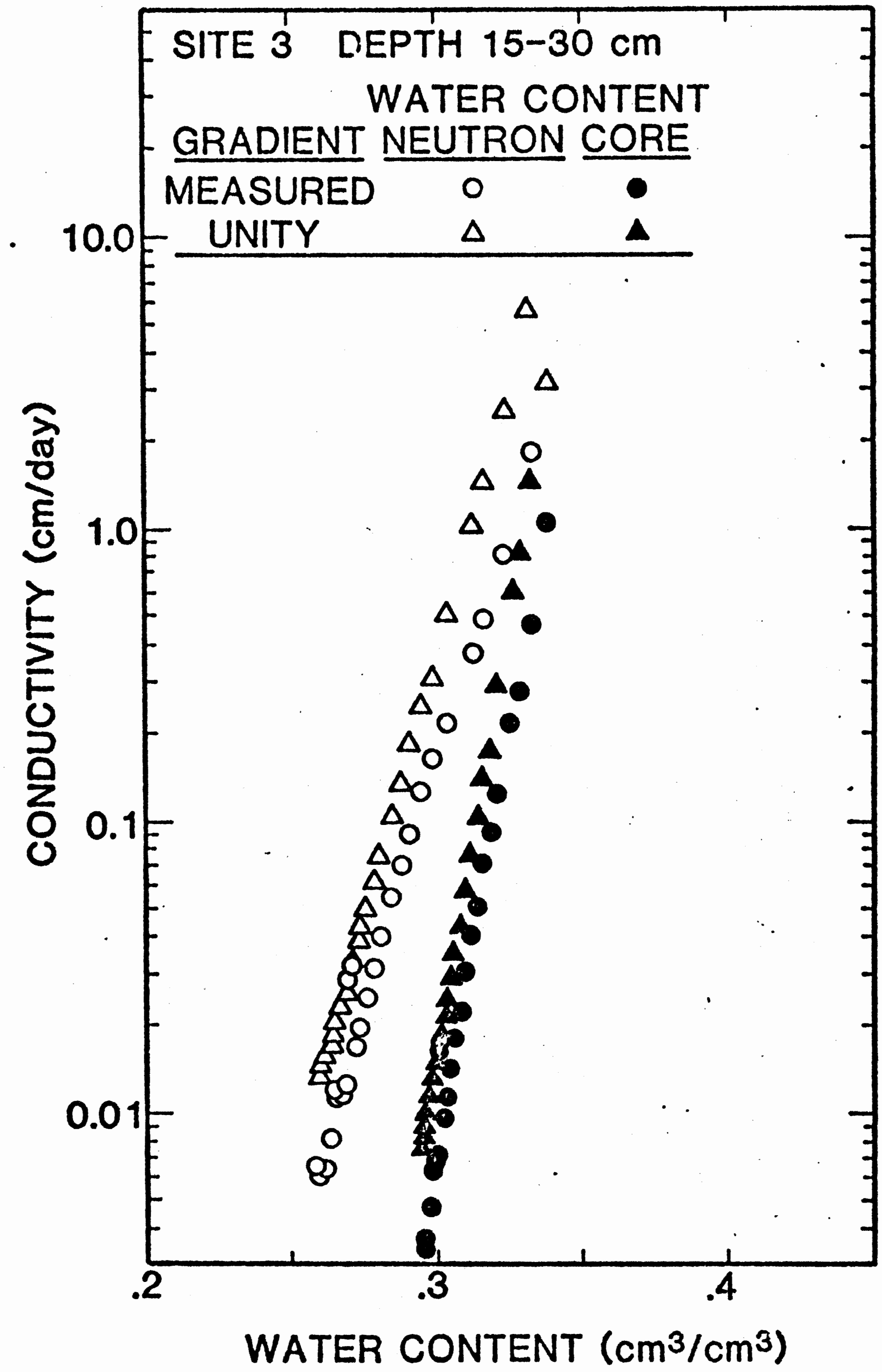

Figure 8. Conductivity as a Function of Water Content for the 15-30 cm Depth for Four Methods

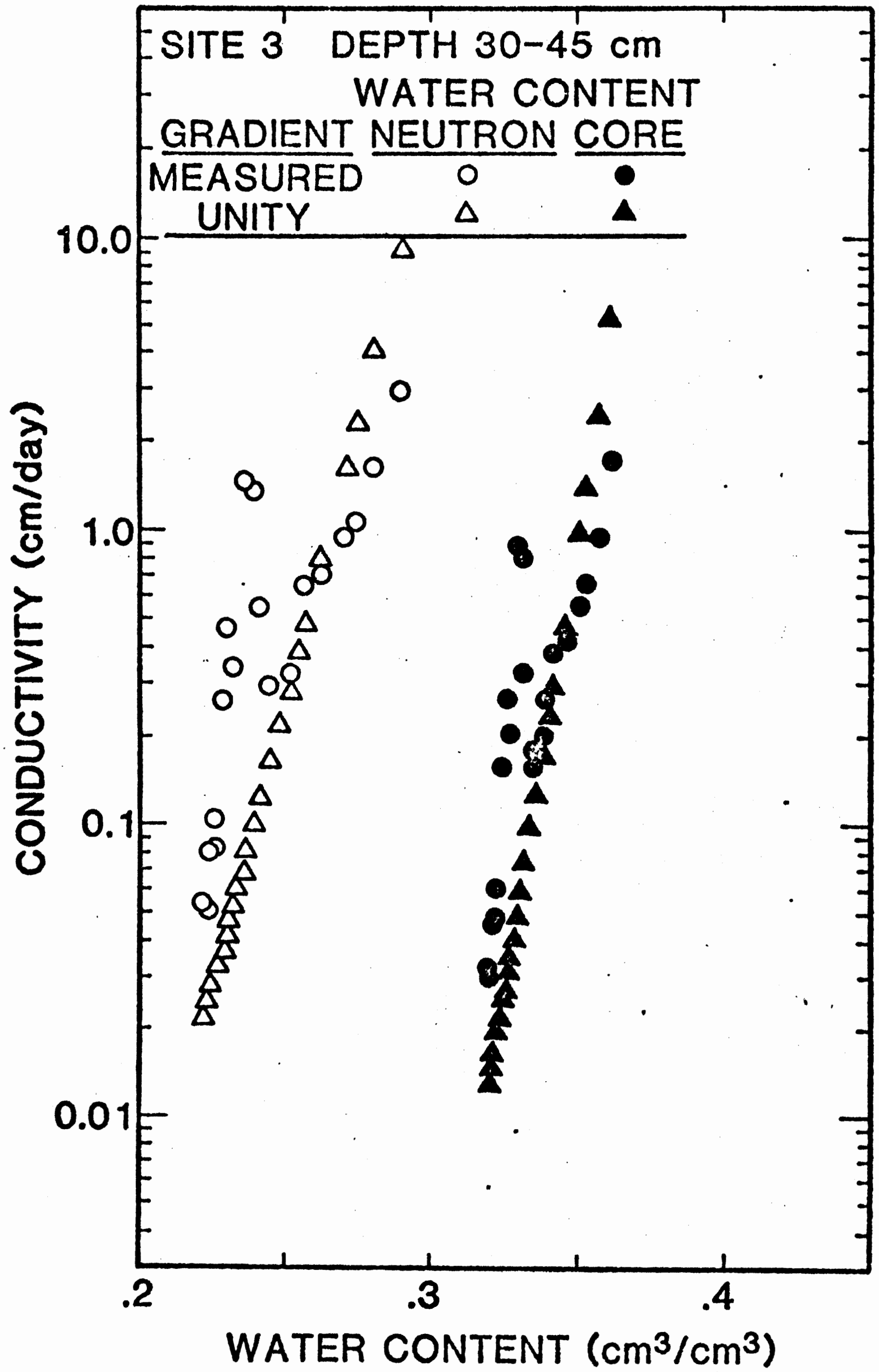

Figure 9. Conductivity as a Function of Water Content for the 30-45 cm Depth for Four Methods

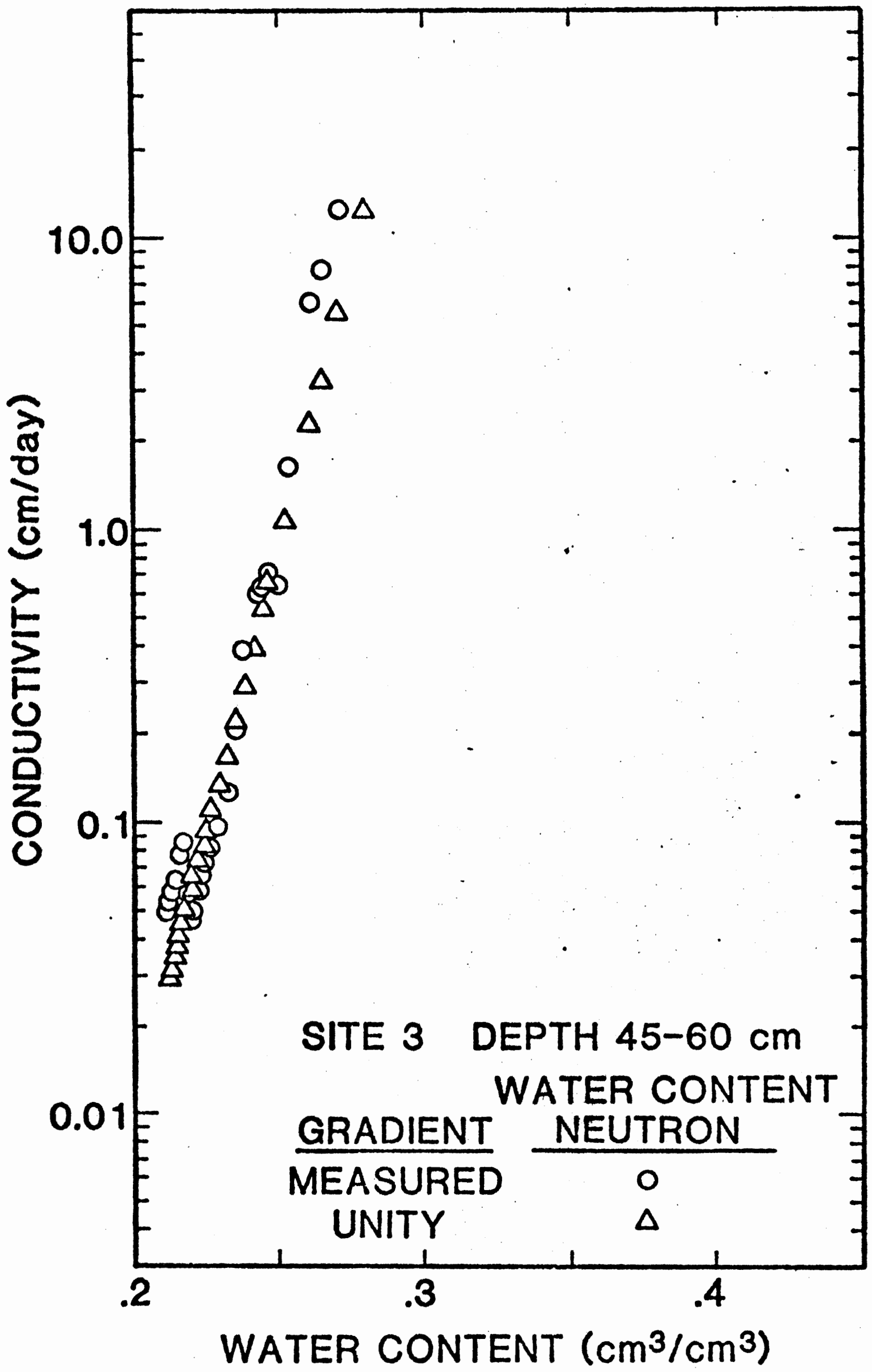

Figure 10. Conductivity as a Function of Water Content for the 45-60 cm Depth for Two Methods

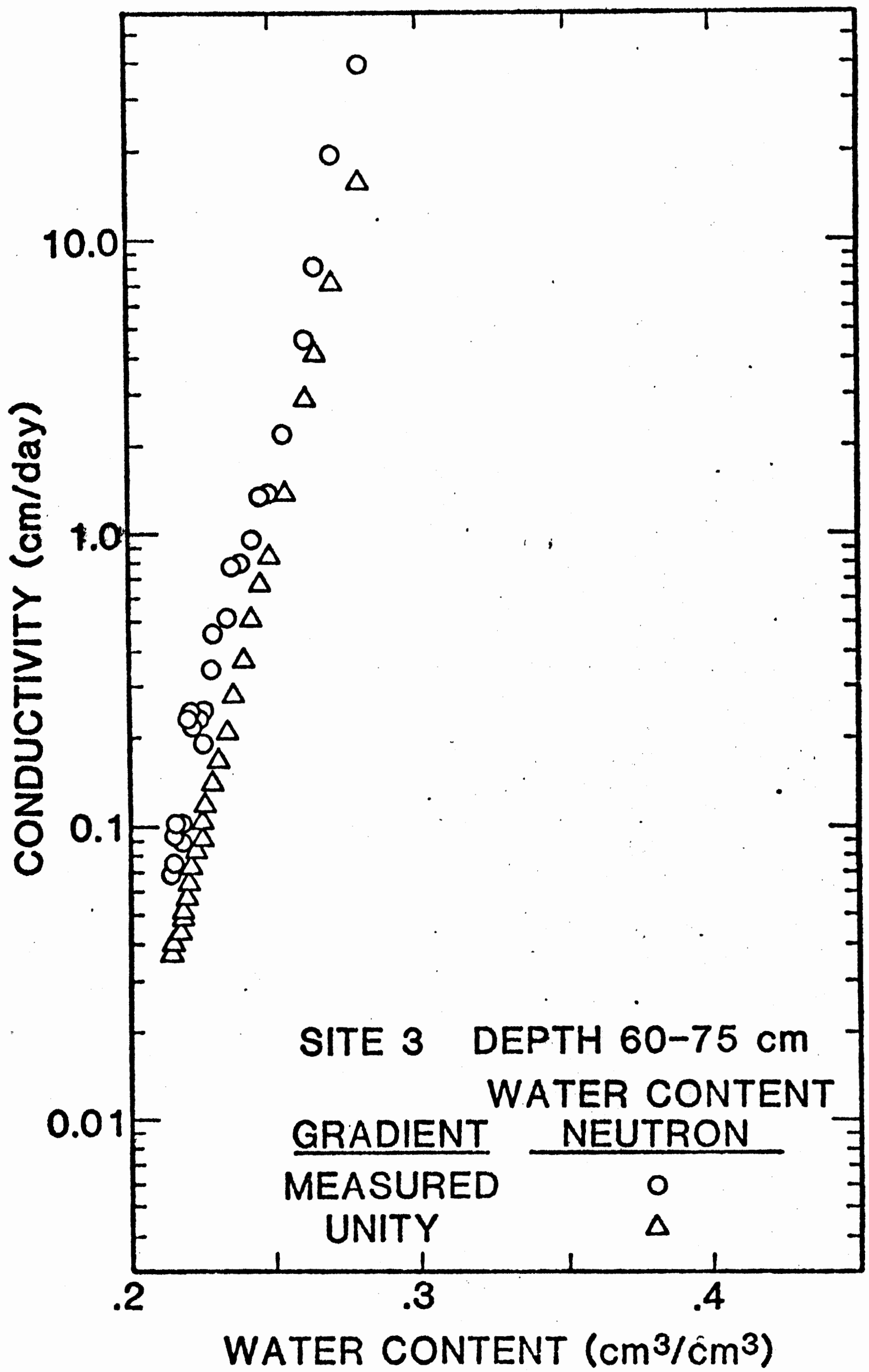

Figure 11. Conductivity as a Function of Water Content for the 60-75 cm Depth for Two Methods

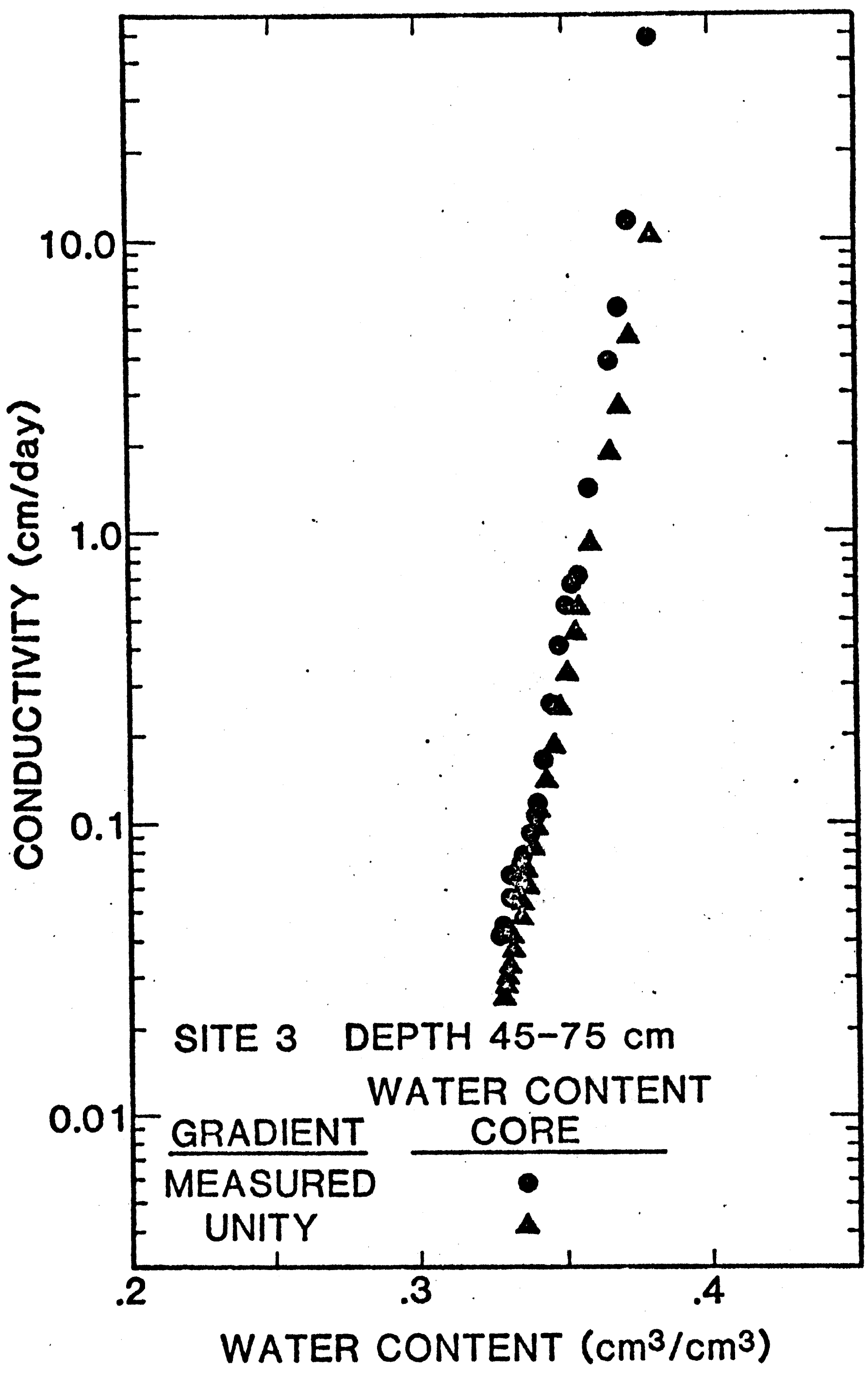

Figure 12. Conductivity as a Function of Water Content for the 45-75 cm Depth for Two Methods

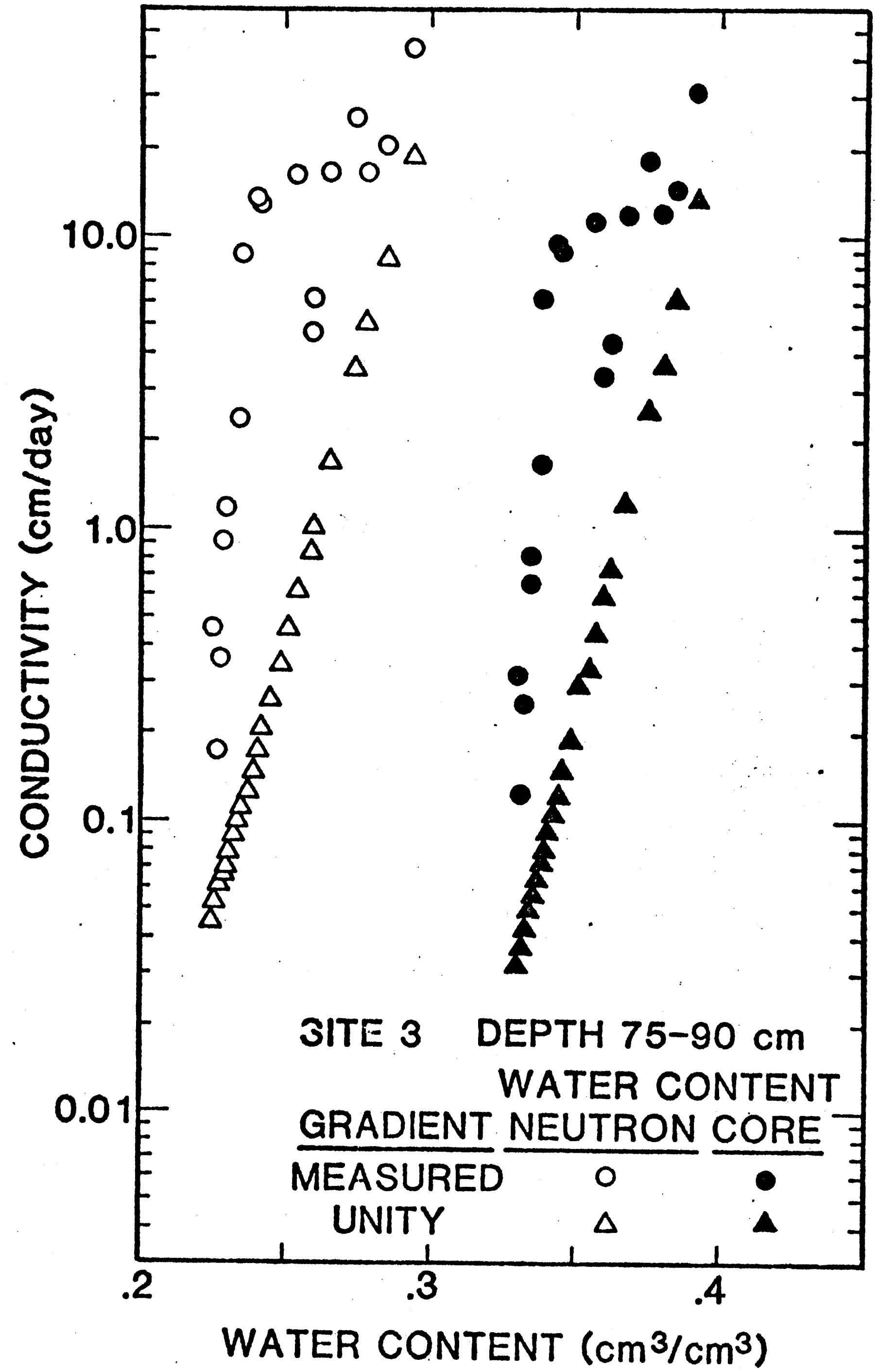

Figure 13. Conductivity as a Function of Water Content for the 75-90 cm Depth for Four Methods

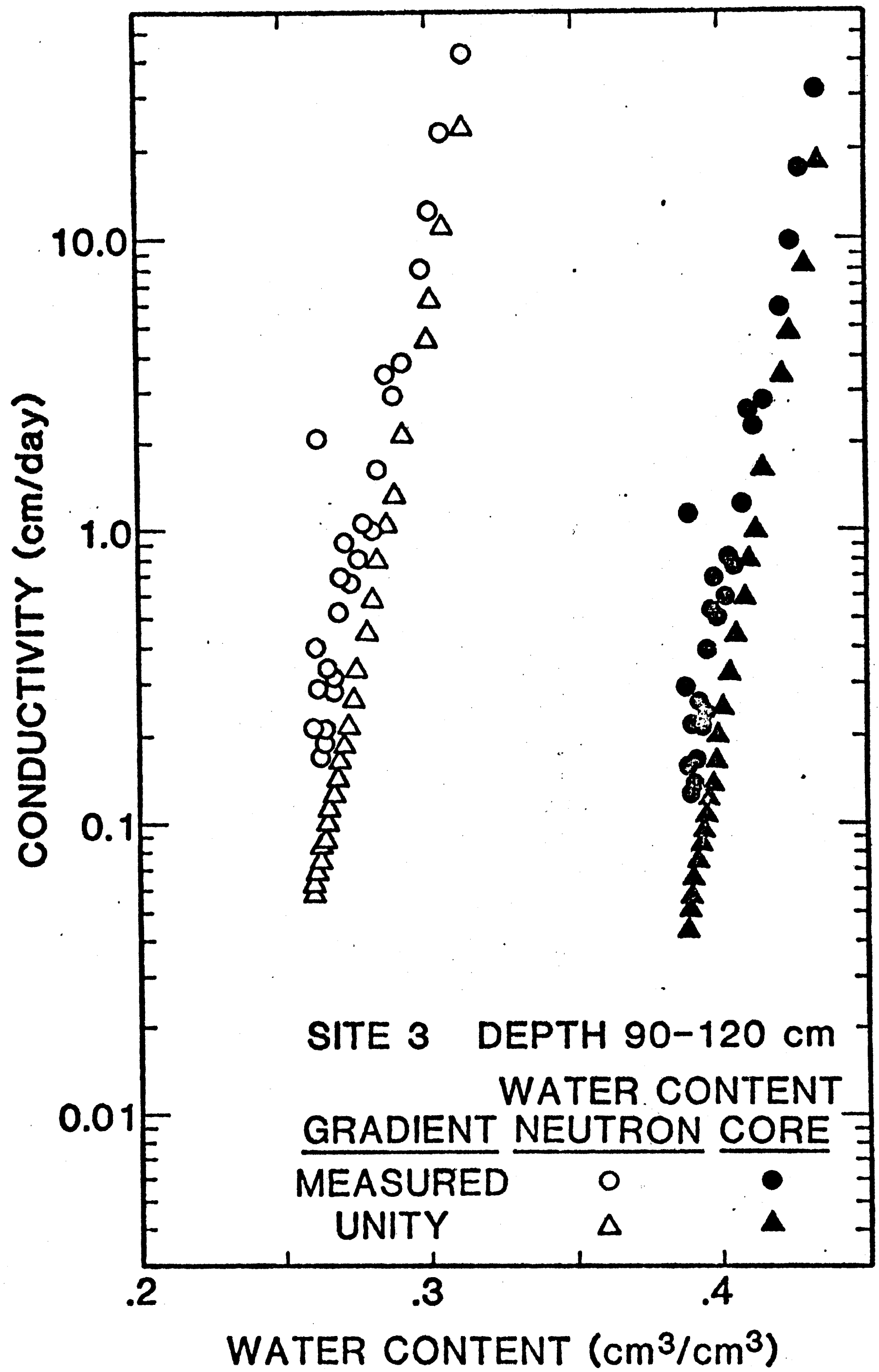

Figure 14. Conductivity as a Function of Water Content for the 90-120 cm Depth for Four Methods

are less for the 15-30 cm depth, approximately 0.02 cm^3/cm^3 for the 15-30 cm depth and approximately 0.05 to 0.06 cm^3/cm^3 for the lower depths. The curves for these lower depths appear to be parallel.

Neutron-derived conductivity curves yielded values of conductivity for the 15-30 cm depth that ranged from approximately 15 times greater than the core-derived values at the lower conductivities to 3 times greater at the higher conductivities for the same water contents. At lower depths, the neutron-derived curves yielded conductivity values more than 1000 times greater than the core data values at the same water content. These indicate considerable differences between the two methods of obtaining water content.

Figures 15-20 illustrate the relation of water content to negative pressure head when the water contents are obtained by neutron moisture probe or water release curves for cores. Water content values obtained from the core analysis were consistently 0.02 to 0.1 cm^3/cm^3 higher than water contents obtained with the neutron moisture probe at the same negative pressure head. This was true for all depths sampled except for the 15 cm depth. The water contents at the 15 cm depth were greater for the neutron moisture probe than for the soil cores. Although surface effects in neutron moderation could be responsible for the results at the 15 cm depth (Grant, 1975), such effects cannot explain the results at greater depths.

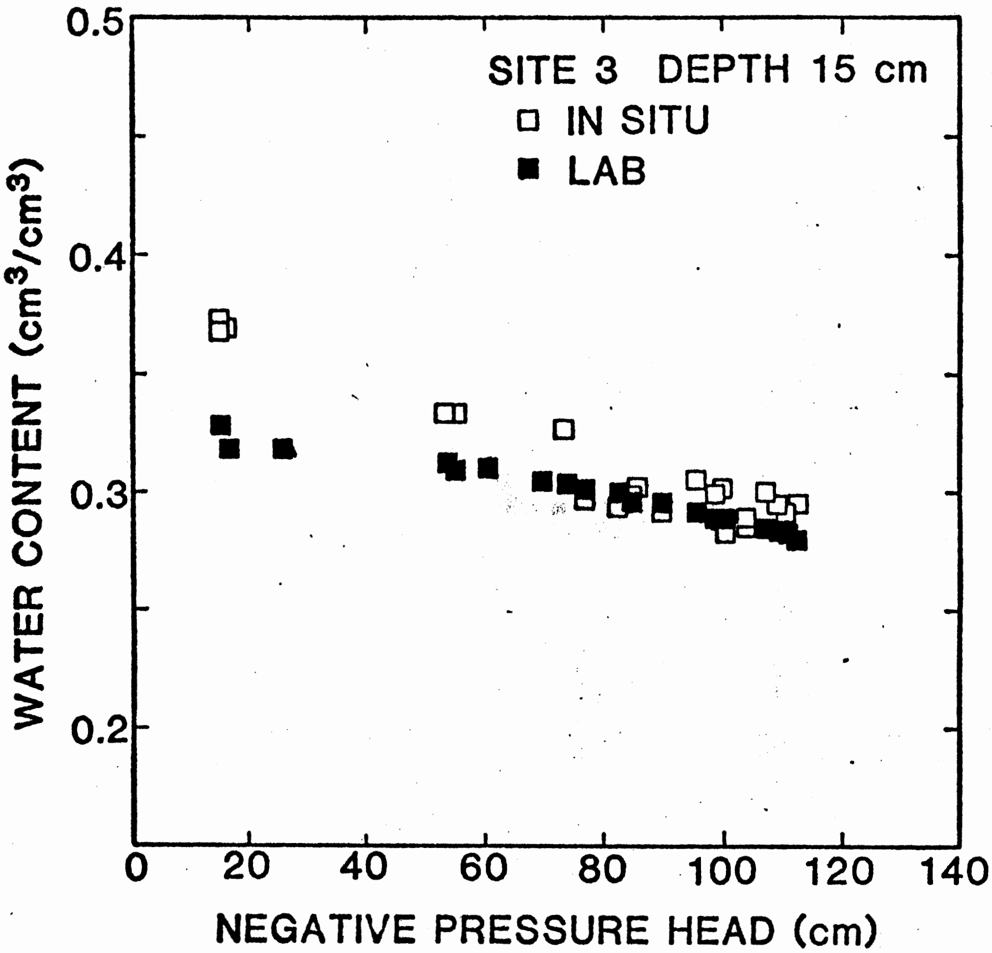

Figure 15. _In Situ_ and Laboratory Determined Water Release Curves for the 15 cm Depth for Site 3

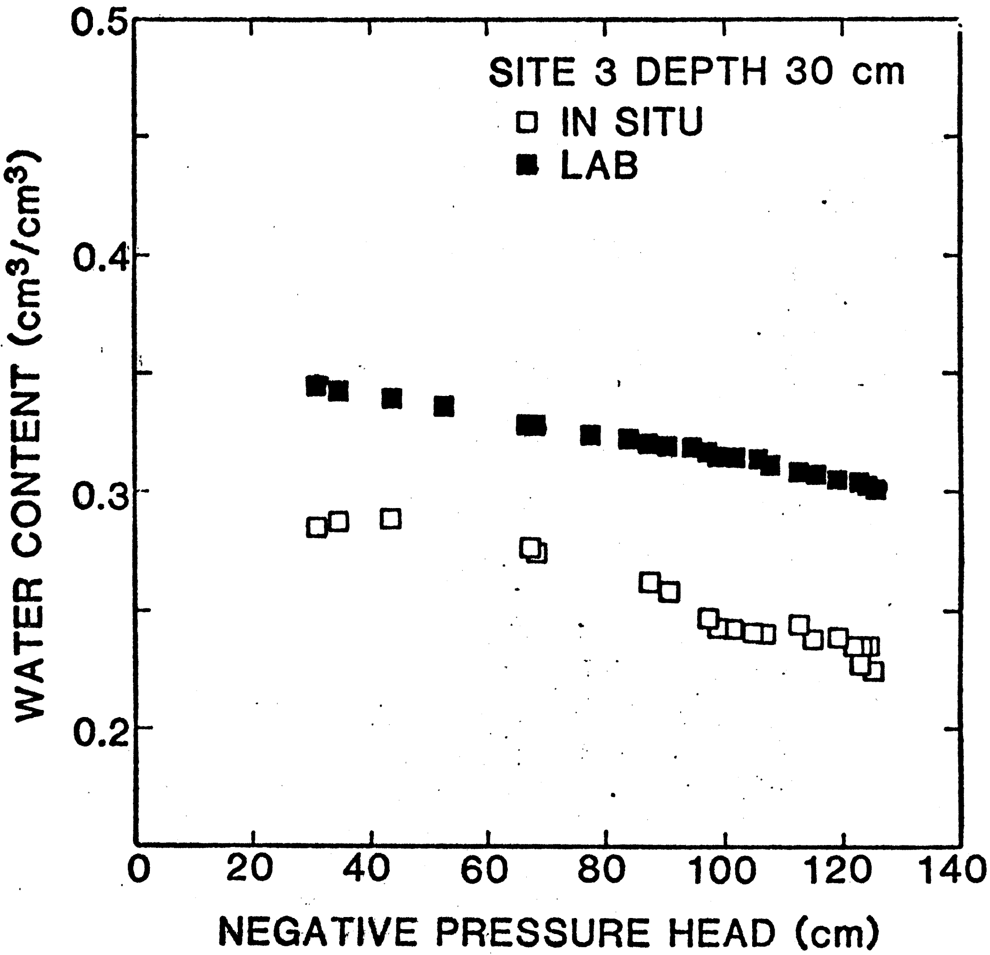

Figure 16. In Situ and Laboratory Determined Water Release Curves for the 30 cm Depth for Site 3

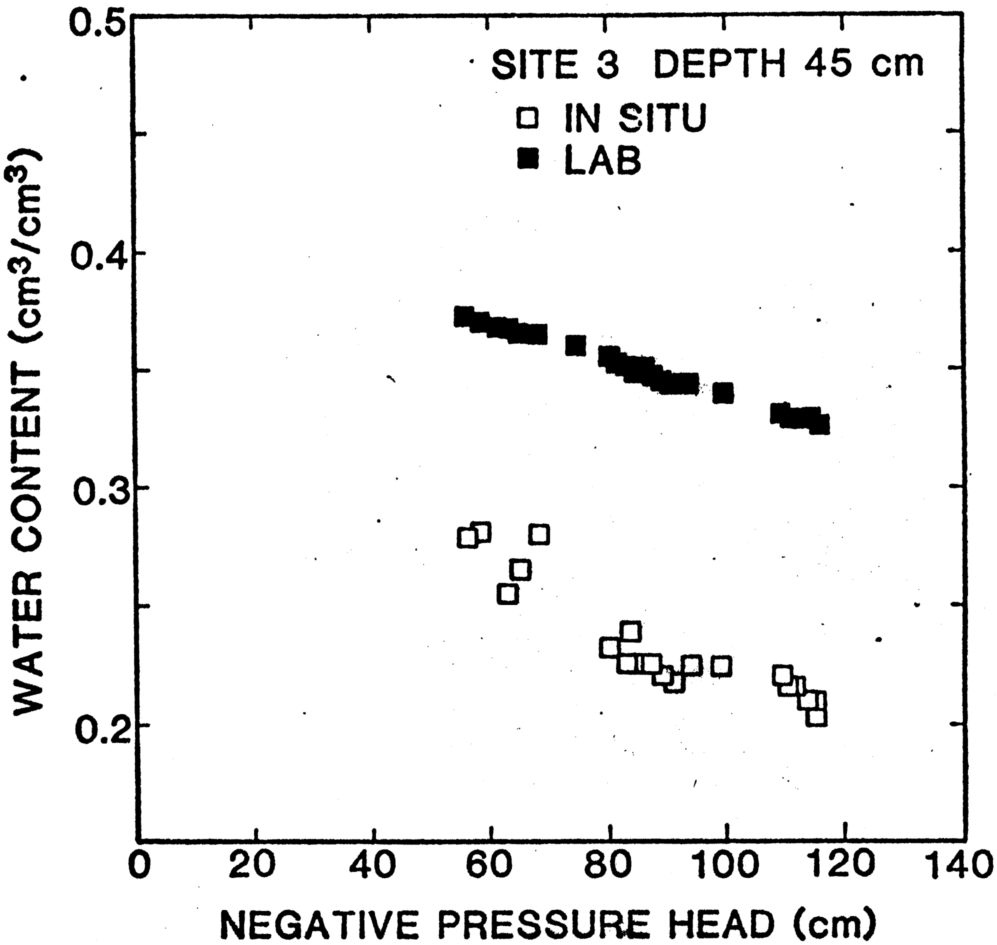

Figure 17. In Situ and Laboratory Determined Water Release Curves for the 45 cm Depth for Site 3

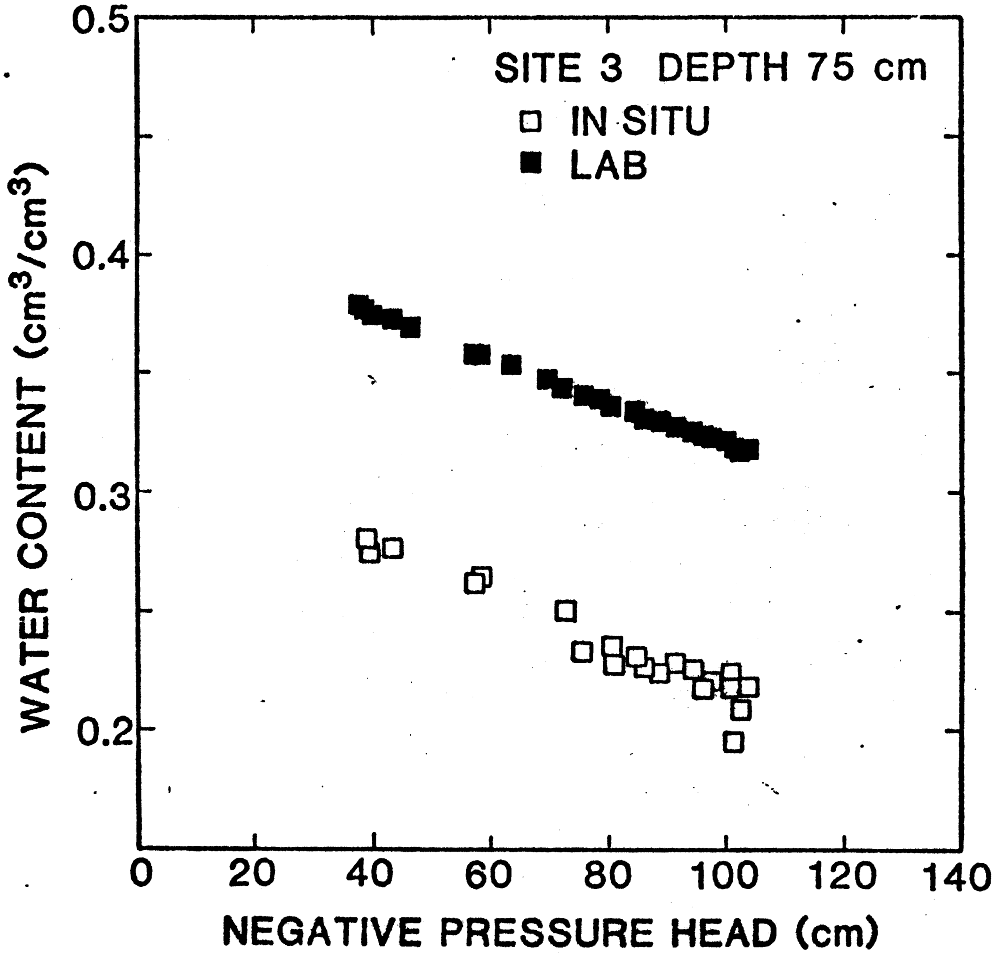

Figure 18. *In Situ* and Laboratory Determined Water Release Curves for the 75 cm Depth for Site 3

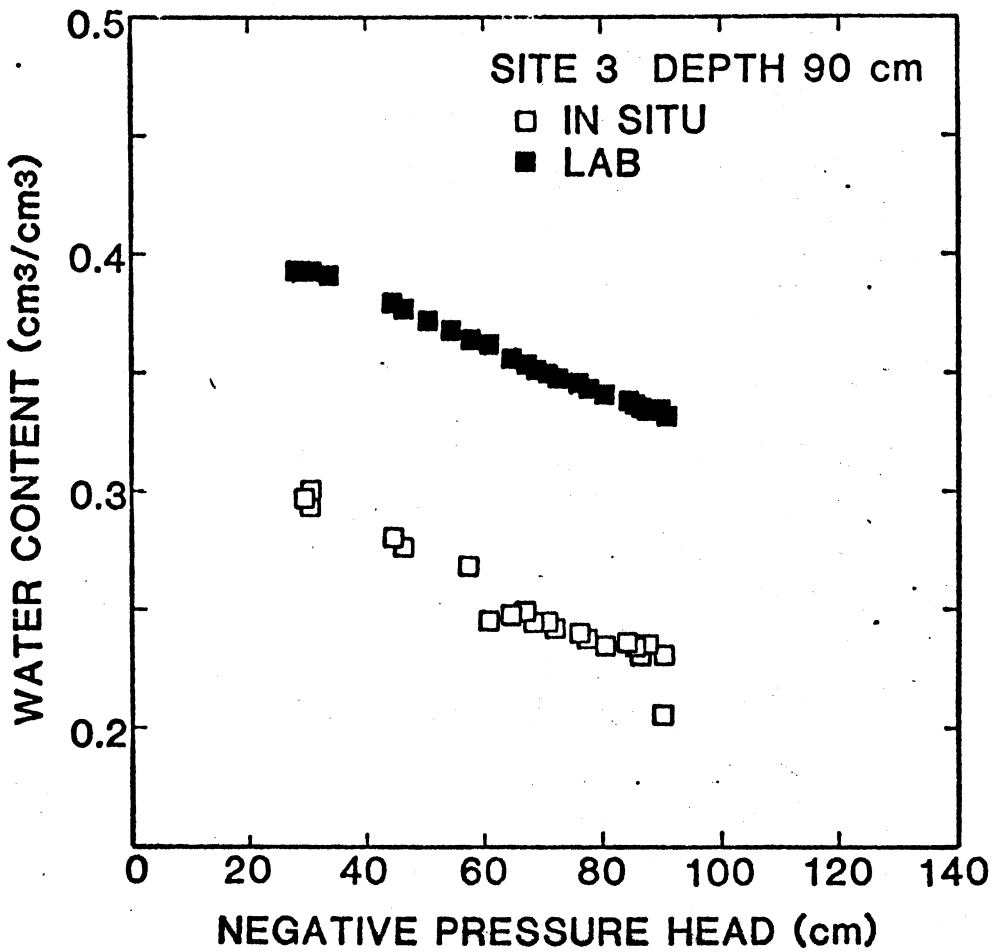

Figure 19. _In Situ_ and Laboratory Determined Water Release Curves for the 90 cm Depth for Site 3

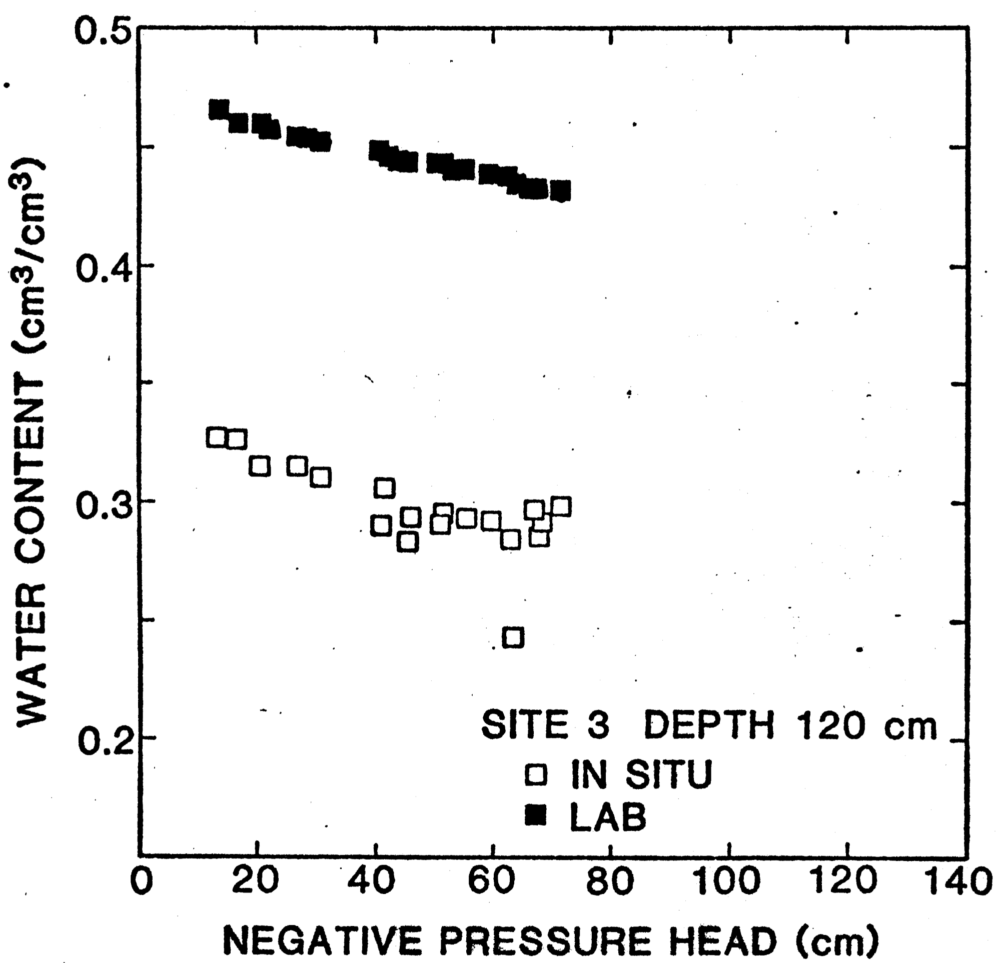

Figure 20. In Situ and Laboratory Determined Water Release Curves for the 120 cm Depth for Site 3

Since this research was conducted, the neutron probe was recalibrated to determine if it could be the source of these differences. The new curve differed by less than 0.01 cm^3/cm^3 from the one used here. Calibration does not appear to explain these differences. Another source of explanation for the differences may be that the cores swelled during saturation beyond the ends of the cylinders. The maximum swelling was noted in the more heavy textures. These cores would extend, at maximum, approximately 0.5 cm beyond the ends. This would result in overestimated water contents for the cores. This overestimation could partially explain the results seen in Figures 15-20, since the swelling effect could explain an overestimation of as much as 0.04 cm^3/cm^3. The cores estimated as much as 0.10 cm^3/cm^3, for depths below 15 cm, above the water contents obtained with the neutron probe at the same negative pressure heads. Ahuja *et al*. (1980) found a similar situation in their study. They indicate that entrapped air could cause an overestimation of the water contents obtained with cores. Further investigation is needed to explain these differences. The closer relation between the methods of obtaining water content values found in the 15 cm depth could partially explain why the conductivity curves were more in agreement for the 15-30 cm depth.

The validity of the unit gradient assumption is indicated in Figures 8-14. Figures 9-14 indicate that the conductivity is somewhat underestimated, 2 to 5 times lower with this assumption, but the overall agreement is quite good. The 15-30 cm depth shows a slight overestimation of the conductivities. These under and overestimations did not affect the variability between sites when using a single method. Conductivities calculated with the measured gradients were 2 to 5 times higher than the unity gradient calculations for all depths except the 75-90 cm depth in site 3. This depth, 75-90 cm depth in site 3, had measured gradient calculated conductivity curves which were 4 times, at the lower water contents, to 16 times, at middle water contents, to 3 times, at the higher water contents, greater than conductivities calculated with the unit gradient at the same water contents. Further investigations are required to understand the results of the 75-90 cm depth in site 3. These results, except for the slight disagreement found in the 75-90 cm depth in site 3, indicate the unity gradient assumption is a good one for these conditions for the Tipton soil series. Additional investigations of the validity of this assumption should be made in other soils. This assumption could save time and expenses when there is a need for a great many experimental sites.

CHAPTER V

SUMMARY

Unsaturated hydraulic conductivity curves for three sites of the Tipton soil series were obtained. A drainage method was used to obtain in situ measurements. An instantaneous profile method of calculation was used to calculate conductivity values.

Spatial varability of the conductivity was shown graphically. Two of the three sites studied showed good agreement for all depths except the 90-120 cm depth. The third site tended to have lower conductivities at the same water contents. The greatest difference in conductivities occurred in the 90-120 cm depth. There appeared to be a difference of 1000 times between the highest and lowest conductivity curves obtained at the same water contents. The least differences occurred in the 15-30 cm depth where the three curves for the three sites appeared to coincide.

Two methods, utilizing a neutron moisture probe and undisturbed core samples, were used to obtain water content measurements. The core obtained water contents were consistently higher (approximately 0.02 to 0.10 cm^3/cm^3) than the neutron moisture probe values for all depths sampled except for the 15 cm depth. The 15 cm depth showed the neutron moisture probe values to be approximately 0.04 cm^3/cm^3 higher than the core values at low negative pressure heads to 0.005 cm^3/cm^3 at the higher negative pressure heads. The swelling of the cores beyond the ends of the cylinders during saturation could account for as much as one-half of the difference in measured water contents. The swelling effect could account for 0.04 cm^3/cm^3 of the overestimation, at maximum. The total overestimation obtained with the cores was as much as 0.10 cm^3/cm^3 over the neutron probe water contents. The neutron probe was recently recalibrated to determine if it could be the source of these differences. New calibration curves differed from the curves used by less than 0.01 cm^3/cm^3. From this it was determined that calibration of the probe does not appear to explain the differences found.

Two methods of obtaining the hydraulic gradients were used. One method involved measured gradients utilizing tensiometers, while the second method assumed the gradient to be one. Conductivities calculated with the measured gradients were 2 to 5 times greater than the unity gradient calculations for all depths except the 75-90 cm depth in site 3, where the measured gradient was as much as 16 times greater at the same water contents. The unity gradient does, however, appear to be a valid assumption for Tipton soil series. Through further investigation it may be found that the unity gradient assumption could lead to methods of obtaining representative conductivity curves without the added expense of tensiometers and mercury. The drainage method, without tensiometers, could be applied to smaller sample sites, thus preventing variances in the soil at a particular site from affecting results. This would allow for more samples to be used in spatial variability studies of the conductivity.

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APPENDIX

SOIL DESCRIPTIONS OF EXPERIMENTAL SITES

Experimental Site 1

Location: Tillman County, Oklahoma, about 31.1 meters (102 feet) east and 169.2 meters (555 feet) south of the northwest corner of the NW$\frac{1}{4}$ Sec. 32 T. 1 S R. 18 W.
Slope: Nearly level, plowed field, slightly concave.

Horizon	Depth (cm)	Description
Ap	0-22	Dark brown (7.5YR 3/3) moist; loam; weak fine granular structure; friable; few fine and medium random pores; few fine roots; slightly acid; clear boundary.
A12	22-59	Dark brown (7.5YR 3/2) moist; loam; weak medium subangular blocky breaking to moderate medium and fine granular structure; friable; few earthworm casts; many medium vertical pores; few roots; slightly acid; clear boundary.
B21t	59-72	Dark reddish brown (5YR 3/3) moist; loam; weak coarse prismatic breaking to weak medium subangular blocky structure; friable; thin clay films on ped surfaces and coating sand grains; many medium and fine vertical pores; few fine roots; few earthworm casts; neutral; gradual boundary.
B22t	72-150	Reddish brown (5YR 4/4) moist; loam; weak coarse prismatic breaking to weak medium subangular blocky structure; friable; thin clay films on ped surfaces and coating sand grains; many medium and fine vertical pores; few fine roots; few earthworm casts; few fine $CaCO_3$ concretions, neutral; clear boundary.

Horizon	Depth (cm)	Description
IIB3ca	150-230	Light brownish gray (10YR 6/2) moist; silty clay loam; common medium mottles in shades of brown; weak medium and fine prismatic breaking to subangular blocky structure; firm; common, very fine, and fine pores; few fine roots; clay films on ped surfaces; common bodies of $CaCO_3$; few $CaCO_3$ concretions; moderately alkaline.

Classification: Pachic Argiustolls, fine-loamy, mixed, thermic

Series: Tipton

Experimental Site 2

Location: Tillman County, Oklahoma; about 8.2 meters (27 feet) south and 326.4 meters (1,071 feet) west of the northwest corner of the SE$\frac{1}{4}$ Sec. 25 T. 1 S R. 19 W.
Slope: Nearly level; linear slope.

Horizon	Depth (cm)	Description
Ap	0-25	Dark brown (7.5YR 3/3) moist; loam; weak fine granular structure; friable; few fine and medium random pores; few fine roots; neutral; clear boundary.
A12	25-60	Dark brown (7.5YR 3/2) moist; loam; weak medium subangular blocky breaking to moderate medium and fine granular structure; friable; few earthworm casts; many medium vertical pores; few fine roots; neutral; gradual boundary.
B21t	60-103	Reddish brown (5YR 4/3) moist; loam; weak coarse prismatic breaking to weak medium subangular blocky structure; friable; thin clay films on ped surfaces and coating sand grains; many medium and fine vertical pores; few fine roots; few earthworm casts; mildly alkaline; few fine $CaCO_3$ concretions; clear boundary.
IIB22t	103-143	Dark grayish brown (10YR 4/2) moist; silty clay loam; moderate medium prismatic breaking to moderate medium subangular blocky structure; firm; clay films on ped surfaces; common very fine and fine random pores; few fine roots; few fine $CaCO_3$ concretions; few threads of mycelia carbonate; moderately alkaline; diffuse boundary.

Horizon	Depth (cm)	Description
IIB3ca	143-236	Light brownish gray (10YR 6/2) moist; silty clay; few fine distinct mottles in shades of brown; weak medium prismatic breaking to weak fine subangular blocky and blocky structure; very firm; clay films on ped surface; common very fine and fine random pores; few fine roots; common bodies of $CaCO_3$; few fine $CaCO_3$ concretions; moderately alkaline.

Classification: Pachic Argiustolls, fine-loamy, mixed, thermic

Series: Tipton

Experimental Site 3

Location: Tillman County, Oklahoma; about 76.8 meters (252 feet) south and 128.9 meters (423 feet) west of the northeast corner of the SE$\frac{1}{4}$ Sec. 25 T. 1 S R. 19 W.
Slope: Nearly level; linear slope.

Horizon	Depth (cm)	Description
Ap	0-21	Dark brown (7.5YR 3/2) moist; loam; weak fine granular structure; friable; few fine random pores; few fine roots; mildly alkaline; clear boundary.
A12	21-46	Dark brown (7.5YR 3/2) moist; loam; weak coarse subangular blocky breaking to moderate fine and medium granular structure; friable; few earthworm casts; many medium vertical pores; few fine roots; moderately alkaline; gradual boundary.
B21t	46-99	Dark reddish brown (5YR 3/3) moist upper; and (5YR 3/4) moist lower; loam; moderate medium prismatic breaking to moderate medium subangular blocky structure; friable; many fine random pores; few fine roots; few earthworm casts; few threads mycelia carbonates; thin clay films on ped surfaces; moderately alkaline; gradual boundary.
IIB22t	99-142	Brown (7.5YR 4/2) moist; silty clay loam; few bodies and mottles in shades of brown; moderate medium prismatic breaking to moderate fine subangular blocky structure; firm; clay films on ped surfaces; common very fine and fine random pores; few fine roots; few fine $CaCO_3$ concretions; few mycelia threads of carbonates; few bodies of $CaCO_3$; diffuse boundary.

Horizon	Depth (cm)	Description
IIB3ca	142-226	Light brownish grey (10YR 6/2) moist; few distinct mottles in shades of brown; weak medium prismatic breaking to weak fine blocky and subangular blocky structure; very firm; common very fine and fine random pores; few fine roots; common bodies of $CaCO_3$; few fine $CaCO_3$ concretions; moderately alkaline.

Classification: Pachic Argiustolls, fine-loamy, mixed, thermic

Series: Tipton

VITA

Joseph Robert Williams

Candidate for Degree of

Master of Science

Thesis: SPATIAL VARIABILITY OF UNSATURATED HYDRAULIC CONDUCTIVITY OF TIPTON SOIL SERIES

Major Field: Agronomy

Biographical:

Personal Data: Born in Memphis, Tennessee, May 1, 1956, the son of Walter C. and Ruth P. Williams.

Education: Graduated from Central High School in Bolivar, Tennessee, May, 1974; received Bachelor of Science degree in Natural Resource Management from University of Tennessee, Martin, June, 1978; completed requirements for the Master of Science degree in Agronomy at Oklahoma State University, Stillwater, Oklahoma, December, 1980.

Professional Experience: Employed by Soil Conservation Service, Bolivar, Tennessee, June 1975 to August 1975, June 1978 to August 1978; employed by Soil Conservation Service, Student Trainee-Soil Scientist, Chattanooga, Tennessee, June 1977 to August 1977; employed by University of Tennessee, Martin, Tennessee, January 1977 to June 1977, August 1977 to June 1978; employed by Oklahoma State University, Research Assistant, Stillwater, Oklahoma, August 1978 to present.