Testing of unit gradient soil drainage models using undisturbed cores collected by a new technique

by Mark David Tomer

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Soils
Montana State University

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Models tested were the CGA (Chong et al., 1981), and four Lax algorithm models (Sisson et al., 1980), obtained from applying a 0 (single measurement) and W (profile storage) approach to two possible K(0) relationships.

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Hydraulic conductivities of core samples were highly variable; therefore none of the models were shown superior in their ability to predict K(0). However, the average of 69 Ks values collected from measurements on core samples was 0.35 cm/min. This was within on order of magnitude of most Km values predicted by field models. Magnitudes of K(0) estimates given by field models generally followed the order CGA > 0 methods > W methods.

A highly satisfactory method of collecting undisturbed core samples from any depth was developed, which should prove most useful for obtaining samples from deep in the profile, where in situ studies are not possible.

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Mark David Tomer

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Symbol	Meaning
Θ	Soil water content (cm3/cm3)
Θs	Saturated water content (cm3/cm3)
Θm	Maximum field water content (cm3/cm3)
Θ'	Average water content (cm3/cm3)
Θg	Gravimetric water content (g/g)
V	Soil water flux, or flow velocity (cm/min)
H	Total hydraulic head (cm)
h	Matric soil water potential (cm)
he	Air entry potential (cm)
W	Profile water storage (cm)
K	Hydraulic conductivity (cm/min)
Km	Maximum field hydraulic conductivity (cm/min)
Ks	Saturated hydraulic conductivity (cm/min)
$K(\Theta/h)$	Unsaturated hydraulic conductivity (cm/min)
$K(\Theta)$	Unsaturated hydraulic conductivity as a function of soil water content (cm/min)
K(h)	Unsaturated hydraulic conductivity as a function of soil water potential (cm/min)
z	Vertical distance, or a given depth (cm)
$D(\Theta)$	Hydraulic diffusivity as a function of soil water content (cm2/min)
x	Distance (cm)

LIST OF SYMBOLS-Continued

Symbol	Meaning
t	Time
ρ	Fluid density (g/cm3)
η	Fluid viscosity (g/cm min)
k	Intrinsic permeability (cm2)
q	Quantity of flow (cm3)
g	Acceleration of gravity (cm/sec2)
r	Pore radius (cm)
d	Pore diameter (cm)
w	Pore width (cm)
To	Surface tension (dyn/cm)
Y	Wetting angle (degree)
fi	Incremental fraction of pore area (cm2/cm2)
F	Porosity, or pore area (cm2/cm2)
F(r)	Pore size distribution
N	Empirical constant (Eq. [12])
R	Largest water filled pore (Eq. [12]) (cm)
b	Exponent in empirical relationship between 0 and h (Eq. [13])
c,d	Empirical constants in relationship between W and t (Eq. [20])
c',d'	Empirical constants in relationship between V and t (Eq. [22])
c",d"	Empirical constants in relationship between W, z, and t (Eq. [23])
I	Quantity of infiltrated water (Eq. [24]) (cm)

LIST OF SYMBOLS-Continued

Symbol	Meaning
E	Quantity of infiltrated water which evaporates (Eq. [24]) (cm)
U	Quantity of infiltrated water which drains (Eq. [24]) (cm)
ΔM	Quantity of infiltrated water which is stored (Eq. [24]) (cm)
Rat	Neutron count ratio
BD	Bulk density (g/cm3)
β	Exponent in K(0) relationship given in Eq. [32]
α	Exponential parameter in K(0) relationship given in Eq. [32]
a,j	Empirical constant in relationship between 0' and t (Eq. [44]), from "CGA" method
a'	Slope of line relating 0 and 0'
ha	Hectare
m	Meter
cm	Centimeter

ABSTRACT

Several recently proposed mathematical models use a unit gradient assumption and water content measurements collected during drainage of a flood plot to estimate K(θ). The objective of this study was to test the accuracy of five of these models for estimating hydraulic conductivity by comparison with laboratory data collected from measurements on undisturbed cores.

Models tested were the CGA (Chong et al., 1981), and four Lax algorithm models (Sisson et al., 1980), obtained from applying a θ (single measurement) and W (profile storage) approach to two possible K(θ) relationships.

A new procedure for encasing undisturbed cores was developed, which involves coating cores with a liquid rubber latex molding compound. Cores were collected around two adjacent field flood plots located on a silt loam soil. Two laboratory methods were used; direct measurement of hydraulic conductivities, and a method of predicting K(θ) from desorption and Ks data (Campbell, 1974).

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INTRODUCTION

Drainage of water from soil is an important aspect of many environmental problems. Saline seep, groundwater pollution by septic drainfields, aquifer recharge on mine disturbed lands, and irrigation system design are important examples of such problems. Characterization of soil hydrologic behavior would be helpful in finding problem solutions. Data on infiltration rates, desorption curves, and hydraulic conductivities ($K(\theta)$) which can be applied to large land areas are particularly needed. However, little of these types of data are available to land managers and engineers. Reasons for this include time and expense involved with field studies, and difficulty with extrapolating measurements from small plots to large land areas. Determination of $K(\theta)$ has proven particularly difficult for these reasons. Field methods are also inadequate for obtaining data from deep in the profile (<1.5m).

Procedures for field determination of $K(\theta)$ require constant monitoring of flood plot sites for up to one week. Reliability of tensiometers for measuring potential gradients has also been questioned (Baker et al., 1974; Luxmoore et al., 1981). Installation of tensiometer stacks is difficult, and elaborate steps are required to prevent occurence of temperature gradients which adversely affect accuracy (Schuh et al., 1984). Tensiometers therefore contribute to the expense of field studies, while at the same time providing data which may be inaccurate. Assumption of a unit hydraulic gradient, however, allows calculation of K(θ) without tensiometric data. Black et al. (1969) found the unit hydraulic gradient closely approximated actual gradient conditions in a uniform profile after thorough wetting. Since then, several mathematical models have been proposed which provide for calculation of K(θ) using only moisture content measurements at known times during drainage (Libardi et al., 1980; Sisson et al., 1980; Chong et al., 1981). However, different models give different estimates of K(θ) from the same drainage data. The first objective of this study was to determine which model, if any, is most accurate for a specific set of drainage data. It was decided that laboratory measurements would provide the best hydraulic conductivity data to test the models, and that undisturbed soil cores from the field study site would provide the best samples for measurement.

While no soil core sample is truly undisturbed, due to release of overburden pressure, and sample shearing, La Rochelle et al. (1981) have reviewed criteria for minimal soil sample disturbance. For a soil core to be considered undisturbed, it must be collected with minimal effects on structure, density, and moisture content. Also, if K(θ) is to be determined on cores in the laboratory, samples must be encased so that flow does not occur at the boundary between the soil and encasing material. Although attempts at obtaining undisturbed cores for laboratory water flow analysis have been made (Noel, 1982), no encasement method has been satisfactory. Therefore, if the unit gradient models are to be adequately tested by lab data, a satisfactory method of encasing, transporting, and performing laboratory water flow analysis on undisturbed soil cores must be developed. This was the second objective of this work. Invention of such a sampling method would also provide a way to get data from deep in the profile, where flood plot techniques are unreliable.

LITERATURE REVIEW

In recent years proper management of water resources has become more important as demands for quality water have increased. In the arid and semi arid western U.S., where water supplies are limited, improving water use efficiency and maintaining the quality of water supplies are important management objectives. Because of the important role of soils in water supply and use, knowledge of soil water behavior is crucial to achieving these objectives.

Applications of soil hydrologic characterization data include design of irrigation systems, design of septic drainfields, and prediction of aquifer recharge rates. General information often provided in soil surveys, such as drainage classes, is not specific enough to be helpful in engineering problems such as these, where flow rate predictions are required (Bouma, 1973). Knowledge of hydraulic conductivity as a function of water content is needed for these predictions.

Hydraulic Conductivity

Hydraulic conductivity (K) is the constant of proportionality in Darcy's Law (Hillel, 1982) which equates soil water flux (V) and hydraulic gradient (dH/dz):

$$V = K * dH/dz \qquad [1]$$

where K is constant for any given soil which is saturated, and dz specifies vertical flow. Under unsaturated conditions, however, the value of K (cm/min) varies greatly with small changes in soil water content or potential. Therefore Darcy's Law may be written

$$V = K(\theta/h) * d(h+z)/dz \quad [2]$$

for unsaturated steady state conditions, where $K(\theta/h)$ implies the dependence of K on soil water content and potential conditions, and (h+z) indicates matric and gravitational components of the hydraulic gradient (Hillel, 1982).

Hysteresis is a phenomenon which may complicate determination of $K(\theta/h)$. Water contents are greater during desorption than sorption at a given potential. This has led to questions of hysteresis effects on unsaturated hydraulic conductivity. Although K(h) may be highly hysteretic, $K(\theta)$ is much less so, and effects of hysteresis on $K(\theta)$ are generally ignored. Inference of K(h) from $K(\theta)$ may be difficult, however, due to hysteresis (Topp, 1971).

Hydraulic Diffusivity

Equation [2] may be expressed as

$$V = K(\theta/h) * dH/d\theta * d\theta/dz \quad [3]$$

$dH/d\theta$ is the reciprocal of soil specific water capacity, which is the slope of the moisture characteristic curve at a specific point. Equation [4]

$$K(\theta/h)\ dH/d\theta = D(\theta) \quad [4]$$

is substituted into Eq. [3]; where $D(\theta)$ is hydraulic diffusivity, with dimensions x2 t-1. The result is

$$V = D(\theta)\ d\theta/dz. \quad [5]$$

Calculation of $D(\theta)$ does not require knowledge of soil water potential, but moisture characteristic curves are required to convert $D(\theta)$ to $K(\theta)$. The specific water capacity and moisture characteristic curve is assumed to be uniform in Eq. [5]. Therefore, this equation cannot be applied to heterogeneous soil, and hysteresis effects must be negligible. The term "diffusivity" may be misleading here, as a mass flow rather than a diffusion process is being described (Hillel, 1982).

Water Flow Within Single Pores

The magnitude of K depends on the size districbution, continuity, and geometry of conducting pores, as well as the nature of the fluid. Therefore K may be written as

$$K = g\rho k/\eta, \qquad [6]$$

where ρ/η (fluid density over viscosity) accounts for the temperature dependent effect of the fluid on flow rate. Intrinsic permeability (k) indicates effects of conducting pores. Flow rates within individual pores are governed by Poiseuilles Law, given laminar flow. Equations governing flow through cylindrical and planar voids are

$$q/t = \rho\ g\ \pi\ (r{*}{*}4)/8\eta\ *\ dH/dx \qquad [7]$$

and

$$q/t = \rho\ g\ w\ (d{*}{*}3)/12\eta\ *\ dH/dx \qquad [8]$$

respectively, where q/t is flow rate, g is acceleration due to gravity, and r, d, and w are the pore radius, diameter, and width, respectively (Hillel, 1971). Flow rate dependence on fourth power of the radius means that small changes in pore size can result in large changes in flow rate. Flow velocities within pores also vary, according to distance from the pore boundary wall, as described by:

$$V(x) = \rho\ g\ ((r**2) - (x**2))/4\eta * dH/dx \qquad [9]$$

where x is the distance from the pore's center (Hillel, 1982). Variability of flow velocities within and between pores has important implications for water flow in natural porous systems. Piston type (Darcian) flow can be used to describe quantities and rates of water flow in such systems, but it cannot be used to describe or predict rates of solute movement, which will vary within such systems as do flow velocities.

Pore Size Distribution and Water Flow In Soils

Hydraulic conductivity will vary greatly with small changes in water content (θ). As soil water potential decreases, large pores are drained first, according to the equation

$$h = -2\ To\ (\cos Y)/(\rho g r) \qquad [10]$$

where To is the surface tension of water, Y is the wetting angle, and h is the potential in cm, expressed on a weight basis (Hillel, 1982). When a soil's largest pores are drained, water content may be only slightly reduced, since large pores generally occupy a small fraction of total porosity (except in coarse textured soils). Yet the hydraulic conductivity is greatly reduced due to dependence of flow rate on pore radius raised to the fourth power. Large soil pores (macropores) occur between structural units (peds) in natural soils, and are caused by soil animals, plant roots, and shrinkage due to dessication. Continuous macropores (>.60 microns) may allow water to be channeled rapidly through the solum (Thomas and Phillips, 1979), but there is not complete agreement on the conditions under which this will occur. Arguments based on Eq. [6] state that water tends to enter small pores (micropores) first due to greater capillary (matric) forces, and that larger pores will be filled only after micropores are saturated. Depending on the rate of water addition, however, flow through macropores may occur ahead of a wetting front during infiltration (Bevin and Germann, 1982).

Water content, tillage, and structural properties such as clay orientation and soil fabric, which determine pore size distribution and continuity within peds, will influence extent of macropore flow during infiltration (Thomas and Phillips, 1979). Water movement into peds is affected by intrapedal conductivities and hydraulic gradients, plus the spatial distribution of vertical macropores (Anderson and Bouma, 1977). Bouma (1973) found that presence of intrapedal mottles does not necessarily indicate poor drainage if interpedal pores are available for flow. The importance of macropore flow in infiltration and drainage will therefore vary with soil texture and fabric.

Measurement of Unsaturated Hydraulic Conductivity

Many steady and non-steady state approaches for estimating $K(\theta)$ in the field and lab are available. It is beyond the scope of this review to present them all. Klute (1972) and Black (1965) reviewed laboratory methods of determining $K(\theta/h)$. Herein, discussion of lab methods is limited to pore size distribution models, particularly the method of Campbell (1974). Field methods are then discussed in detail.

One point is to be made relative to lab studies utilizing undisturbed soil cores. Reliability of data from undisturbed cores has been questioned, since accuracy may be affected by changes in sample properties caused by removal from the field. Also, large sample sizes and numbers may be required to obtain representative data (Hillel, 1982). Very few data exist on spatial variability of hydraulic conductivities in the field. The major work has been done by Nielsen et al. (1973), who studied spatial variability of field hydraulic conductivities; using 20 flood plots on a 150 ha field. Maximum hydraulic conductiviy (Km) was log-normally distributed over the 20 plots, with a range nearly two orders of magnitude. There was one order of magnitude difference between mean and mode Km. Variability increased as percent saturation decreased.

Laboratory Determination of $K(\theta)$

Pore Size Distribution Models. A soil moisture characteristic curve (the relationship between θ and h) can be used with Eq. [10] to determine pore size distribution. This may be combined with Poiseuilles Law, Eq. [7], to give an estimate of $K(\theta/h)$. Methods of determining $K(\theta/h)$ in this way are called pore size distribution models. Childs and Collis-George (1950) were the first to present such an approach. Marshall (1958), Millington and Quirk (1961), and Green and Corey (1971) have presented modifications. One example of such an equation is

$$K = F(\Sigma f_i r_i^2) \rho g/8\eta \qquad [11]$$

where F is the porosity, and f_i is the fraction of the pore area (pore volume) occupied by pores of radius r_i. Eight to ten pores size classes are used in the summation. Matching factors are generally used to obtain agreement with experimental values and account for physical difficulties such as swelling of clays, air entrapment, and pore interactions (Kunze et al., 1968). Green and Corey (1971), Bruce (1972), Brust et al. (1968), and Kunze et al. (1968) were all able to obtain reasonable agreement between experimentally measured values and values calculated by various pore size distribution models with matching factors. Hysteresis will complicate direct conversion of a moisture characteristic curve to pore size distribution, particularly due to pore "bottlenecks".

Campbell (1974) proposed a method to estimate K(θ) using desorption data and a pore size distribution model given by Childs (1969) as

$$K = N \int [\int R**2\ F(r)dr]\ F(r)dr \qquad [12]$$

where R is the radius of the largest filled pore, N is a constant, and F(r) is the pore size distribution function. An empirical expression relating water content to water potential (Hillel, 1971)

$$h = he\ (\theta/\theta s)**-b \qquad [13]$$

where he is air entry potential, is substituted into Eq. [10] to give

$$r = -(2To/he)\ (\theta/\theta s)**b. \qquad [14]$$

This equation, and

$$F(r)dr = d\theta \qquad [15]$$

are substituted into Eq. [12]. The result is

$$K = N'\ \theta**(2b+2) \qquad [16]$$

where N' includes N and constants from integration. If Ks is determined,

$$N' = Ks / \theta s**(2b+2) \qquad [17]$$

and

$$K(\theta) = Ks\ (\theta/\theta s)**(2b+2) \qquad [18]$$

A pore interaction term θp with $p=1$ is included (Jackson, 1972), so

$$K(\theta) = Ks\ (\theta/\theta s)**(2b+3) \qquad [19]$$

Campbell (1974) tested this method and found it reliable for most purposes.

Field Determination of K(θ)

Field methods generally fall under two categories; infiltration through an impeding layer (steady state), and drainage from a profile (non-steady state) thoroughly wetted by flooding.

Field methods using flood plots. Richards et al. (1956) were the first to publish results of a flood plot investigation. In their study, a tensiometer stack was installed, and there was no attempt to prevent evaporation. Water contents during drainage were determined gravimetrically from daily collected core samples. Total depth of water stored in the profile, W, above depth z was related to t by

$$W = c\ t**-d \qquad [20]$$

where the c and d parameters were determined through regression analysis. This equation was differentiated with respect to time to give drainage rate, dW/dt:

$$dW/dt = c(-d)\ t**(-d-1) \qquad [21]$$

Differences in dW/dt between adjacent depths gave flow velocities, which divided by the hydraulic gradient gave K. Flow velocities at 40cm were regressed against time to fit

$$V = c' t^{-d'} \quad [22]$$

which, integrated over time, gave total drainage.

Tensiometric data were used to determine direction (upward or downward) of the hydraulic gradient, from which depth of a "static zone" was determined at different times. This zone was a boundary depth, separating water loss by evaporation (above) and drainage (below). The drainage component was subtracted from total change in W to estimate evaporation losses. Arya et al. (1975) used the static zone approach in the presence of a growing crop.

Ogata and Richards (1957) performed a drainage study in which evaporation was prevented by a plastic cover and straw mulch. Flow velocities were determined as above, except W was fitted to

$$W = c'' Z t^{-d''} \quad [23]$$

with flow velocity determined by differentiation. Hydraulic gradients determined from tensiometer data were used to calculate K(h), which increased with depth. Sisson (1972) pointed out that d'' in Eq. [23], given unit gradient conditions, is the ratio between hydraulic conductivity and the depth of water stored in the profile above depth z at the start of drainage.

Nielsen et al. (1964) did a flood plot study on the Panoche clay loam. Their methods were expanded over previous work, in that a neutron probe was used to collect moisture data, and undisturbed cores were collected for determination of moisture characteristic curves.

Neutron probe data were used little, however, since poor depth resolution and inherent scatter of neutron probe data make it difficult to determine water content changes with the accuracy required for calculation of K by Darcy's Law. Changes in θ were therefore inferred from changes in h using desorption curves from core samples. This technique has been used frequently since (Arya et al., 1975; Davidson et al., 1969; LaRue et al., 1968; and Nielsen et al., 1973). Ahuju et al., (1980) derived a method of determining K(h) without desorption data by substituting expressions of K(h) and θ(h) into the flow equation (Eq. [2]).

Rose and associates (Rose et al., 1965; Rose and Stern, 1965) used a water budget approach for determining hydraulic conductivities. Conservation of mass dictates that the quantity of water which penetrates a soil surface (I) will evaporate (E), drain from the soil (U), or be stored in the soil (ΔM):

$$1 = E + \Delta M + U \qquad [24]$$

Recognizing that

$$\Delta M = \int \int (d\theta/dt)\ dz\ dt \qquad [25]$$

and

$$U = \int Vz\ dt \qquad [26]$$

rearrangement of Eq. [24] and substitution of Eq. [25] and Eq. [26] into the result gives

$$\int (I - E - Vz)\ dt = \int \int (d\theta/dt)\ dz\ dt \qquad [27]$$

Substituting

$$Vz = Kz + Kz\ dh/dz \qquad [28]$$

into Eq. [27] and solving for Kz gives

$$Kz = \int (I - E - (\int d\theta/dt\ dz))dt\ /\ t(dh/dz + 1) \qquad [29]$$

This approach was applied using four plots established on a fine sandy loam field soil, where moisture profiles were determined wih a neutron probe, soil water potentials were inferred from characteristic curves, and initial evaporation rate was estimated from Penman's equation (Hillel 1982). Linear regression of ln K on θ gave estimates of K(θ) at four depths. Values of K(θ) decreased with increasing depth, and scatter of results were attributed to plot differences, neglect of hysteresis effects below 100 cm depth, and measurement variability.

A commonly used method of determining K(θ) is the instantaneous profile method (IPM) (Watson 1966), designed to include possible dynamic effects of non-steady state flow in calculation of K, and first tested in the lab using soil columns. Assuming one dimensional vertical flow and no evaporation,

$$(d\theta/dt)z = (-dV/dz)t \qquad [30]$$

If water content and soil water potential profiles are monitored during drainage, velocity profiles for any time may be obtained by integrating dθ/dt over depth. Potential profiles (combining matric and gravitational components) are plotted, and the gradient at any depth is equal to slope of the plot at that depth. Hydraulic conductivity is obtained by dividing velocity at a given time and depth by corresponding potential gradient, which may then be plotted against the corresponding water content to determine the K(θ) curve.

Hillel et al. (1972) provide a summary of the data handling procedure for use of the IPM in the field, where no water table is present.

Cassel (1974) developed a computer program for calculation of average θ, flow rate, hydraulic gradient, and conductivity for all depths and times, given desorption and tensiometer data collected during drainage of a covered flood plot.

VanBavel et al. (1968) used the instantaneous flux method in the field with a static zone approach, but found that it breaks down when water movement lags behind diurnal variation in evaporative demand.

The Unit Hydraulic Gradient

Under steady state conditions, which are approached during drainage of a thoroughly wetted profile, the matric component of the potential gradient becomes negligible, and the gravitational component (equal to one) dominates. A unit hydraulic gradient results, and Eq. [2] becomes

$$V = -K \qquad [31]$$

Black et al. (1969) found that K(θ) curves determined in the lab under unit gradient conditions agreed with drainage rates found in the field, indicating unit gradient conditions in the field. Van Bavel et al. (1968) found near unit gradient conditions during drainage of a deeply wetted fallow soil. Where a unit gradient can be applied, tensiometric data are not necessary to calculate potential gradients. This greatly simplifies field determination of K(θ).

Several mathematical models have been proposed recently which assume a unit gradient, and provide for calculation of K(θ) using only water content measurements at known times during drainage. These are the Lax algorithm (Sisson et al., 1980), the "CGA" (Chong et al., 1981), and the Theta and Flux models (Libardi et al., 1980).

Lax Algorithm. Sisson et al. (1980) summarized use of the Lax algorithm. Two possible K-θ relationships are given by Watson (1967) and Davidson et al. (1969), respectively, as

$$K(\theta) = Km\ (\theta/\theta m)**1/\beta \qquad [32]$$

$$K(\theta) = Km\ \exp\ \alpha(\theta - \theta m) \qquad [33]$$

where θm is maximum water content, Km is maximum hydraulic conductivity, and α and β are exponential constants to be determined. Differentiation of K with respect to θ gives

$$dK/d\theta = A\ (\theta/\theta m)**(1-\beta/\beta) \qquad [34]$$

and

$$dK/d\theta = A'\ \exp\ \alpha(\theta - \theta m) \qquad [35]$$

where A = Km/βθm and A' = Kmα. Replacement of dK/dθ with z/t and rearrangement of Eq. [34] and Eq. [35] gives θ as a function of z and t:

$$\theta = \theta m\ (z/At)**\beta/1-\beta \qquad [36]$$

$$\theta = \theta m + 1/\alpha\ \ln\ (z/A't) \qquad [37]$$

These can be rearranged to show a linear relationship between ln θ/θm and ln t for the Watson (1967) equation, and (θm-θ) and ln t for the Davidson et al. (1969) equation:

$$\ln\ \theta/\theta m = -\beta/1-\beta\ \ln\ A/z - \beta/1-\beta\ \ln\ t \qquad [38]$$

$$\theta m-\theta = 1/\alpha\ \ln\ A'/z + 1/\alpha\ \ln\ t \qquad [39]$$

Integration of Eq. [36] and Eq. [37] over depth gives

$$W = \int \theta \, dz = z \, (1-\beta) \, \theta m \, (z/At) ** \beta/1-\beta \qquad [40]$$

$$W = \int \theta \, dz = \theta m \, z + z/\alpha \, [\ln \, (z/A't) \, -1] \qquad [41]$$

where W, the total water stored above depth z, is expressed as a function of time. Rearranged, Eq. [40] and Eq. [41] show linear relationships between ln W/z and ln t (Eq. [42]) and between W/z and ln t (Eq. [43]):

$$\ln W/z = \ln \, ((1-\beta) \, \theta m \, (A/z)**-\beta/1-\beta) - \beta/1-\beta \ln t \qquad [42]$$

$$W/z = \theta m - 1/\alpha \, (1+ \ln A'/z) - 1/\alpha \ln t \qquad [43]$$

Slope and intercept results from regressions of ln W/z and W/z (dependent) versus ln t (independent) are used to calculate Km and exponential constants for the W method. Regressions for the θ method (Eq. [38] and Eq. [39]) are ln θ/θm and θm-θ (dependent) versus ln t.

CGA Method. The CGA method (Chong et al., 1981), assumes that under flood plot drainage conditions the average water content (θ') above any depth is related to time by

$$\theta' = a \, t**j \qquad [44]$$

where e is less than zero. Differentiating with respect to time yields

$$d\theta'/dt = aj \, t ** j-1 \qquad [45]$$

If Eq. [45] is multiplied by z, under the unit gradient theory

$$z \, d\theta'/dt = K \qquad [46]$$

so

$$K = zaj \, t ** j-1 \qquad [47]$$

Equation [44] is then solved for t, and the result is substituted for t in Eq. [47], leaving K(θ') as a function of (θ')

$$K(\theta) = z\ j\ a^{**}1/j\ \theta'^{**}((j-1)/j) \quad [48]$$

The unknowns a and j are determined by expressing Eq. [44] in its logarithmic form:

$$\ln \theta' = \ln a + j \ln t \quad [49]$$

and by linear regression of ln θ' on ln t using the drainage data. Note that W/z = θ', so the regression variables for the Watson W and CGA methods are identical.

Theta and Flux Methods. Libardi et al. (1980) present two methods of determining K(θ), using water content data collected during flood plot drainage and a unit gradient assumption. Combining Eq. [33], Eq. [46], and a linear relationship between θ and θ' results in

$$a'\ z\ d\theta/dt = Km \exp [\alpha(\theta - \theta m)] \quad [50]$$

where a' is the slope of the θ vs θ' relation. Integrating with respect to time gives (at large times)

$$\theta m - \theta = 1/\alpha \ln t + 1/\alpha \ln \alpha Km/a'z \quad [51]$$

which is similar to the result of the Lax algorithm where the same K(θ) expression is used. This is the Theta method. The logarithmic form of Eq. [50] is called the Flux method.

Previous Studies Utilizing Unit Gradient Models. Dane (1980) found excellent agreement between the Theta method and the IPM on a sandy soil. Luxmoore et al. (1981) found good agreement between the IPM and the flux method, although the Theta and CGA methods gave high estimates of K(θ). Jones and Wagenet (1984) found that the CGA method gives higher estimates of K(θ) than the Theta and Flux method, and that the W method (Lax algorithm) gives lower estimates.

Schuh et al. (1984) compared the IPM with the method of Ahuju et al. (1980), and Libardi's Flux and Theta methods on 5 soils. Ahuja's method and the IPM agreed well on all soils. Libardi's methods gave good estimates of drainage, but poor estimates of K(θ), particularly on layered soils. This was attributed to problems with indirect calculation of Km.

Methods Using Infiltration Through an Impeding Layer. Hillel and Gardner (1969) first proposed this method, and tested it in the lab. Impeding crusts were placed on soaked soil columns, which had two tensiometers installed at 2 and 12 cm. A minimal ponding depth was maintained over the crust until steady state flow was attained. Equation [31] and tensiometer data give one point on the K(h) curve. Increasing crust resistance led to increased tension and lower flow rates. The method has been successfully used in the field. Bouma et al. (1971) were the first to publish field results. In the field, crust resistances are decreased, resulting in K(h) data for wetting, rather than drying.

Baker et al. (1974) report that conductivities for potentials greater than -20 cm cannot be accurately determined from the IPM, and that the crust technique gives better results in this range, which is important to evaluation of septic drainfield suitability.

Gardner (1970) presented a method for calculation of D(θ) in the field, using the crust technique. Under unit gradient conditions,

$$z(d\theta/dt) = K(z) \qquad [52]$$

is expressed as

$$z\ d\theta/dh\ dh/dt = K \qquad [53]$$

or

$$z\ dh/dt = D, \qquad [54]$$

so the average diffusivity above any depth z may be calculated with a single set of tensiometer data.

PROBLEM STATEMENT

Information obtained from the K(θ) relationship includes K values at specific water contents and rate of change in K with changes in water content. Since water movement is most rapid when soil water content is high, (>30%), K values for high water contents are most important in determining the quantity of water which will rapidly drain from a soil. This project's basic objective was to test the Theta and W Lax algorithm (Sisson et al., 1980) and "CGA" (Chong et al., 1981) unit gradient models for accurate estimation of Km and K(θ) with laboratory data collected from measurements on undisturbed cores. To ensure accuracy of the lab data, the second objective was to devise a reliable procedure for encasing undisturbed cores which would minimize disturbance, and allow for safe transport and reliable water flow analysis. The models were applied to two sets of data from one soil, and undisturbed soil cores were collected around the flood plots where drainage data was obtained.

Given the extreme variabilility of hydraulic conductivities in the field (Nielsen et al., 1973), and time and expense involved in obtaining a large sample size, statistical comparison of lab measurements and field estimates of K values was not attempted. Field unit gradient models which give K(θ) estimates within the range of lab determined values were considered valid. Data were collected on the

Bozeman silt loam. Results may apply only to soils of similar texture and morphology.

MATERIALS AND METHODS

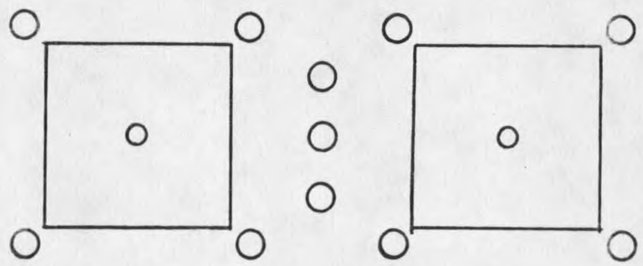
Bozeman silt loam (Pachic Argiboroll) was chosen as the field soil for this study. Two 3.65 by 3.65 m plots 3.05 m apart were established at the A.H. Post Experimental Farm, 9.7 km west of Bozeman, Montana. After the soil surface was leveled, an aluminum neutron probe access tube was installed to a depth of 2.4 m at the center of one plot (Plot A) and to a depth of 1.8 m at the center of the other (Plot B). Soil cores were extracted with a Giddings soil sampler. Cores collected around plot perimeters were 5cm in diameter, while cores extracted for access tube installation were 3.5 cm in diameter.

Flood Plot Procedure

On August 1, 1984, after each plot had been diked with 3.65 m 30.5 cm x 2.5 cm boards, they were flooded with the Post Farm's irrigation water. Neutron probe readings were taken at 15 cm increments (the first depth was at the 15 to 30 cm midpoint, 22.5 cm) before flooding began, and at 15 minute intervals for two hours thereafter. Intervals were then increased to one half hour until the wetting front reached a depth of about 1.5 m (4-5 hours after flooding began). Dikes were then broken, and infiltration ceased shortly thereafter when free water was no longer standing on the soil surface. At that time the plots were covered with a plastic tarp to prevent evaporation.

To characterize drainage, neutron probe readings were taken every twenty minutes to half hour for the first four or five hours of drainage. Reading intervals were then increased to one hour for the next 12 hours, then to two hours for the next 12 hours. Readings were then taken 3 or 4 times daily for 4 days, twice daily for 5 days, and once daily for the next ten days. Readings were then taken once every two or three days, until the last reading was taken about 29 days after drainage began.

Figure 1. Field study design showing two 3.65 m by 3.65 m plots. Small circles show neutron probe access tubes, large circles show sample collection points.



Field Study Layout

While drainage was being monitored, undisturbed cores were collected from around the plots as shown in Figure 1, and encased as described below. Cores removed for neutron probe access tube installation were similarly sectioned and encased. Eleven cores were collected outside the plots from each 15 cm depth increment, so 13 cores from each depth were collected. The coring depth was 1.8 m at all points, except that the four holes around plot A were sampled to 2.4 m. Care was taken to ensure that cores were sectioned so that the middle of each core coincided with a depth at which neutron probe readings were being taken.

Field Encasement of Core Samples

This procedure was developed to minimize handling of core samples. In the operation of the Giddings sampler, the core barrel was driven into the soil slowly (about 1/2 cm/sec), in order to minimize frictional resistance and therefore sample disturbance. The core barrel was 1.3 m in length, so the sampler was driven into the soil twice to recover soil from 1.8 or 2.4 m. There was generally full sample recovery.

After extraction, the soil core was sectioned into 15 cm lengths while still in the core barrel. The core section was then slid to the upper, open end of the core barrel, and trimmed flush. An eight inch length of PVC plastic pipe (2" ID for 3.5 cm diameter samples, 2 5/8" ID for 5 cm samples) with a fiberglass screen glued to one end was then placed over the core barrel. A small plastic bag was attached around the PVC pipe with a rubber band. A cardboard spacer was used to center the soil core inside the PVC pipe. After checking to see that the trimmed end of the core was against the screen, the tube and pipe were rotated 90 degrees to a vertical position, taking care not to disturb the core remaining at the core barrel's lower end. The PVC pipe was then lowered away from the Giddings core barrel, leaving the soil core standing balanced on the screen, inside the PVC pipe. The pipe was then clamped to a rack to facilitate sample encasement in the field.

To encase the core sample, a liquid rubber latex molding compound[1] was poured over the soil core, taking care to coat it completely. Excess latex was collected in the attached plastic bag for reuse. This rubber latex dries to form a mold around the sample, yet is viscous enough in its liquid state to prevent it from penetrating the soil itself. After the latex dried (1-2 days), wax was melted and poured over the core to prevent evaporation. The PVC pipe was then filled with a light weight concrete (75% Zonolite, ground to pass a #10 seive, 25% cement). After the cement had dried, the samples were ready for transport to the laboratory.

Neutron Probe Calibration

The neutron probe was calibrated for Bozeman silt loam at the Post Farm in September, 1984. Sixty five core samples 15 cm in length were collected for determination of gravimetric water content (θg) and bulk density (BD), from which volumetric water content (θ) was calculated by

$$\theta g \times BD = \theta . \qquad [55]$$

Neutron counts were taken in the bore holes from which the cores were extracted immediately after collection. Care was taken to place the fast neutron source at the center of the 15 cm depth increment from which the core samples were taken. Moist and dry soil conditions were

[1]Product #4701, manufactured by Adhesive Products, 1660 Boone Ave., Bronx, NY 10460.

included in the sampling. Linear regression was performed, using volumetric % moisture as the dependent variable, and neutron count ratio as the independent variable. The result of the calibration was

$$\theta = 45.474*(Rat) - 5.703 \qquad [56]$$

where Rat denotes neutron count ratio. The r2 of the regression was 0.95.

Treatment of Drainage Data

The Lax algorithm was applied to two forms of the K - θ relationship (Eq. [32] and [33], referred to herein as the Watson and Davidson equations, respectively) with a θ and W based approach for each, for a total of four Lax algorithm models. The CGA Method was also used, so 5 models were applied to the drainage data. Therefore five K - θ relationships were estimated at each plot and depth from the drainage data. Table 1 shows regression variables and constants determined by regression for each model. Moisture content data collected during drainage were converted to the dependent variables using a Fortran program on the CP6 computer. Regressions were run with the MREGRESS program on MSUSTAT (Lund, 1979), and the constants defining the K(θ) equations were calculated from slope and intercept results (see Appendix I).

Laboratory Procedures

Two methods of determining K(θ) were attempted in the lab using the undisturbed cores; direct measurement, and the method of Campbell (1974).

Table 1. Regression variables used in determination of K(θ) by each model tested, with constants determined by regression results for each model.

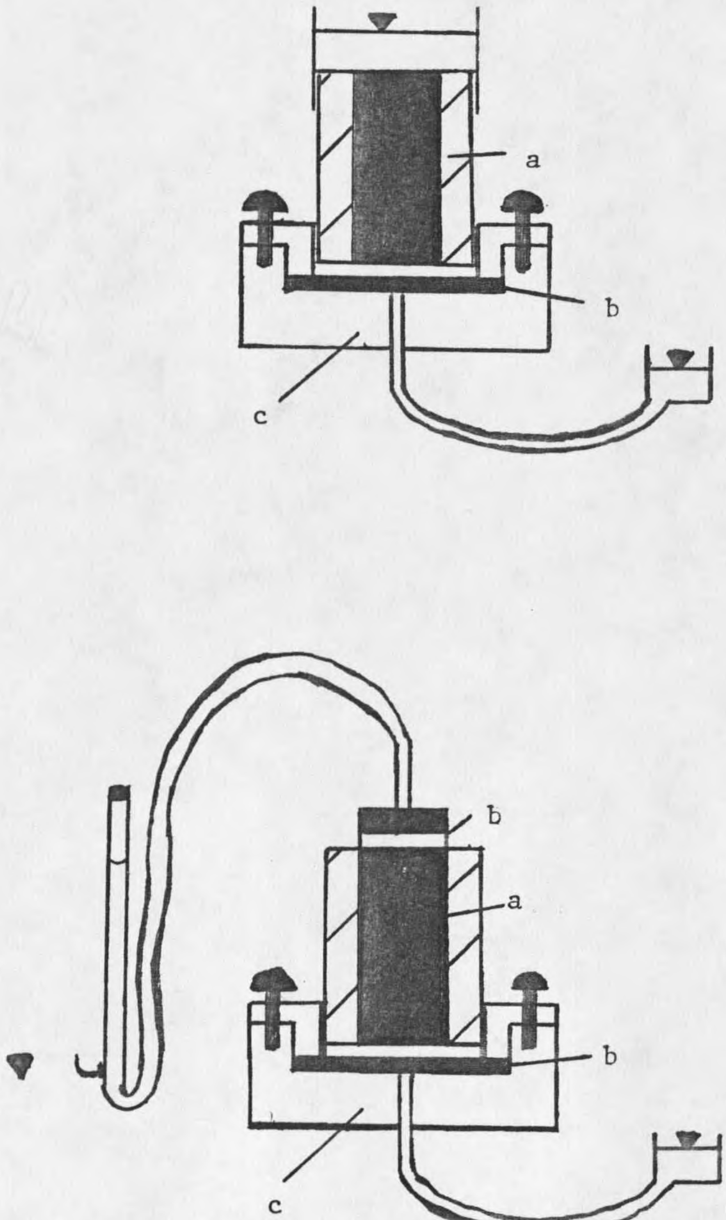
Model	Regression Variables: Dependent	Regression Variables: Independent	Constants Determined
Lax:			
θ, Watson	ln (θ/θn)	ln t	Km, β
θ, Davidson	θn-θ	ln t	Km, α
W, Watson	ln (w/z)	ln t	Km, β
W, Davidson	w/z	ln t	Km, α
CGA:	ln θ'	ln t	a,j

Direct measurement of Ks and K(θ) are discussed by Klute in Black (1965). Various porous plates were examined to determine their ability to conduct water rapidly (for Ks determinations), and still hold water under tensions for K(θ) determinations. Two sintered bronze powder plates were selected which could hold tensions up to 30 cm of water.[2] Two permeameter bases were built from plexiglass. Figure 2 shows the permeameter design and set-up for determining Ks and K(θ) directly.

The procedure for cutting the core samples open, saturating and performing the flow analysis was as follows. A carborundum impregnated wire gauze blade was used to cut the samples on a table saw. The PVC pipe was first cut, then the cement and rubber, so the core sample unit was rotated during cutting. The soil core itself was then broken

[2]Sintering was done by Alcan Ignot and Powders, Elizabeth, NJ.

Figure 2. Permeameter design for determination of Ks (top) and K(θ) (bottom) showing water levels (▼), soil column (a), porous pads and plates (b), and plexiglass base (c).



carefully by hand. After both ends of the core were cut and broken, the core length was measured, and outside edges of the PVC pipe were beveled with a wood rasp to allow easier installation of the core sample into the permeameter. The permeameter brace and PVC connector (for ponding water for Ks determination) were then placed around the bottom and top of the core sample, respectively. Exposed cement was then greased to ensure water flow did not occur through the cement. Any cavities at the bottom of the core were filled with fine glass beads, and an O ring was placed at the bottom of the core unit. A cellulose filter pad was saturated, placed on the bottom of the core, and sealed to the O ring with high vacuum grease. The core unit was then braced to the saturated porous plate with screws, and the soil was saturated overnight from below.

For determination of Ks, a bubbler was used to maintain a constant ponding depth over the top of the core. The outflow level was kept constant, and rate of outflow was monitored for calculation of Ks. To measure unsaturated conductivity, the water column conducting outflow was clamped, and the water ponded on the top of the core was removed. Cavities on the top of the core were filled with fine glass beads, a saturated filter pad was applied, and a weighted porous plate, attached to a burette by a water column, was placed on the pad. The burette bubbler height was then adjusted to the desired tension, and a unit gradient was established through the core. Inflow rates were measured for calculation of $K(\theta)$. Flow rates and unsaturated hydraulic conductivity were determined at 10 and 20 cm of tension. Subsamples of the cores were collected at the saturation and the tensions applied, for moisture content determination, so K(h) could be converted to K(θ). This was done for four cores from each depth.

The above procedure was followed for all cores collected from four depths. By then, the K(θ) data were beginning to become very consistent, indicating that flow was being controlled by the porous plates or pads.

Campbell's method (1974) of determining K(θ) from desorption data was then tried. The following procedure was followed for three depths. Seven or eight core sections per depth were cut to a length of 5 cm and saturated from below. (Seven cores from 30 to 45 cm, eight from the 45 to 60 cm and 75 to 90 cm depths.) Modified PVC caps attached to the core base facilitated saturation. Saturated conductivities were determined as above, except an unsealed filter pad served as a base for the soil sample, and silicon rubber was used to seal the cement. Volumetric water contents were determined at saturation (0 bar), 0.1, 0.33, 0.50, 0.75 and 1 bar for two of the depths (30 to 45 cm and 45 to 60 cm). For the third depth (75 to 90 cm) 0.5 and 0.75 bar were not determined due to time limitations, and .14 bar was applied instead of .10, due to difficulty with the pressure regulator. Eight core sections were used per depth (seven cores from 30 - 45 cm), as this was all that would fit in the pressure apparatus. Water contents were averaged to determine he and b from

$$h = he\ (\theta/\theta s)**b \qquad [13]$$

using linear regression of ln h (h in cm) on ln θ/θs. The constant b was used in

$$K(\theta) = Ks\ (\theta/\theta s)**(2b+3) \qquad [19]$$

which was plotted for comparison with field estimates of K(θ). In all such plots of θ vs. K, θ/θs (lab) and θ/θm (field) are placed on the same scale to allow easier comparison of lab and field results.

RESULTS AND DISCUSSION

After this drainage study was performed it was discovered that the fast neutron source of the probe was 5 cm below where previously believed. This depth increase was included in data analysis, and is included in presentations of field data. For this reason, laboratory data from both 15 - 30 (direct measurement) and 30 - 45 cm (Campbell's method) depth cores are compared to field results for the 35 cm depth. Laboratory data for the 45 - 60 cm and 60 -75 cm depths are compared to field results for 50 and 65 cm, respectively, and so on. Also, glue attaching the fiberglass screen to the PVC pipe did not hold many 3.5 cm diameter samples long enough for the latex to dry. Many of these samples therefore were lost.

Field Results

Results of the Lax algorithm models are presented for each plot and depth in Tables 2 through 5. Tables 2 and 3 give results for the Watson equation (Eq. [32]), and Tables 4 and 5 for the Davidson equation (Eq. [33]). Data include Km, exponential parameters, and r^2 of the regression. Results of the CGA model are presented in Table 6. Although Km is not a variable determined by this model, it is presented for comparative purposes, and corresponds to 0m (.427 cm3/cm3), the approximate maximum water content observed at the initiation of drainage. Results of all field models are also presented graphically in figures (lab data are also shown in these figures). Models may be compared using these figures. Data for depths below 140 cm have been omitted, because water contents below this depth continued to increase during the early stages of drainage. This violated the conditions under which unit gradient models may be applied.

Table 2. Results for both plots using the Watson equation, and the θ method of the Lax algorithm.

	Plot A			Plot B		
Depth cm	Km cm/min	β	r^2	Km cm/min	β	r^2
35	1.86	.032	.86	.42	.041	.93
50	.68	.033	.81	.86	.039	.82
65	.39	.037	.86	.47	.047	.81
80	.14	.055	.89	.11	.055	.87
95	.10	.055	.85	.09	.049	.80
110	.11	.046	.83	.06	.045	.79
125	.14	.047	.83	.07	.041	.72
140	.10	.043	.79	.16	.042	.72

Table 3. Results for both plots using the Watson equation, and the W method of the Lax algorithm.

	Plot A			Plot B		
Depth cm	Km cm/min	β	r^2	Km cm/min	β	r^2
35	.70	.032	.86	.16	.041	.93
50	.65	.033	.85	.25	.040	.91
65	.53	.034	.86	.26	.040	.90
80	.32	.038	.88	.19	.043	.90
95	.23	.041	.88	.16	.044	.88
110	.20	.041	.88	.14	.044	.88
125	.18	.042	.87	.13	.044	.86
140	.17	.042	.87	.13	.044	.85

Table 4. Results for both plots using the Davidson equation, and the θ method of the Lax algorithm.

Depth cm	Plot A Km cm/min	Plot A α	Plot A r^2	Plot B Km cm/min	Plot B α	Plot B r^2
35	4.35	91.7	.86	.78	72.7	.94
50	1.21	85.9	.80	1.96	77.5	.82
65	.61	76.4	.87	.64	71.5	.81
80	.20	52.8	.91	.15	52.1	.89
95	.13	51.7	.87	.11	57.8	.82
110	.13	60.6	.85	.07	60.4	.81
125	.18	59.1	.85	.09	66.3	.73
140	.12	63.0	.81	.21	67.2	.73

Table 5. Results for both plots using the Davidson equation, and the W method of the Lax algorithm.

Depth cm	Plot A Km cm/min	Plot A α	Plot A r^2	Plot B Km cm/min	Plot B α	Plot B r^2
35	1.60	91.7	.86	.29	72.7	.94
50	1.36	89.9	.86	.48	74.1	.92
65	1.03	86.4	.87	.50	73.4	.91
80	.57	77.2	.88	.34	68.2	.91
95	.37	71.6	.89	.26	66.3	.90
110	.30	69.9	.89	.21	65.5	.89
125	.27	68.4	.88	.19	65.6	.88
140	.25	67.8	.88	.19	65.7	.86

Examination of the Lax algorithm results shows that the Davidson equation (Tables 4 and 5) generally gave higher estimates of Km than the Watson equation (Tables 2 and 3) for both the θ and W based methods. Model estimates of Km on plot A are greater than on plot B

Table 6. Results of the CGA method for both plots.

Depth cm	Plot A j	a	Km cm/min	Plot B j	a	Km cm/min
35	-.033	.41	1.92	-.042	.43	.44
50	-.034	.41	1.75	-.042	.43	.69
65	-.035	.42	1.47	-.042	.44	.73
80	-.039	.43	.90	-.045	.45	.53
95	-.042	.45	.63	-.046	.46	.44
110	-.043	.45	.54	-.046	.46	.38
125	-.044	.46	.50	-.046	.47	.35
140	-.044	.46	.47	-.046	.47	.36

for all models. Km decreases with depth on both plots for all models. At the shallower depths, the θ methods give higher estimates of Km than the W methods (e.g. 35cm. Compare Table 2 vs 3, Table 4 vs. 5). The opposite is true deeper in the profile (e.g. compare tables 2 vs. 3, Tables 4 vs. 5 at 125 cm), so results of the W methods show less variability in Km through the profile than θ method results. The W methods gave higher r^2 results in the lower part of the profile, particularly in plot B (Compare r^2 in Table 2 vs. 3, Table 4 vs. 5). This reflects the improvement in K(θ) predictions which result from considering changes in profile storage, rather than changes in water content at one given depth.

The CGA model uses the same regression variables as the Watson W Lax algorithm model, so r^2 results for Table 6 are the same as in Table 3. The CGA method may therefore be considered another W based approach. Km data given by the CGA method are generally higher than for the Lax algorithm models (Compare Km results in Table 6 vs. Tables 2,3,4 and 5) particularly deeper in the profile, and show the same degree of variability within the profiles as the Lax W models (Tables 3 and 5). The Lax θ model (Davidson equation) estimate of Km on plot A at 35 cm (Table 4, 4.35 cm/min) was the highest given by any model on either plot at any depth, and is probably unreasonable.

Laboratory Results

Saturated and unsaturated hydraulic conductivities determined by direct measurement for 15 - 30, 60 - 75, 90 -105, and 120 - 135 cm depths are presented in Table 7. Unsaturated conductivity data are missing for samples where flow was controlled by the porous plates or pads which maintained continuity of the water column through the soil sample. The reason for reduction of flow rate through these materials when under tension is not apparent, since the air entry tension was not exceeded. Tension may have caused shrinkage of cellulose pads. Means and ranges of the same conductivity data are depicted graphically in figures presented later in the text. Saturated conductivities of the samples used for Campbell's method (1974) are given in Table 8.

Saturated conductivities among all samples followed a lognormal distribution, ranging from 0.005 to 8.19 cm/min, (three orders of magnitude) with a mean of 0.35 cm/min. Unsaturated conductivities at 10 cm tension were about one order of magnitude below saturated conductivities, considering averages for each depth. Conductivities at 20 cm tension were, on the average, about one half the values at 10 cm tension (See Table 7).

Table 7. Hydraulic conductivities (cm/min) determined in the lab at 0 cm (Ks), 10 cm (K10) and 20 cm (K20) tension, presented by depth with mean conductivities and water contents for each depth and tension.

Depth cm	Sample	Ks	K10	K20
15-30	A	.048	.003	.0006
	1	.077	.053	.0130
	2	.077	.060	.0110
	3	.013	.002	.0020
	4	.140	.006	.0004
	5	.467	.004	.0018
	6	.103	.038	.0044
	7	.025	.001	---
	8	.371	.001	.0003
	9	.010	.001	.0007
	10	.445	.003	.0013
	11	.017	.002	.0060
	Mean	.149	.015	.0033
	θ cm3/cm3	.526	.424	.403

Depth cm	Sample	Ks	K10	K20
60-75	1	.032	---	---
	2	.046	---	---
	3	.010	.002	.0009
	4	.015	.001	.0004
	5	.010	---	---
	6	.007	.0005	.0004
	7	.059	.0018	.0007
	8	.031	.0008	.0006
	9	.072	.001	.0006
	10	.052	.001	.0007
	11	.099	---	---
	Mean	.039	.0012	.0006
	θ cm3/cm3	.489	.437	.394

--- flow controlled by porous plate or pad

Table 7, continued.

Depth cm	Sample	Ks	K10	K20
90-105	B	.033	.0270	.0090
	1	.062	.0010	.0007
	2	.035	.0020	.0014
	3	.023	.0003	.0003
	4	.005	.0003	.0002
	5	.025	.0007	.0005
	6	.008	.0015	.0011
	7	.023	.0050	.0030
	8	.063	.0004	.0003
	9	.009	.0013	.0003
	10	.049	.0026	.0013
	11	.025	.0005	.0004
	Mean	.030	.0036	.0015
	θ cm3/cm3	.535	.486	.477

Depth cm	Sample	Ks	K10	K20
120-135	1	.015	---	---
	2	.013	.0013	.0007
	3	.063	---	---
	4	.015	.0110	.0090
	5	.025	.0180	---
	6	.015	.0120	---
	7	.015	.0140	.0120
	8	.016	.0010	.0005
	9	.019	---	---
	10	.014	.0110	.0090
	11	.013	---	---
	Mean	.020	.0098	.0062
	θ cm3/cm3	.528	.507	.490

--- flow controlled by porous plate or pad

Table 8. Ks of samples used for Campbell's Method.

Depth (cm)					
35		50		80	
Sample	Ks cm/min	Sample	Ks	Sample	Ks
3	.120	1	.304	1	.037
3i	8.190	2	.088	4	1.713
4	.236	3	.297	5	.150
10	.290	4	.024	6	.016
11	.085	5	.016	8	.008
11i	3.520	6	.109	9	.280
8	.140	10	.035	10	.903
		11	.403	11	2.391
Mean	1.80		.160		.762

No conclusions can be drawn from lab data to substantiate or refute findings of Nielsen et al. (1973) relative to increases in variability of K(θ) with decreases in θ. Ranges of directly determined unsaturated conductivities were larger than saturated conductivity ranges at the 90 - 105 and 120 - 135 cm depths. The opposite was true at the 60 - 75 cm depth, and saturated and unsaturated conductivity ranges were similar at the 15 - 30 cm depth.

Desorption data used with Campbell's method (1974) are presented in Table 9. The average water contents shown for each depth were used to plot ln h (cm) versus ln (θ/θ_s). These plots are presented in Figures 3, 4, and 5 for 30 - 45, 45 - 60, and 75 - 90 cm depth, respectively. Saturated water contents were assigned to an air entry value of 10 cm and included in the regressions of the plotted data. Slopes of the plots (b) were used to calculate slopes of the ln K vs. ln

$\theta/\theta s$ (2b+3) relationship. Results are shown, with Ks averages, in Table 10. Nineteen Ks values were averaged for the 35 cm depth, as twelve values from the 15 - 30 cm depth were included with the seven values from the 30 to 45 cm depth. Eight Ks values were used to obtain averages for the 50 and 80 cm depths. Results of Campbell's method are also shown graphically for each depth in figures presented later in the text.

Table 9. Water contents used in Campbell's method (1974) with averages for each depth.

		Bars					
Depth cm	Sample	0.0	.10	.33	.50	.75	1.00
35	3	.58	.40	.33	.29	.25	.23
	3i	.59	.44	.36	.31	.27	.26
	4	.57	.38	.29	.25	.20	.19
	10	.47	.33	.27	.25	.23	.22
	11	.46	.37	.29	.26	.23	.22
	11i	.56	.34	.28	.25	.24	.23
	8	.50	.34	.27	.24	.23	.22
	Mean	.533	.372	.299	.263	.236	.223
50	1	.59	.50	.36	.33	.29	.26
	2	.60	.52	.37	.34	.30	.26
	3	.59	.51	.40	.38	.32	.28
	4	.51	.43	.37	.35	.32	.31
	5	.52	.42	.35	.34	.31	.29
	6	.61	.49	.36	.33	.30	.25
	10	.58	.43	.34	.31	.28	.25
	11	.61	.48	.32	.30	.27	.24
	Mean	.574	.473	.335	.335	.296	.267

		Bars			
Depth cm	Sample	0.0	.14	.33	1.00
80	1	.59	.48	.42	.31
	4	.57	.43	.37	.23
	5	.60	.46	.39	.24
	6	.52	.40	.30	.19
	8	.53	.40	.33	.21
	9	.47	.44	.27	.19
	10	.60	.45	.38	.25
	11	.60	.43	.35	.22
	Mean	.558	.434	.351	.229

Figure 3. Log-log plot of h vs. θ/θs for 30 - 45 cm.

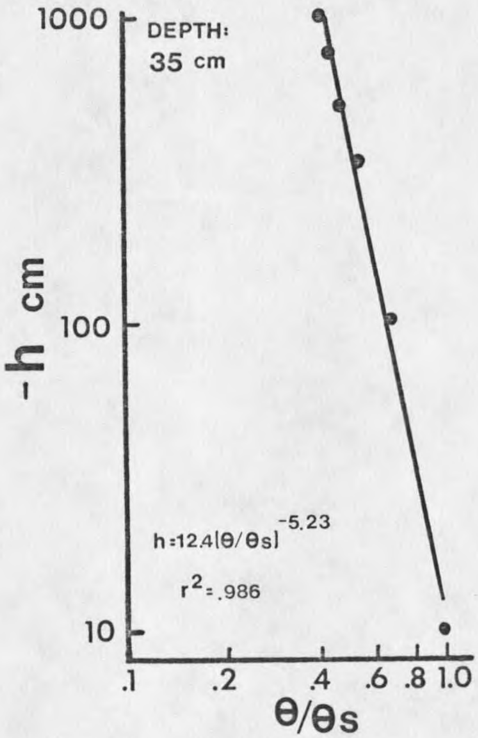


Figure 4. Log-log plot of h vs. θ/θs for 45 - 60 cm.

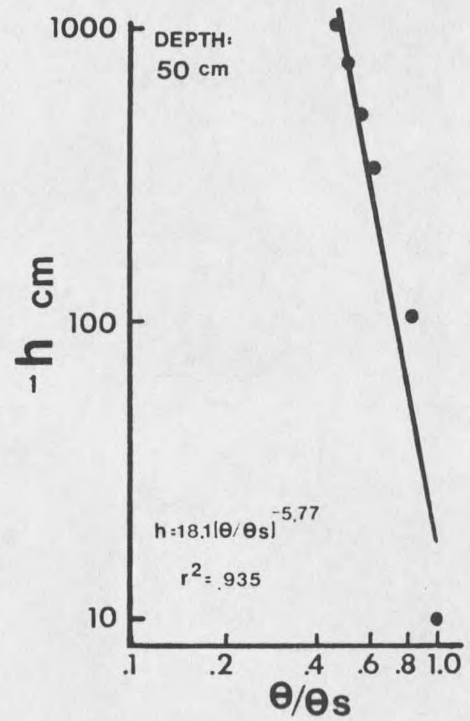


Figure 5. Log-log plot of h vs. θ/θs for 75 - 90 cm.

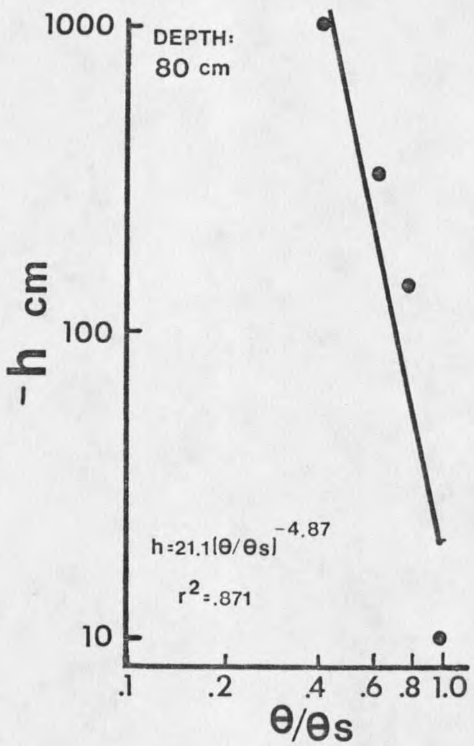


Table 10. Results for Campbell's Method.

Depth (cm)	b	2b+3	Ks	r2
35	5.23	13.46	.757*	.99
50	5.77	14.54	.160+	.94
80	4.87	12.74	.762+	.87

* Average of 19 values + Average of 8 values

Graphical Comparison of Lab and Field Results

Comparisons of laboratory and field data are presented graphically in Figures 6 through 17. Graphs are presented for both plots at depths of 35, 50, 65, 80, 95, and 125 cm. At 35 cm, results of Campbell's method and direct measurement are presented with results of unit gradient models. For this depth, the mean of the directly determined saturated conductivities and Ks for Campbell's method coincide (Figures 6 and 7). At 65, 95, and 125 cm, direct measured conductivities (averages and ranges) are depicted in the appropriate graphs (Figures 10, 11, 14, 15, 16, and 17) for comparison with field model results. At 50 cm (Figures 8 and 9) and 80 cm (Figures 12 and 13), Campbell's method is compared with the field models. The reader is reminded that $\theta/\theta s$ and $\theta/\theta m$ have been placed on the same scale in these figures to facilitate comparisons. The range of $\theta/\theta m$ shown covers the range of water contents observed during the field drainage trials. Note that there are two figures for each depth, because there are two sets of field data (Plots A and B) for each depth. Lab data presentation is repeated in each pair of figures (Figures 6 and 7, 8 and 9, and so on.)

At 35 cm (Figures 6 and 7), Km estimates of the models follow the order Davidson θ > CGA = Watson θ > Davidson W > Watson W, an order repeated at 50 cm (Figures 8 and 9). At 65 cm and below (Figures 10 through 17), the model estimates of Km follow the order CGA > Davidson W > Watson W > Davidson θ > Watson θ. Over most of the range of water contents, particularly at lower depths, the CGA method gives the greatest K(θ) estimates, and the W methods give the most conservative estimates. This is similar to findings of Jones and Wagenet (1984).

Lab determined Ks data tend to be less than model estimates of Km. This tendency is strongest at the 65, 95, and 125 cm depths (Figures 10 and 11, 14 and 15, 16 and 17). At 35 cm, the range of 20 Ks values includes Km estimates given by all five field models (Figures 6 and 7). Unsaturated conductivity values obtained by direct measurement were greater than unit gradient model estimates at 35 cm. The opposite was true at the greater depths, where directly measured values were less than field model estimates of K(θ) (Figures 8 through 17).

Slopes of K(θ) curves as estimated by Campbell's method were less than slopes given by the models at the three depths (35, 50, and 80 cm) where Campbell's method was tried (see Figures 6, 7, 8, 9, 12, and 13). Therefore Campbell's method generally gives greater estimates of K(θ) than the field models. This is particularly true at 35 and 80 cm (Figures 6, 7, 12, and 13). A lower Ks estimate mitigates the influence of slope difference at 50 cm (Figures 8 and 9).

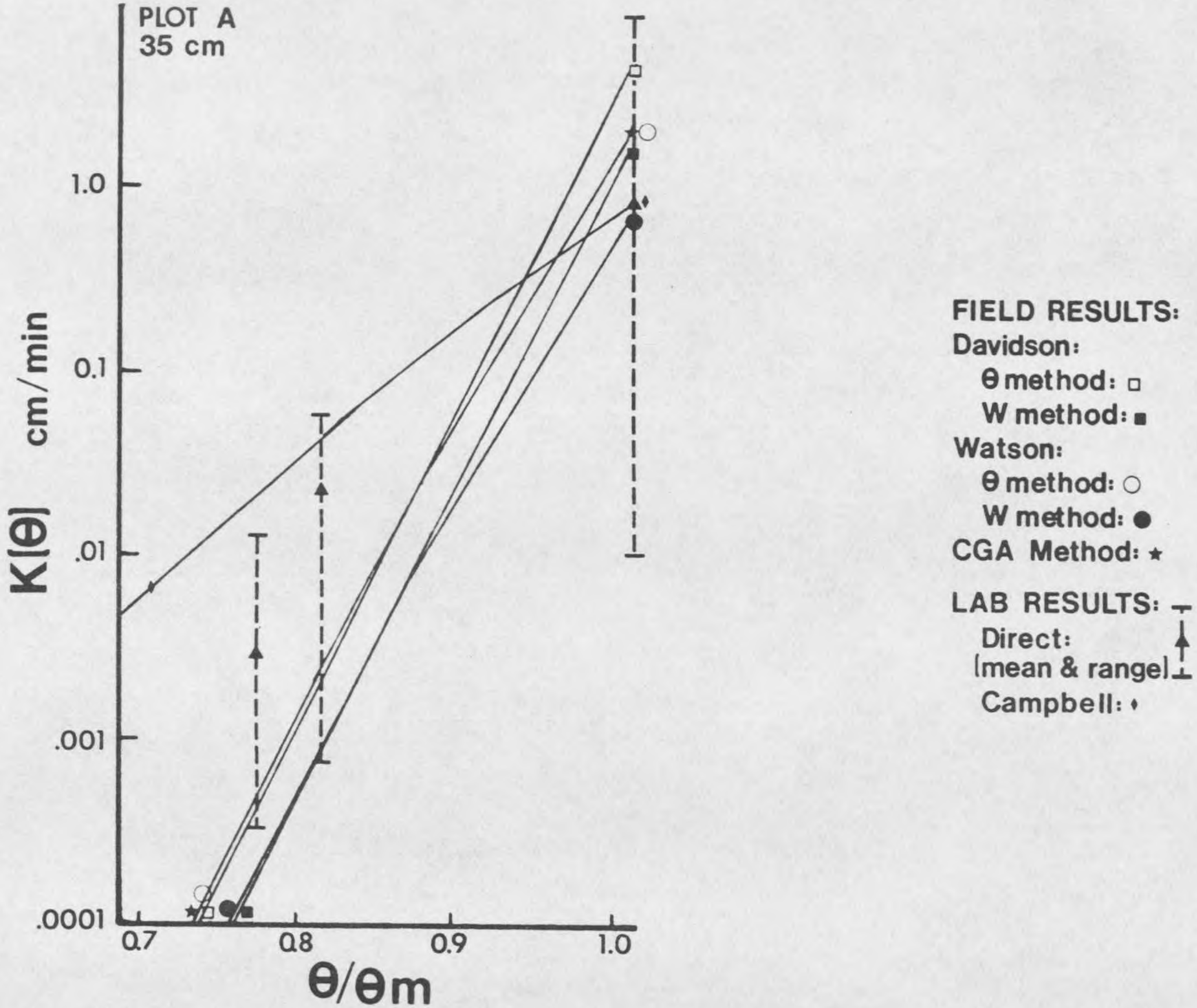


Figure 6. Lab and Field Conductivities, plot A, 35 cm

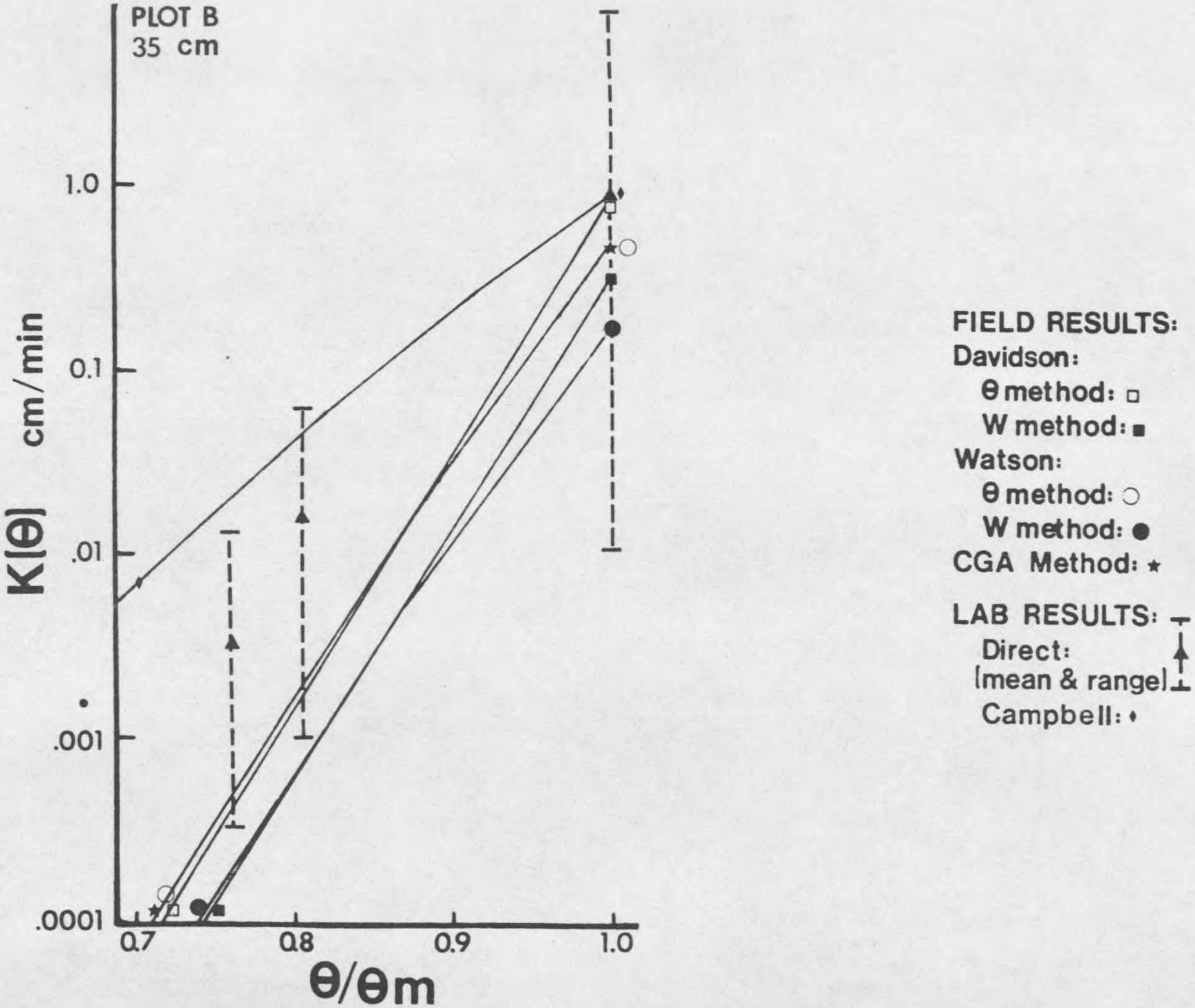


Figure 7. Lab and Field Conductivities, plot B, 35 cm

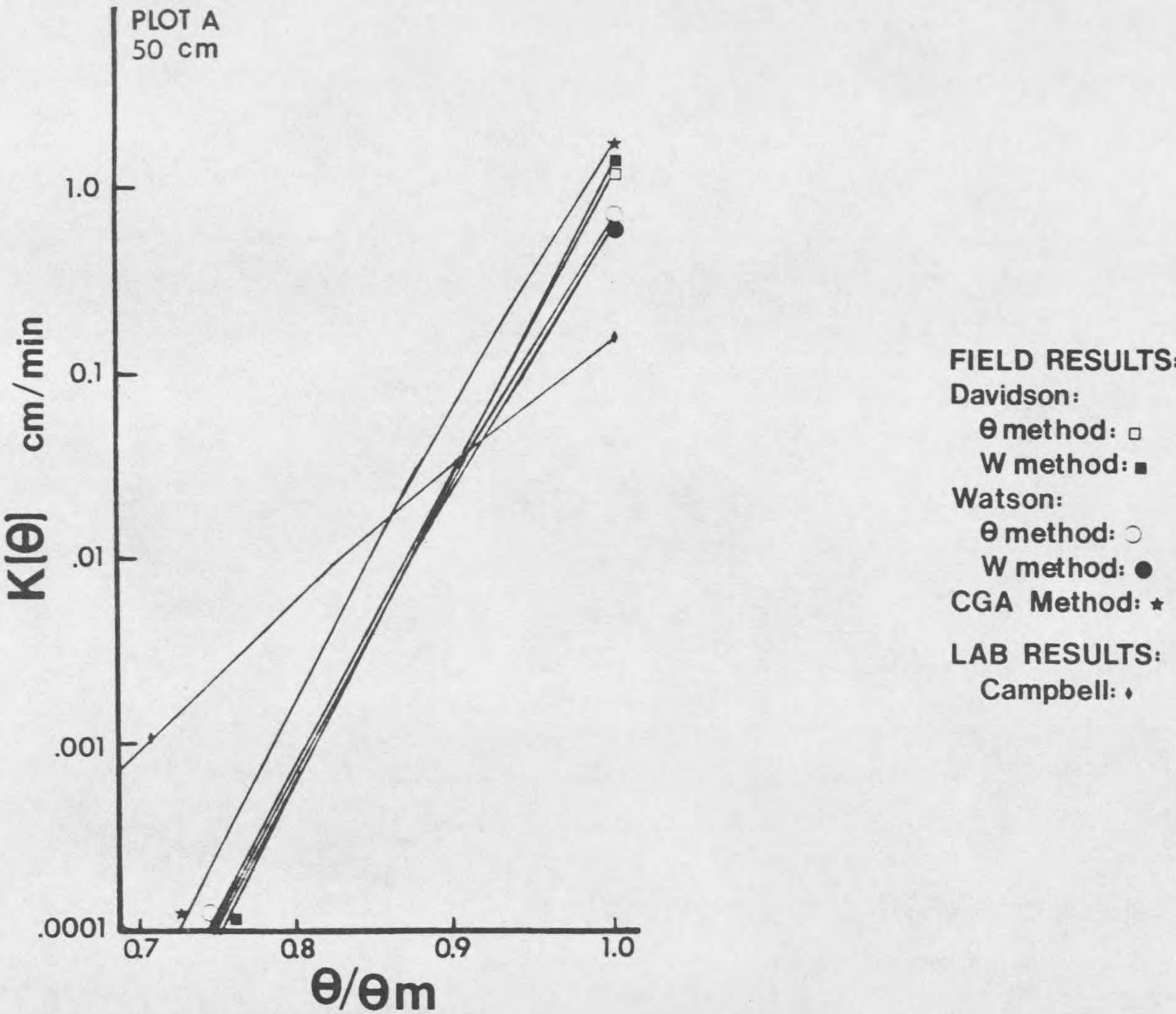


Figure 8. Lab and Field Conductivities, plot A, 50 cm

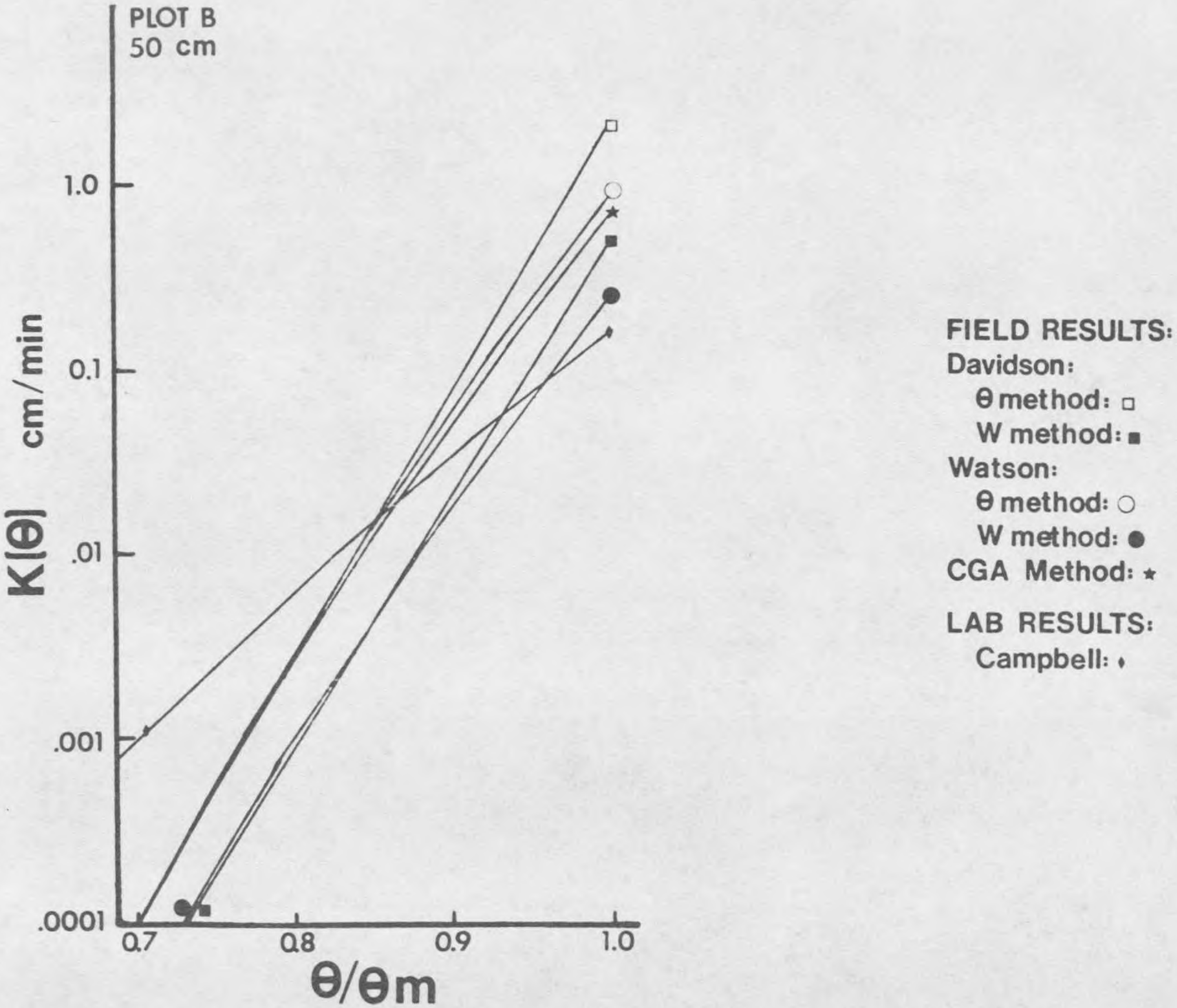


Figure 9. Lab and Field Conductivities, plot B, 50 cm

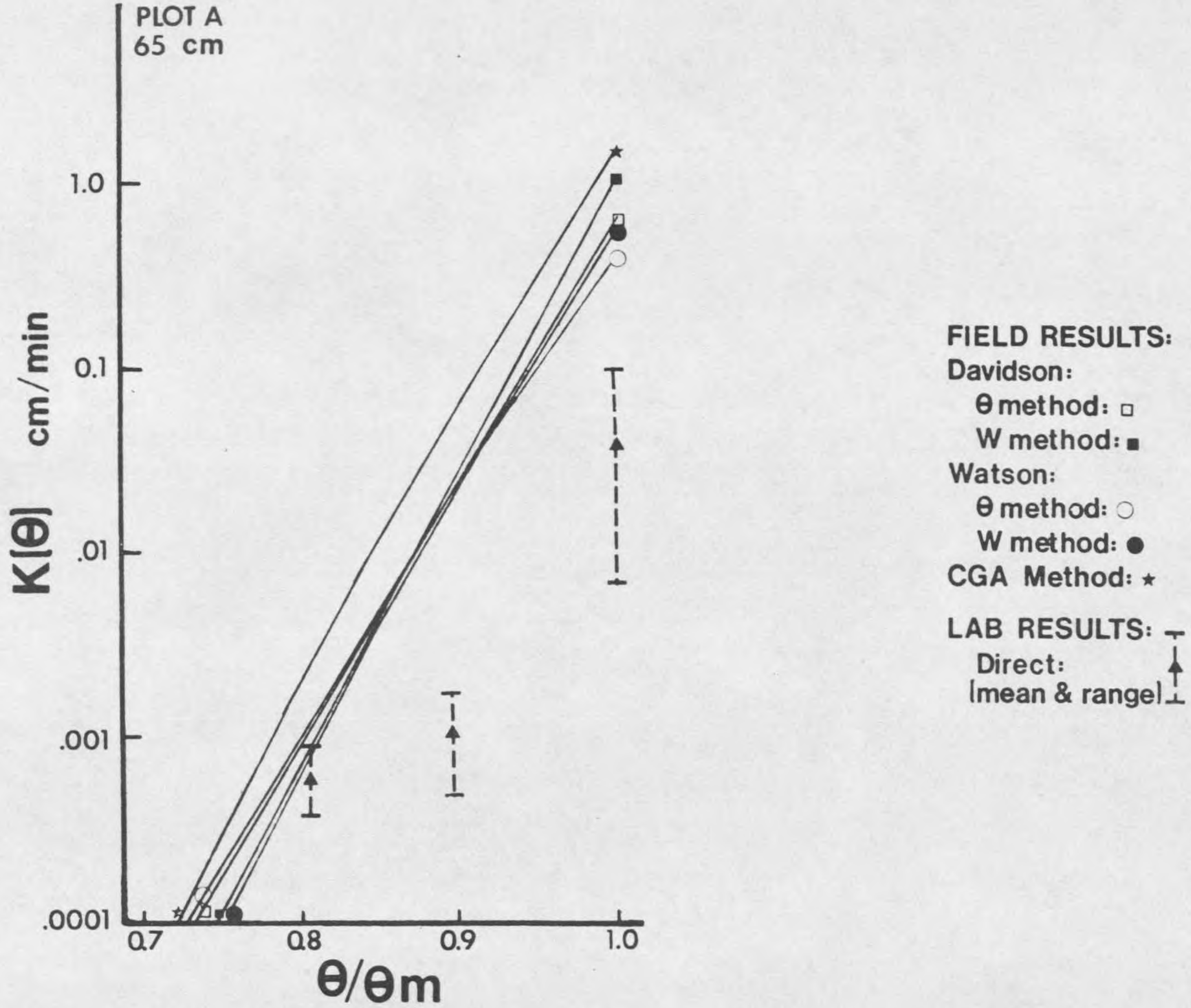


Figure 10. Lab and Field Conductivities, plotA, 65 cm

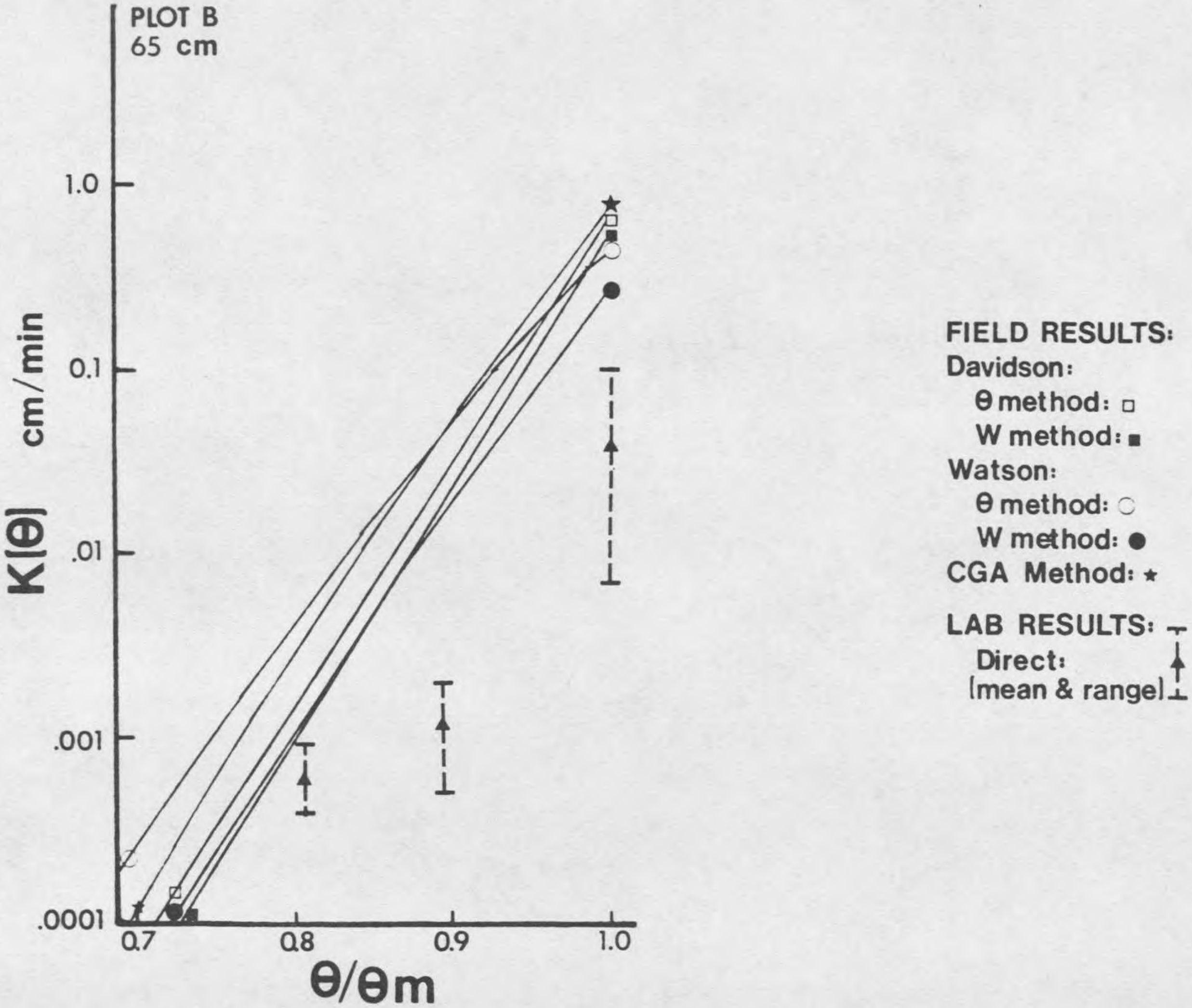


Figure 11. Lab and Field Conductivities, plot B, 65 cm

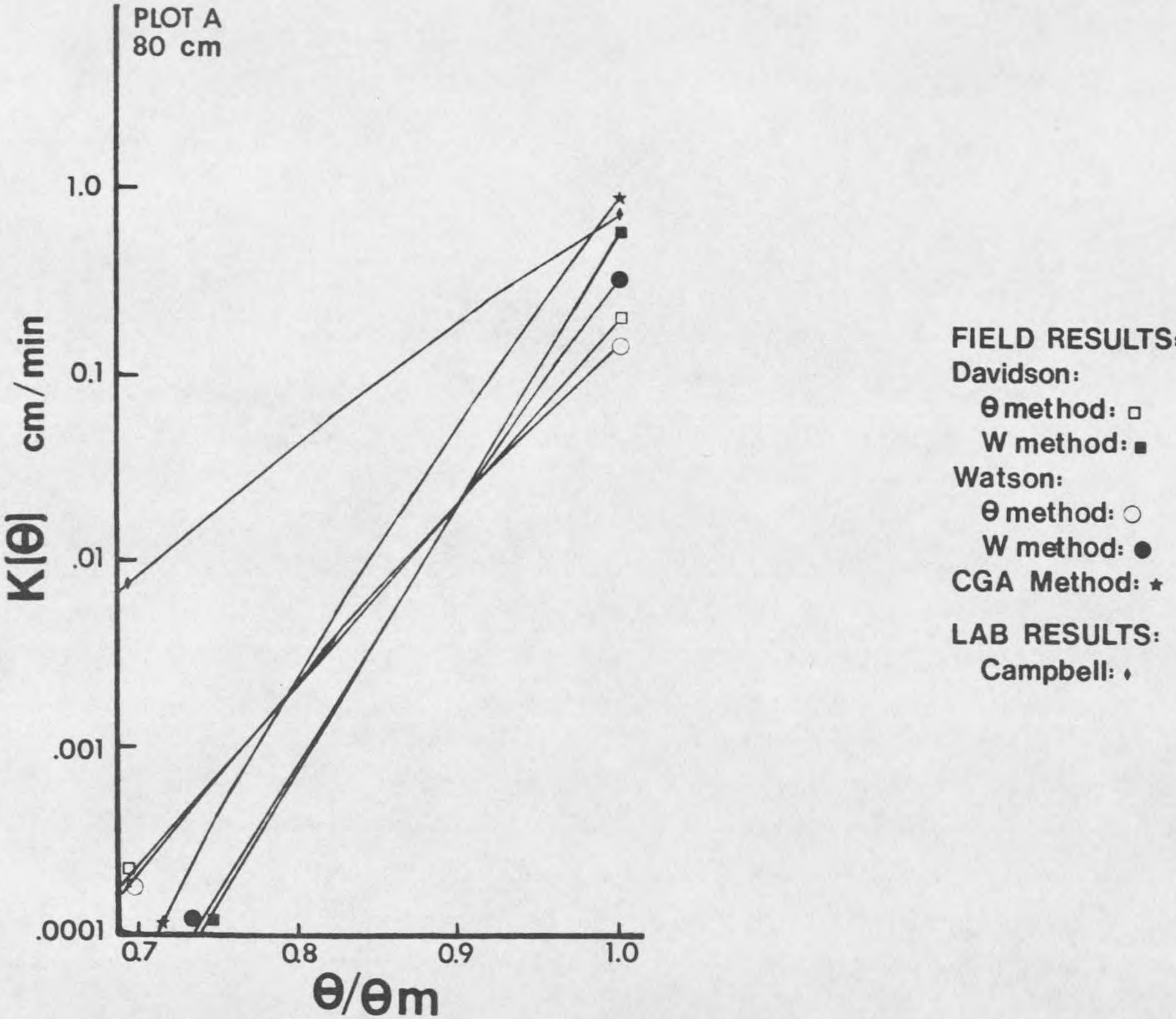


Figure 12. Lab and Field Conductivities, plot A, 80 cm

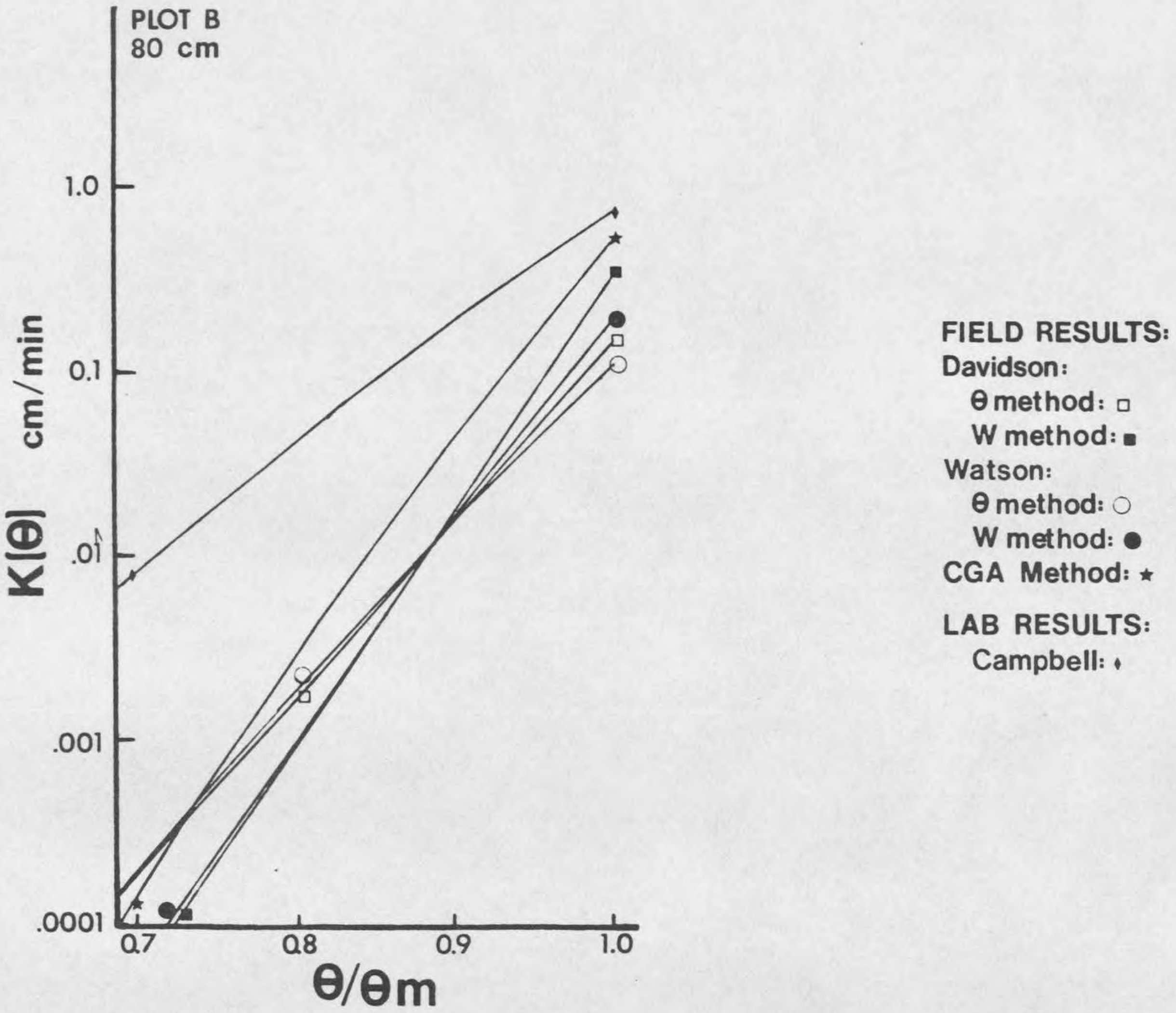


Figure 13. Lab and Field Conductivities, plot B, 80 cm

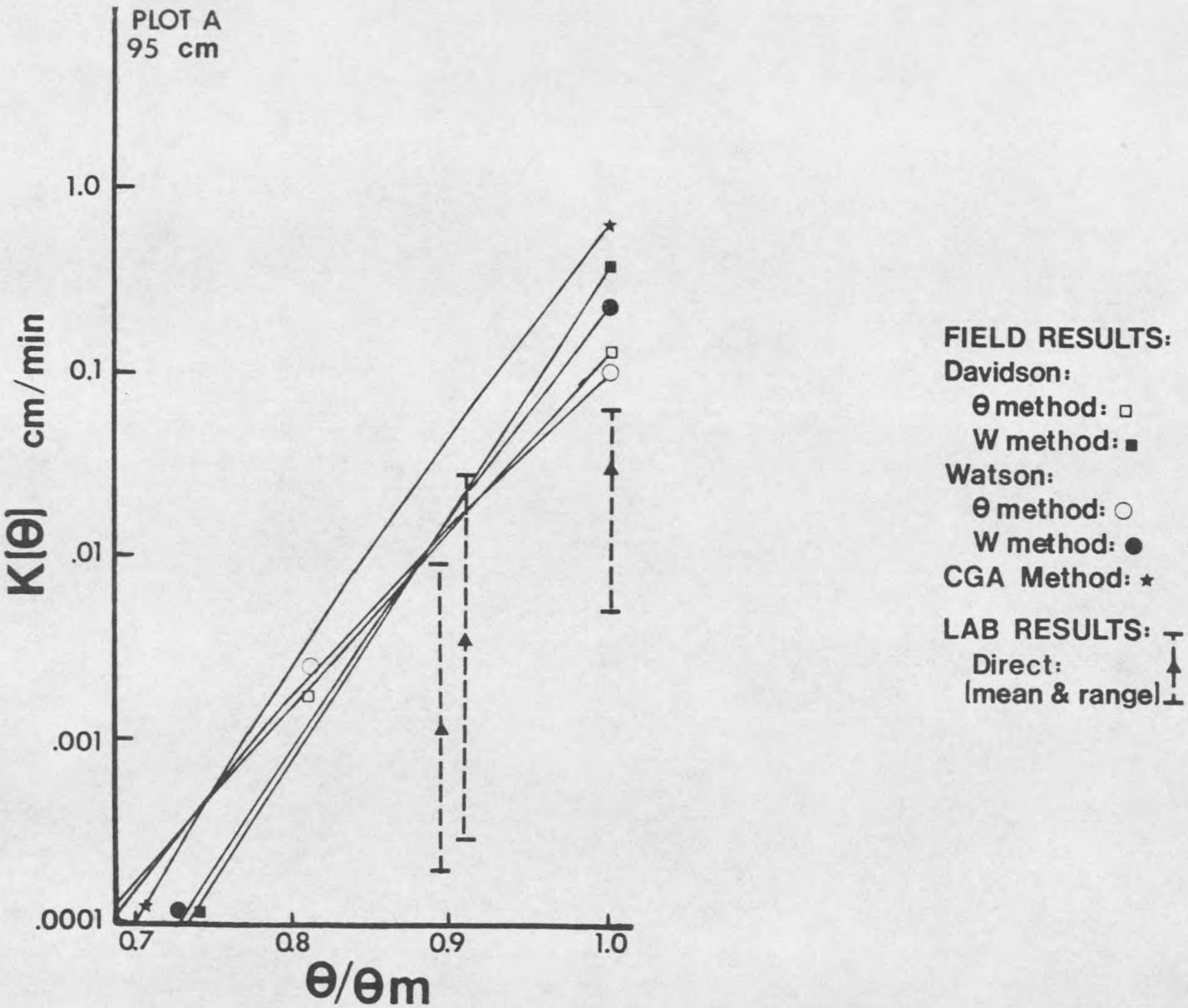


Figure 14. Lab and Field Conductivities, plot A, 95 cm

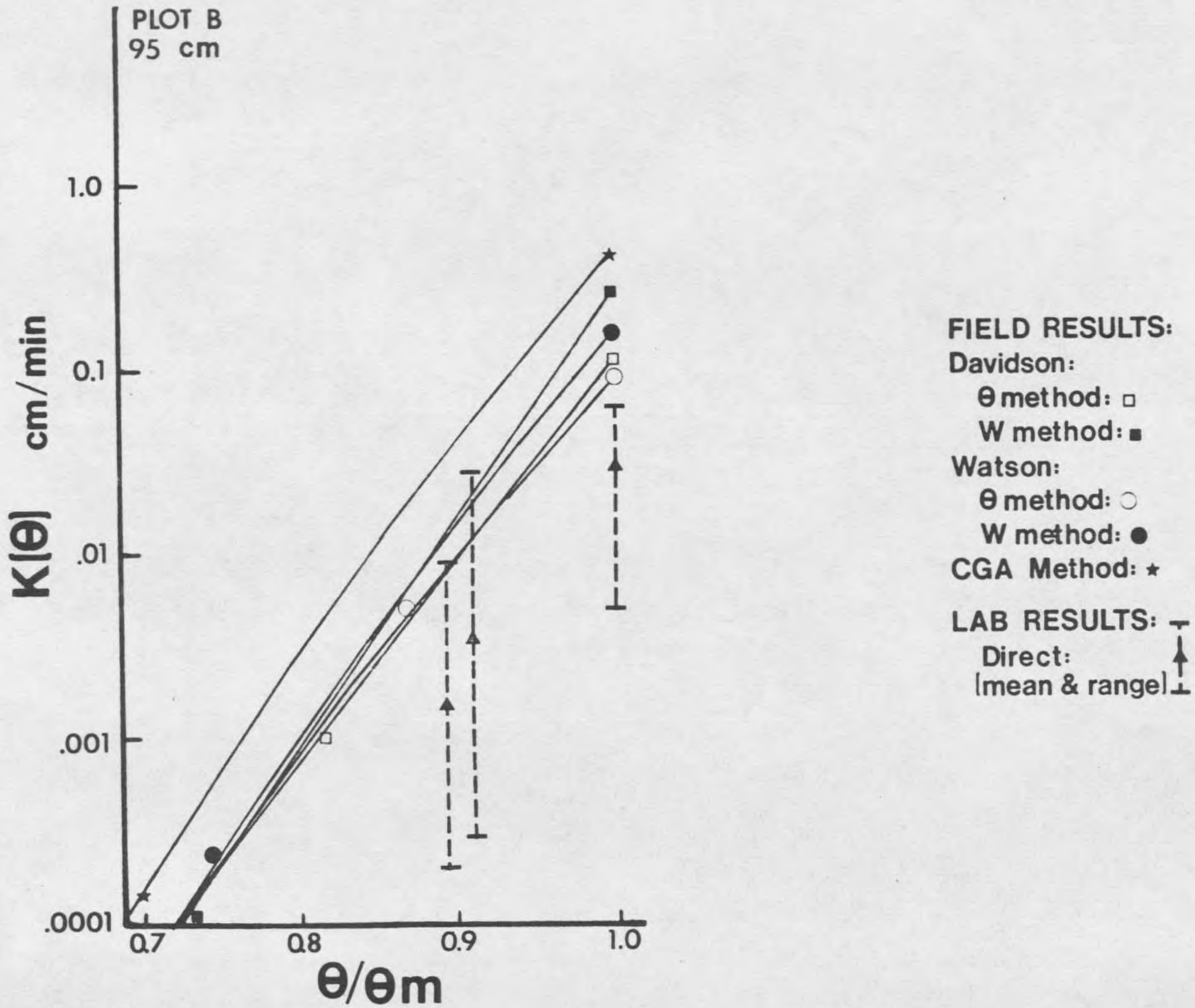


Figure 15. Lab and Field Conductivities, plot B, 95 cm

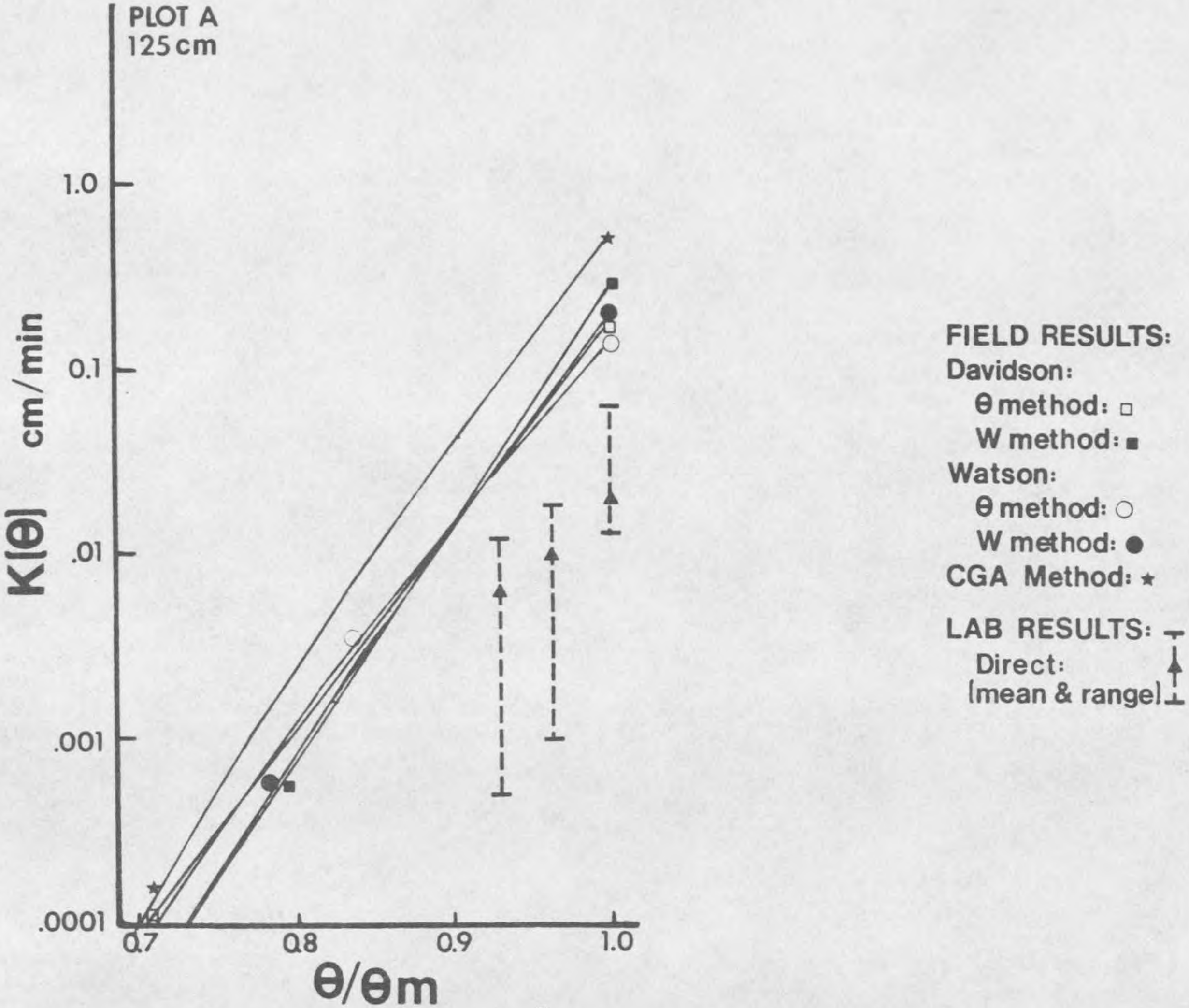


Figure 16. Lab and Field Conductivities, plot A, 125 cm

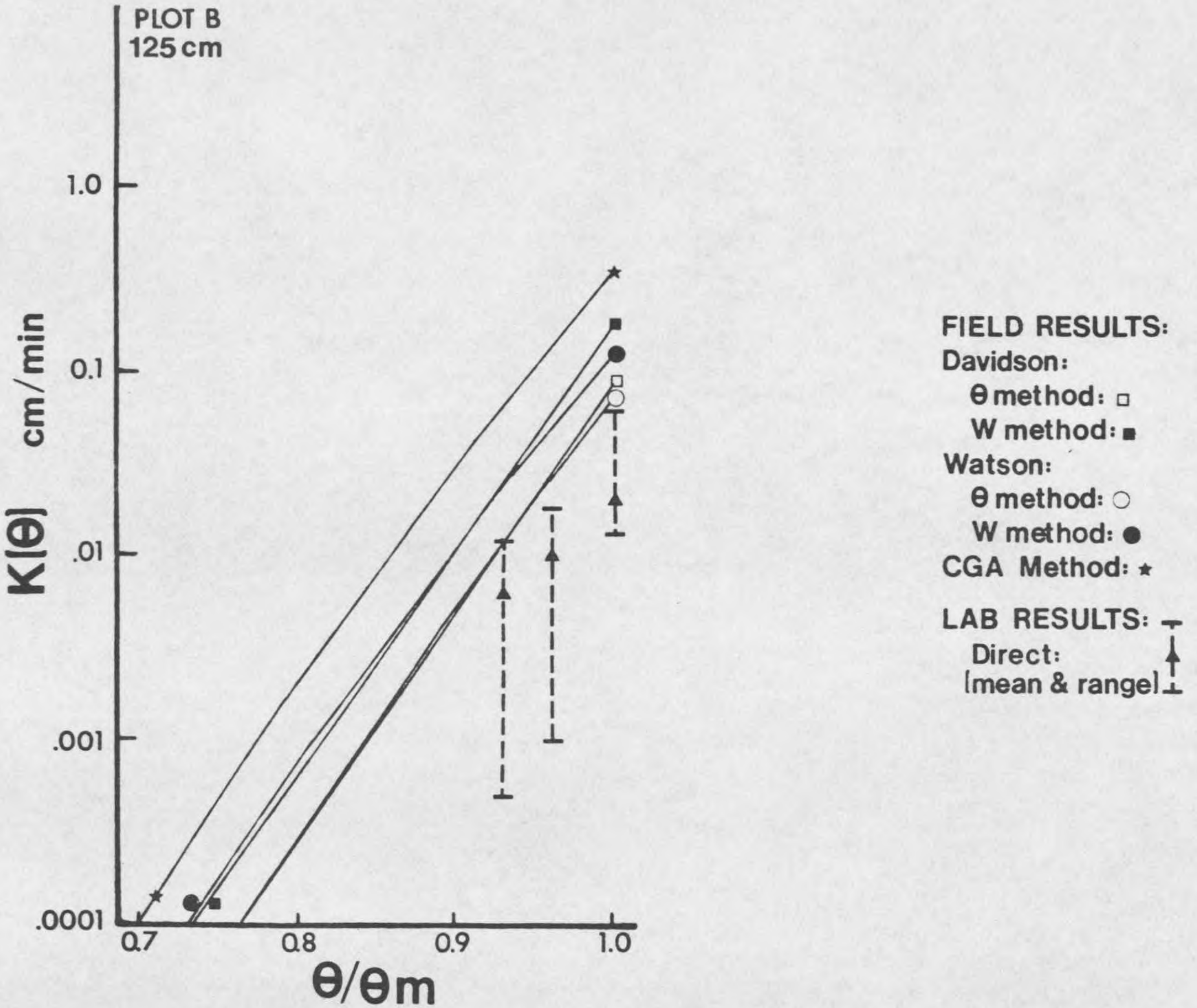


Figure 17. Lab and Field Conductivities, plot B, 125 cm

Discussion

Field models generally gave estimates of K(θ) different from direct measurement and Campbell's method. In fact, model estimates of K(θ) were generally in closer agreement with each other than with laboratory results. This discussion will therefore focus on possible causes of inconsistencies between methods.

Direct measurement results show smaller hydraulic conductivities, on the average, than field results. Although compaction of core samples would cause this, the author feels this an unlikely explanation. Bulk density data collected during neutron probe calibration did not show compaction problems with the Giddings sampler, since few samples showed densities over 1.33 g/cm3. Another explanation would be lateral movement of water during field trials, particularly during early times of drainage. This would lead to more rapid decreases in water content than if lateral movement did not occur, would violate assumptions inherent to the use of unit gradient models, and lead to high estimates of Km. Although the author again feels this is an unlikely explanation, it is a possible scenario which would result in the observed differences between lab and field data.

The reason for smaller lab values probably lies in the log normal distribution of hydraulic conductivity. If a population parameter is lognormally distributed, 95 percent of that population may exhibit parameter values which are less than the mean. Therefore, using a small sample size to calculate an estimate of that mean will generally result in an underestimate. Because of the relatively large volume of soil sampled by a neutron probe, results of such measurements should be more representative than measurements on smaller volume samples, such as cores. If this is true, then core measurements would again be expected to show smaller conductivities, given a lognormal distribution. The overall average of 69 Ks measurements performed on core samples (0.35 cm/min) is within the range of Km estimates given by the field models. This shows that model estimates of Km are reasonable, and that a large sample size is needed to accurately estimate the mean.

Results of Campbell's method (1974) show lower slopes in $K(\theta)$ relationships at 35, 50, and 80 cm than the field unit gradient models. Therefore field model conductivity estimates decrease more rapidly with decreases in water content than estimates obtained using Campbell's method. Campbell's method uses a direct substitution of a modification of the capillary rise equation (Eq. [10]) into Eq. [12], in effect treating the soil as a bundle of capillary tubes. This, along with Eq. [15], neglects the influence hysteresis has on any relationship between pore size distribution and moisture characteristic curves. A consideration of bottle neck pores by the reader will demonstrate this influence. A sorption curve would tend to have a steeper slope than a desorption curve; therefore, Campbell's method may give a steeper slope for $K(\theta)$ with sorption data. Also, a randon distribution of pores, assumed by most pore size distribution models, may be questionable for undisturbed cores. It is questions such as these which lead the author to question Campbell's method in this case.

CONCLUSIONS

1. This study did not show superior capability for prediction of K(θ) in any of the tested models. Large variability of saturated hydraulic conductivities among lab samples (undisturbed cores) indicates that: a) soil hydraulic properties are highly variable even within small plots, and b) accurate testing of unit gradient models in the field may not be feasible.

2. Field model results substantiated findings of Jones and Wagenet (1984), that magnitude of K(θ) estimates follow the order CGA > Lax θ methods > Lax W methods. The CGA and W methods offer the advantage of being based on measurements of profile storage rather than water contents at a single depth. Regression of ln W/z vs. ln t should be the first choice in the analysis of field data, because both the CGA and Lax W (Watson equation) models may be applied to results, and a range of values may then be reported from a single data handling procedure.

3. The average of 69 measurements of Ks performed in the lab was 0.35 cm/min. This was within the same order of magnitude of model estimates of Km, indicating that the models give a reasonable estimate of maximum hydraulic conductivity.

4. A satisfactory method of encasing undisturbed soil cores was developed in this study. Good desorption curves and Ks data were obtained from measurements on undisturbed cores in the lab. This core sampling technique should be useful for obtaining samples from deep in the profile, where in situ studies are not possible. In deeper systems, many factors contributing to variability of $K(\theta)$, such as structural development, plant roots, and faunal activity are not prevalent. Therefore use of cores for estimation of $K(\theta)$ may be most reasonable in deep soil systems.

REFERENCES CITED

REFERENCES CITED

Ahuja, L.R., R.E. Green, S.K. Chong, and D.R. Nielsen. 1980. A simplified functions approach for determining soil hydraulic conductivities and water characteristics in situ. Water Resources Res. 16: 947 - 953.

Anderson, J.L. and J. Bouma. 1977. Water movement through pedal soils: II. Unsaturated Flow. Soil Sci. Soc. Am. J 41: 419-423.

Arya, L.M., D.A. Farrell, and G.R. Blake. 1975. A field study of soil water depletion patterns in the presence of growing soybean roots: I. Determination of hydraulic properties of the soil. Soil Sci. Soc. Sci. Proc. 39: 424-430.

Baker, F.G., P.L.M. Veneman, and J. Bouma. 1974. Limitations of the instantaneous profile method for field measurement of unsaturated hydraulic conductivity. Soil Sci. Soc. Am. Proc. 38: 885-888.

Bevin, K., and P Germann. 1982. Macropores and water flow in soils. Water Resources Res. 18(5): 1311-1325.

Black, C.A.(ed). 1965. Methods of Soil Analysis, Part 1. Am. Soc. Agron., Madison, WI pp. 210-221, 253-261.

Black, T.A., W.R. Gardner, and G.W. Thurtell. 1969. The prediction of evaporation, drainage, and soil water storage for a bare soil. Soil Sci. Soc. Sci. Proc. 33: 655-660.

Bouma., J. 1973. Use of physical methods to expand soil survey interpretations of soil drainage conditions. Soil Sci. Soc. Am. J 37: 413-421.

Bouma, J., D. Hillel, F.D. Hole, and C.R. American. 1971. Field measurement of unsaturated hydraulic conductivity by infiltration through artificial crusts. Soil Sci. Soc. Am. Proc. 35: 362-364.

Bruce, R.R. 1972. Hydraulic conductivity evaluation of the soil profile from soil water retention relations. Soil Sci. Soc. Am. Proc. 36: 555-561.

Brust, K.J., C.H.M. VanBavel, and G.B. Stirk. 1968. Hydraulic properties of a clay loam soil and the field measurement of water uptake by roots: III. Comparison of field and laboratory data on retention and of measured and calculated conductivities. Soil Sci. Soc. Am. Proc. 32: 322-326.

Campbell, G.S. 1974. A simple method for determining unsaturated conductivity from moisture retention data. Soil Sci. 117(6): 311-314.

Cassel, D.K. 1974. In situ unsaturated soil hydraulic conductivity for selected North Dakota soils. N. Dakota St. Univ. Ag. Exp. Stn. Bull. no. 494. Fargo, ND 20 pp.

Childs, E.C. 1969. An Introduction to the Physical Basis of Soil Water Phenomena. Wiley (Interscience), New York.

Childs, E.C. and N. Collis-George. 1950. The permeability of porous materials. Proc. Royal Soc. London 201A: 392-405.

Chong, S., R.E. Green, and L.R. Ahuja. 1981. Simple in situ determination of hydraulic conductivity by power function descriptions of drainage. Water Resources Res. 17: 1109-1114.

Dane, J.H. 1980. Comparison of field and laboratory determined hydraulic conductivity models. Soil Sci. Soc. Am. J 44: 228-231.

Davidson, J.M., L.R. Stone, D.R. Nielsen, and M.E. LaRue. 1969. Field measurement and use of soil water properties. Water Resources Res. 5: 1312-1321.

Gardner, W.R. 1970. Field measurement of soil water diffusivity. Soil Sci. Soc. Am. Proc. 34: 832-833.

Green, R.E. and J.C. Corey. 1971. Calculation of hydraulic conductivity, a further evaluation of some predictive methods. Soil Sci. Soc. Am. Proc. 35: 3-8.

Hillel, D. 1971. Soil and Water: Physical principles and processes. Academic Press, New York.

Hillel, D. 1982. Introduction to Soil Physics. Academic Press, New York. 365pp.

Hillel, D. and W.R. Gardner. 1970. Measurement of unsaturated conductivity and diffusivity by infiltration through an impeding layer. Soil Sci. 109: 149-153.

Hillel, D. and W.R. Gardner. 1969. Steady infiltration into crust-topped profiles. Soil Sci. 108: 137-142.

Hillel, D., V.D. Krentos, and Y Stylianou. 1972. Procedure and test of an internal drainage method for measuring soil hydraulic characteristics in situ. Soil Sci. 114: 395-400.

Jackson, R.D. 1972. On the calculation of hydraulic conductivity. Soil Sci. Soc. Am. Proc. 36: 380-382.

Jones, A.J. and R.J. Wagenet. 1984. In situ estimation of hydraulic conductivity using simplified methods. Soil Sci. Soc. Am. J. Submitted for publication.

Klute, A. 1972. The determination of the hydraulic conductivity and diffusivity of unsaturated soils. Soil Sci. 113: 264-276.

Kunze, R.J., G. Uehana, and K Graham. 1968. Factors important in the calculation of hydraulic conductivity. Soil Sci. Soc. Am. Proc. 32: 760-765.

LaRochelle, P., J. Sarrailh, F. Tavenas, M. Roy, and S. Leroueil. 1981. Causes of sampling disturbance and design of a new sampler for sensitive soils. Can. Geotech. J. 18:52-66.

LaRue, M.E., D.R. Nielsen, and R.M. Hagan. 1968. Soil water flux below a ryegrass root zone. Agron. J 60: 625-629.

Libardi, P.L., K. Reichardt, D.R. Nielsen, and J.W. Biggar. 1980. Simple field methods for estimating soil hydraulic conductivity. Soil Sci. Soc. Am. J 44: 3-7.

Lund, R.E. 1979. A user's guide to MSUSTAT, an interactive statistical analysis package. Tech. Rep., Dept. Math. Sci. Stat. Center. Montana State University, Bozeman.

Luxmoore, R.J., T. Grizzard, and M.R. Patterson. 1981. Hydraulic properties of Fullerton cherty silt loam. Soil Sci. Soc. Am J 45: 692-698.

Marshall, T.J. 1958. A relation between permeability and size distribution of pores. J. Soil Sci. 9(1): 1-8.

Millington, R.J. and J.P. Quirk. 1961. Permeability of porous solids. Faraday Soc. Trans. 57: 1200-1207.

Nielsen, D.R., J.M. Davidson, J.W. Biggar, and R.J. Miller. 1964. Water movement through Panoche clay loam soil. Hilgardia 35(7): 491-506.

Nielsen, D.R., J.W. Biggar, and K.T. Erb. 1973. Spatial variability of field measured soil water properties. Hilgardia 42: 215-259.

Noel, R.D. 1982. A Premining Soil Water Drainage Study on a Natural Soil. M.S. Thesis, Mont. St. Univ., Bozeman. 73pp.

Ogata, G. and L.A. Richards. 1957. Water content changes following irrigation of bare field soil that is protected from evaporation. Soil Sci. Soc. Am. Proc. 21: 355-356.

Richards, L.A., W.R. Gardner, and G. Ogata. 1956. Physical processes determinimg water loss from soil. Soil Sci. Soc. Am. Proc. 20: 310-314.

Rose, C. W. and W. R. Stern. 1965. The drainage component of the water balance equation. Aust. J Soil Res. 3: 95-100.

Rose, C.W., W.R. Stern, and J.E. Drummond. 1965. Determination of hydraulic conductivity as a function of depth and water content for soil in situ. Aust. J Soil Res. 3: 1-9.

Schuh, W.M., J.W. Bauder, and S.C. Gupta. 1984. Evaluation of simplified methods for determining unsaturated hydraulic conductivity of layered soils. Soil Sci. Soc. Am. J 48: 730-736.

Sisson, J.B. 1972. Hydraulic properties of the Gerber soil. M.S. Thesis. Montana State University, Bozeman, Montana. 79 pp.

Sisson, J.B., A.H. Ferguson, and M.Th. van Genuchten. 1980. Simple method for predicting drainage from field plots. Soil Sci. Soc. Am. J. 44:1147-1152.

Thomas, G.W. and R.E. Phillips. 1979. Consequences of water movement in macropores. J Env. Qual. 8(2): 149-152.

Topp, G.C. 1971. Soil water hysteresis in silt loam and clay loam soils. Water Resources Res. 7(4): 914-920.

VanBavel, C.H.M., G.B. Stirk, and K.J. Brust. 1968. Hydraulic properties of a clay loam soil and the field measurement of water uptake by roots: I. Interpretation of water content and pressure profiles. Soil Sci. Soc. Am. Proc. 32: 310-317.

Watson, K.K. 1966. An instantaneous profile method for determining the hydraulic conductivity of unsaturated porous materials. Water Resources Res. 2(4): 709-715.

Watson, K.K. 1967. The measurement of the hydraulic conductivity of unstaurated porous materials utilizing a zone of entrapped air. Soil Sci. Soc. Am. Proc. 32: 716-720.

APPENDICES

APPENDIX A

DATA HANDLING PROCEDURE

This section explains the procedure followed for conversion of drainage data to the variables used in the linear regression for each of the models. Recommendations for the regression procedure and equations for calculation of K(θ) are included. The water contents observed during drainage, and the time in hours past initiation of drainage, are presented in Tables 11 and 12 for plots A and B, respectively. These tables serve as examples of input file format. The first line gives data sets in the file (001), the number of drainage readings (050 for plot A, 043 for plot B), and the number of depths (014 for plot A, 010 for plot B). Reading across each succeeding line, the first three digits give the set of data, and the position in the sequence of drainage readings. For example, 110 specifies the tenth reading on the first set of data. The water content readings (cm3/cm3) follow, beginning with the uppermost reading, and proceeding down through the profile. The last number gives the time into drainage, in hours, at which the preceding water contents were read. The format shown for the placement of the decimal posnts must ve repeated, or line 12 in the program described below must be changed to reflect any new format.

The Fortran program DATGEN, shown in Figure 18, takes the input from the drainage data files, and converts the water content data to regression data used in the models. Meanings of symbols used in the program are:

ND - number of depths read

K - counting variable, varies from 1 to ND

NT - number of times the profile was read during drainage

J - counting variable, varies from 1 to NT

WC - water content (input data)

SUMWC - sum of water contents

Z - depth in the profile (cm)

W - depth of water present in the profile above a given depth at a given time

S - average water content above a given depth at a given time, W/Z

The number of depths and times are established in the first three lines of the program. These should be changed to suit a given set of input data. In lines 4 through 6, spaces are reserved for ND depths (cm), ND SUMWC's (a temporary dummy variable), NT times (hours), and three ND by NT matrices for WC, W, and S. Line 7 reserves spaces for the output data. Line 8 reads the first line (nine digits) of the input file. Line 9 sets the first depth in cm; 35 cm in this study, 30 cm for most field data collected with a neutron probe.

Lines 10 through 25 are a loop repeated NT times, in which the WC input data are summed and averaged in two nested loops. Line 11 reads a line of input data, assigning it to the appropriatespaces in the WC matrix established in line 6. The user must set the input file to 25 before running this program. (Type: {SET INFILENAME TO 25} before running DATGEN.) Lines 13 through 17 fill the SUMWC "dummy" variable slots; a small loop (lines 15 through 17) facilitates the summation. Lines 18 through 24 convert the dummy variables to W and S. Lines 18 and 19 do this for the first depth. (Make sure SUMWC(1) is multiplied by the correct depth in line 18.) The loop contained in lines 20 through 24 performs the conversions for subsequent depths, which must be at constant intervals. (If this interval is not 15 cm, change the "15" in lines 21 and 22 to the interval in cm which applies.) The W and S data are automatically saved and placed in the matrices reserved in line 6.

Lines 26 through 34 calculate the output (regression) data, and write them onto the output file, which should be set to 9 (line 32). (Type: {SET OUTFILENAME TO 9} before running DATGEN.) The output file will have six columns; in order they are K and J (combined in the first column), ln(θ/θm) (Y1), θm-θ (Y2), and W/z (Y4) (the four dependent variables), followed by ln t (independent variable, with t in minutes), and time in hours in the sixth column. Move the output file from the CP6 to the Discovery system, and fill the blank spaces in the first column with zeros (lines one through nine for each depth).

The MSUSTAT program MREGRESS (Lund, 1979) can be used to run all the regressions. One data conversion will be needed, from W/z to ln W/z, in order to run the regression for the Lax W (Watson equation) model. First, run the regressions on the data already in the file. Have variables two through five analyzed, and specify NT as the number of cases to be read. Variable five will always be the independent variable; run three separate regressions with vareables two, three and four being dependent. Type {RESTART} after running the first two regressions. After the third regression, begin the program over again, and make the transformation. The transformation command will be 0104040001 (see Lund, 1979). Variables four and five are the only ones to be analyzed in this fourth regression. After the regressions for the first depth are completed, use WORDSTAR to move the regression data for the first depth to the bottom of the file. Then repeat the regression procedure for the second and succeeding depths.

Calculation of K(θ) (cm/min) is shown below, where M is the slope, and I is the intercept given by regression results. Table 1 in the text shows which regressions apply to each model.

Lax algorithm model equations:

Watson (1967) equation:

$$K(\theta) = Km\ (\theta/\theta m)^{**}1/\beta \qquad [32]$$

$$\beta = M/(M-1) \qquad [57]$$

θ method:

$$Km = \beta z(\theta m)(\exp(I/M)) \qquad [58]$$

W method:

$$Km = \beta z(\theta m)((\exp\ I)/(1-\beta)\theta m)^{**}(1/M) \qquad [59]$$

Davidson et al. (1969) equation:

$$K(\theta) = Km\ (\exp\ \alpha(\theta - \theta m)) \qquad [33]$$

θ method:

$$\alpha = 1/M \qquad [60]$$

$$Km = z/\alpha\ (\exp(I/M)) \qquad [61]$$

W method:

$$\alpha = -1/M \qquad [62]$$

$$Km = z/\alpha\ (\exp(a(\theta m-I)-1)) \qquad [63]$$

CGA model equation:

$$K(\theta) = zM(\exp\ I)(\exp(((\ln\theta/\exp\ I)/M)^{**}(M-1))) \qquad [64]$$

Table 11. Drainage data, plot A.

Table 12. Drainage data, plot B.

00104310

101	.407	.363	.376	.422	.392	.400	.391	.376	.374	.360	000.00
102	.352	.358	.363	.372	.386	.404	.392	.373	.380	.368	001.00
103	.370	.366	.387	.389	.410	.414	.409	.395	.396	.386	002.00
104	.361	.372	.382	.393	.400	.412	.413	.394	.395	.388	003.00
105	.338	.344	.349	.362	.371	.390	.377	.369	.371	.359	004.00
106	.359	.364	.382	.379	.397	.394	.406	.405	.393	.374	005.00
107	.332	.343	.348	.355	.365	.387	.384	.379	.371	.365	006.00
108	.333	.346	.355	.369	.377	.390	.394	.380	.380	.376	008.00
109	.331	.341	.345	.360	.374	.379	.376	.383	.368	.375	010.00
110	.336	.335	.356	.357	.377	.393	.389	.382	.382	.379	012.00
111	.347	.357	.370	.379	.394	.408	.419	.402	.394	.392	014.00
112	.323	.323	.342	.341	.367	.381	.376	.378	.367	.369	016.00
113	.333	.326	.338	.352	.365	.381	.391	.374	.372	.367	018.00
114	.327	.324	.337	.340	.360	.370	.375	.368	.369	.369	022.00
115	.316	.326	.329	.336	.358	.370	.370	.358	.361	.362	024.00
116	.315	.310	.325	.341	.350	.369	.372	.358	.362	.360	032.00
117	.316	.313	.332	.335	.351	.357	.379	.357	.355	.353	036.00
118	.321	.322	.339	.330	.353	.368	.390	.375	.361	.369	040.00
119	.300	.300	.328	.321	.358	.358	.360	.353	.350	.345	046.00
120	.299	.297	.312	.313	.337	.351	.351	.341	.331	.339	056.00
121	.307	.306	.320	.329	.341	.368	.372	.350	.342	.340	062.00
122	.300	.299	.312	.315	.329	.341	.348	.339	.344	.344	068.00
123	.297	.295	.313	.309	.322	.336	.343	.333	.324	.329	082.00
124	.307	.301	.318	.311	.337	.348	.360	.341	.332	.344	093.00
125	.293	.308	.307	.305	.324	.343	.344	.328	.329	.332	106.00
126	.296	.290	.302	.294	.317	.320	.340	.330	.324	.321	118.00
127	.303	.298	.305	.300	.322	.336	.345	.338	.322	.325	130.00
128	.297	.288	.298	.300	.318	.333	.341	.328	.313	.326	142.00
129	.291	.284	.304	.292	.306	.332	.331	.329	.323	.322	154.00
130	.294	.287	.304	.295	.310	.325	.329	.322	.317	.325	164.00
131	.291	.280	.304	.288	.304	.321	.322	.316	.304	.307	178.00
132	.287	.286	.296	.290	.304	.324	.327	.314	.313	.321	202.00
133	.294	.288	.300	.286	.304	.315	.322	.317	.313	.317	227.00
134	.292	.291	.297	.287	.306	.321	.321	.311	.309	.316	251.00
135	.289	.278	.285	.276	.288	.313	.311	.307	.293	.305	275.00
136	.288	.280	.290	.275	.293	.307	.315	.310	.299	.299	298.00
137	.282	.281	.291	.273	.298	.314	.308	.296	.296	.307	328.00
138	.282	.286	.285	.275	.289	.305	.314	.293	.291	.293	351.00
139	.280	.279	.281	.266	.286	.302	.307	.294	.291	.294	396.00
140	.270	.284	.273	.255	.282	.292	.296	.281	.276	.284	467.00
141	.277	.279	.272	.265	.282	.297	.293	.282	.277	.287	539.00
142	.276	.283	.277	.267	.280	.290	.297	.288	.272	.286	635.00
143	.273	.264	.272	.245	.266	.278	.291	.279	.272	.274	689.00

Figure 18. Computer program for conversion of drainage data to regression variables.

```
      INTEGER ND,NT
      PARAMETER(ND=10)
      PARAMETER(NT=43)
      DIMENSION DEPTH(ND),SUMWC(ND)
      DOUBLE PRECISION TIME(NT)
      DOUBLE PRECISION WC(ND,NT),W(ND,NT),S(ND,NT)
      REAL Y1,Y2,Y3,Y4,Y5,X
      READ(25,103)NHOLE,NTIME,NDEPTH
      DEPTH(1)=35.
      DO 20 J=1,NTIME
      READ(25,105)LHOLE,JTIME,(WC(I,J),I=1,ND),TIME(J)
  105 FORMAT(I1,I2,14F5,F7)
      SUMWC(1)=WC(1,J)
      SUMWC(2)=WC(2,J)
      DO 25 L=3,ND
      SUMWC(L)=SUMWC(L-1)+WC(L,J)
 25   CONTINUE
      W(1,J)=SUMWC(1)*35.
      S(1,J)=W(1,J)/DEPTH(1)
      DO 10 K=2,NDEPTH
      W(K,J)=(SUMWC(K)*15.)+W(1,J)
      DEPTH(K)=DEPTH(K-1)+15.
      S(K,J)=W(K,J)/DEPTH(K)
 10   CONTINUE
 20   CONTINUE
      DO 40 K=1,ND
      DO 30 J=1,NTIME
      Y1=DLOG(WC(K,J)/.427)
      Y2=.427-WC(K,J)
      Y4=S(K,J)
      X=DLOG((TIME(J)*60.)+1.)
      WRITE(9,160)K,J,Y1,Y2,Y4,X,TIME(J)
 30   CONTINUE
 40   CONTINUE
 160  FORMAT(2I2,7F10.4)
 103  FORMAT(3I3)
      END
```

APPENDIX B

REGRESSION DATA

Table 13. Regression data, plot A.

Depth and Reading	ln(θ/θm)	θm-θ	W/z	ln t(min)	t(hr)
101	-.0754	0.0310	0.3960	0.0000	0.0000
102	-.1325	0.0530	0.3740	3.4340	0.5000
103	-.1460	0.0580	0.3690	4.1109	1.0000
104	-.2486	0.0940	0.3330	4.7958	2.0000
105	-.2699	0.1010	0.3260	5.1985	3.0000
106	-.2730	0.1020	0.3250	5.4848	4.0000
107	-.2853	0.1060	0.3210	5.7071	5.0000
108	-.2427	0.0920	0.3350	5.8889	6.0000
109	-.2577	0.0970	0.3300	6.0426	7.0000
110	-.2075	0.0800	0.3470	6.1759	8.0000
111	-.1875	0.0730	0.3540	6.2943	9.0000
112	-.2730	0.1020	0.3250	6.3986	10.0000
113	-.2337	0.0890	0.3380	6.4938	11.0000
114	-.2791	0.1040	0.3230	6.6349	12.6700
115	-.2607	0.0980	0.3290	6.7813	14.6700
116	-.2730	0.1020	0.3250	6.9090	16.6700
117	-.2730	0.1020	0.3250	7.0173	18.5800
118	-.2017	0.0780	0.3490	7.1238	20.6700
119	-.2853	0.1060	0.3210	7.2161	22.6700
120	-.2668	0.1000	0.3270	7.3006	24.6700
121	-.2699	0.1010	0.3260	7.4508	28.6700
122	-.3042	0.1120	0.3150	7.5182	30.6700
123	-.3106	0.1140	0.3130	7.7498	38.6700
124	-.2916	0.1080	0.3190	7.8482	42.6780
125	-.2916	0.1080	0.3190	7.9378	46.6700
126	-.3299	0.1200	0.3070	8.0587	52.6700
127	-.3597	0.1290	0.2980	8.2251	62.2100
128	-.3234	0.1180	0.3090	8.3172	68.2100
129	-.3299	0.1200	0.3070	8.4015	74.2100
130	-.3398	0.1230	0.3040	8.5743	88.2100
131	-.2885	0.1070	0.3200	8.6985	99.8800
132	-.3563	0.1280	0.2990	8.8208	112.8800
133	-.3398	0.1230	0.3040	8.9218	124.8800
134	-.3431	0.1240	0.3030	9.0136	136.8800
135	-.3365	0.1220	0.3050	9.0948	148.4600
136	-.3332	0.1210	0.3060	9.1751	160.8800
137	-.3563	0.1280	0.2990	9.2344	170.7100
138	-.3800	0.1350	0.2920	9.3132	184.7100
139	-.3698	0.1320	0.2950	9.4354	208.7100
140	-.3464	0.1250	0.3020	9.5485	233.7100
141	-.3698	0.1320	0.2950	9.6462	257.7100
142	-.3800	0.1350	0.2920	9.7353	281.7100
143	-.3497	0.1260	0.3010	9.8147	305.0000
144	-.3766	0.1340	0.2930	9.9069	334.4600

Table 13, continued.

145	-.3938	0.1390	0.2880	9.9734	357.4600
146	-.4220	0.1470	0.2800	10.0914	402.2100
147	-.4292	0.1490	0.2780	10.2539	473.2100
148	-.4149	0.1450	0.2820	10.3965	545.7100
149	-.3664	0.1310	0.2960	10.5581	641.4600
150	-.4184	0.1460	0.2810	10.6388	695.3300
201	-.0984	0.0400	0.3933	0.0000	0.0000
202	-.0455	0.0190	0.3842	3.4340	0.5000
203	-.0881	0.0360	0.3756	4.1109	1.0000
204	-.2220	0.0850	0.3357	4.7958	2.0000
205	-.2075	0.0800	0.3323	5.1985	3.0000
206	-.2577	0.0970	0.3265	5.4848	4.0000
207	-.2427	0.0920	0.3252	5.7071	5.0000
208	-.1932	0.0750	0.3401	5.8889	6.0000
209	-.2103	0.0810	0.3348	6.0426	7.0000
210	-.1542	0.0610	0.3527	6.1759	8.0000
211	-.1596	0.0630	0.3570	6.2943	9.0000
212	-.2397	0.0910	0.3283	6.3986	10.0000
213	-.1596	0.0630	0.3458	6.4938	11.0000
214	-.2075	0.0800	0.3302	6.6349	12.6700
215	-.2046	0.0790	0.3347	6.7813	14.6700
216	-.2337	0.0890	0.3289	6.9090	16.6700
217	-.1989	0.0770	0.3325	7.0173	18.5800
218	-.1679	0.0660	0.3526	7.1238	20.6700
219	-.2427	0.0920	0.3252	7.2161	22.6700
220	-.1989	0.0770	0.3339	7.3006	24.6700
221	-.2516	0.0950	0.3278	7.4508	28.6700
222	-.2577	0.0970	0.3195	7.5182	30.6700
223	-.2577	0.0970	0.3181	7.7498	38.6700
224	-.2668	0.1000	0.3214	7.8482	42.6780
225	-.2516	0.0950	0.3229	7.9378	46.6700
226	-.3010	0.1110	0.3097	8.0587	52.6700
227	-.3299	0.1200	0.3007	8.2251	62.2100
228	-.2760	0.1030	0.3135	8.3172	68.2100
229	-.2947	0.1090	0.3103	8.4015	74.2100
230	-.3106	0.1140	0.3067	8.5743	88.2100
231	-.2791	0.1040	0.3209	8.6985	99.8800
232	-.3074	0.1130	0.3035	8.8208	112.8800
233	-.3106	0.1140	0.3067	8.9218	124.8800
234	-.3042	0.1120	0.3066	9.0136	136.8800
235	-.3299	0.1200	0.3056	9.0948	148.4600
236	-.3074	0.1130	0.3084	9.1751	160.8800
237	-.3042	0.1120	0.3038	9.2344	170.7100
238	-.3563	0.1280	0.2941	9.3132	184.7100
239	-.3464	0.1250	0.2971	9.4354	208.7100
240	-.3332	0.1210	0.3032	9.5485	233.7100
241	-.3299	0.1200	0.2986	9.6462	257.7100
242	-.3464	0.1250	0.2950	9.7353	281.7100
243	-.3464	0.1250	0.3013	9.8147	305.0000

Table 13, continued.

244	-.3732	0.1330	0.2933	9.9069	334.4600
245	-.3530	0.1270	0.2916	9.9734	357.4600
246	-.3698	0.1320	0.2845	10.0914	402.2100
247	-.3664	0.1310	0.2834	10.2539	473.2100
248	-.3597	0.1290	0.2868	10.3965	545.7100
249	-.3563	0.1280	0.2968	10.5581	641.4600
250	-.3904	0.1380	0.2834	10.6388	695.3300
301	-.0309	0.0130	0.3981	0.0000	0.0000
302	-.0653	0.0270	0.3878	3.4340	0.5000
303	-.0881	0.0360	0.3792	4.1109	1.0000
304	-.1960	0.0760	0.3392	4.7958	2.0000
305	-.1989	0.0770	0.3364	5.1985	3.0000
306	-.2191	0.0840	0.3303	5.4848	4.0000
307	-.2397	0.0910	0.3277	5.7071	5.0000
308	-.1989	0.0770	0.3424	5.8889	6.0000
309	-.1875	0.0730	0.3392	6.0426	7.0000
310	-.1624	0.0640	0.3551	6.1759	8.0000
311	-.1433	0.0570	0.3600	6.2943	9.0000
312	-.2103	0.0810	0.3324	6.3986	10.0000
313	-.1707	0.0670	0.3491	6.4938	11.0000
314	-.2397	0.0910	0.3315	6.6349	12.6700
315	-.1875	0.0730	0.3392	6.7813	14.6700
316	-.2220	0.0850	0.3319	6.9090	16.6700
317	-.1989	0.0770	0.3365	7.0173	18.5800
318	-.1569	0.0620	0.3555	7.1238	20.6700
319	-.2427	0.0920	0.3275	7.2161	22.6700
320	-.2367	0.0900	0.3346	7.3006	24.6700
321	-.1932	0.0750	0.3334	7.4508	28.6700
322	-.2456	0.0930	0.3228	7.5182	30.6700
323	-.2791	0.1040	0.3192	7.7498	38.6700
324	-.2516	0.0950	0.3238	7.8482	42.6780
325	-.2456	0.0930	0.3255	7.9378	46.6700
326	-.2822	0.1050	0.3125	8.0587	52.6700
327	-.3042	0.1120	0.3040	8.2251	62.2100
328	-.2668	0.1000	0.3166	8.3172	68.2100
329	-.2791	0.1040	0.3132	8.4015	74.2100
330	-.3202	0.1170	0.3075	8.5743	88.2100
331	-.2638	0.0990	0.3225	8.6985	99.8800
332	-.3010	0.1110	0.3064	8.8208	112.8800
333	-.3234	0.1180	0.3072	8.9218	124.8800
334	-.2979	0.1100	0.3090	9.0136	136.8800
335	-.3010	0.1110	0.3080	9.0948	148.4600
336	-.3042	0.1120	0.3099	9.1751	160.8800
337	-.3170	0.1160	0.3055	9.2344	170.7100
338	-.3631	0.1300	0.2948	9.3132	184.7100
339	-.3010	0.1110	0.3015	9.4354	208.7100
340	-.3170	0.1160	0.3050	9.5485	233.7100
341	-.3398	0.1230	0.2998	9.6462	257.7100
342	-.3464	0.1250	0.2966	9.7353	281.7100

Table 13, continued.

343	-.3698	0.1320	0.2998	9.8147	305.0000
344	-.3631	0.1300	0.2942	9.9069	334.4600
345	-.3766	0.1340	0.2919	9.9734	357.4600
346	-.4008	0.1410	0.2848	10.0914	402.2100
347	-.4328	0.1500	0.2819	10.2539	473.2100
348	-.3766	0.1340	0.2882	10.3965	545.7100
349	-.3698	0.1320	0.2965	10.5581	641.4600
350	-.3597	0.1290	0.2868	10.6388	695.3300
401	-.0118	0.0050	0.4026	0.0000	0.0000
402	-.0333	0.0140	0.3926	3.4340	0.5000
403	-.0529	0.0220	0.3840	4.1109	1.0000
404	-.1596	0.0630	0.3439	4.7958	2.0000
405	-.1960	0.0760	0.3391	5.1985	3.0000
406	-.2017	0.0780	0.3338	5.4848	4.0000
407	-.2249	0.0860	0.3302	5.7071	5.0000
408	-.1790	0.0700	0.3451	5.8889	6.0000
409	-.1847	0.0720	0.3422	6.0426	7.0000
410	-.1542	0.0610	0.3571	6.1759	8.0000
411	-.1299	0.0520	0.3628	6.2943	9.0000
412	-.2397	0.0910	0.3331	6.3986	10.0000
413	-.1819	0.0710	0.3504	6.4938	11.0000
414	-.2191	0.0840	0.3337	6.6349	12.6700
415	-.1903	0.0740	0.3417	6.7813	14.6700
416	-.2278	0.0870	0.3334	6.9090	16.6700
417	-.2161	0.0830	0.3379	7.0173	18.5800
418	-.1596	0.0630	0.3571	7.1238	20.6700
419	-.2427	0.0920	0.3289	7.2161	22.6700
420	-.2427	0.0920	0.3347	7.3006	24.6700
421	-.2668	0.1000	0.3322	7.4508	28.6700
422	-.2791	0.1040	0.3229	7.5182	30.6700
423	-.2822	0.1050	0.3197	7.7498	38.6700
424	-.2516	0.0950	0.3254	7.8482	42.6780
425	-.2577	0.0970	0.3263	7.9378	46.6700
426	-.3042	0.1120	0.3130	8.0587	52.6700
427	-.3530	0.1270	0.3033	8.2251	62.2100
428	-.3431	0.1240	0.3141	8.3172	68.2100
429	-.3234	0.1180	0.3124	8.4015	74.2100
430	-.3563	0.1280	0.3059	8.5743	88.2100
431	-.3332	0.1210	0.3194	8.6985	99.8800
432	-.3631	0.1300	0.3046	8.8208	112.8800
433	-.3869	0.1370	0.3040	8.9218	124.8800
434	-.3766	0.1340	0.3060	9.0136	136.8800
435	-.3766	0.1340	0.3052	9.0948	148.4600
436	-.3800	0.1350	0.3066	9.1751	160.8800
437	-.4113	0.1440	0.3012	9.2344	170.7100
438	-.4256	0.1480	0.2918	9.3132	184.7100
439	-.3904	0.1380	0.2991	9.4354	208.7100
440	-.4256	0.1480	0.3001	9.5485	233.7100
441	-.4184	0.1460	0.2963	9.6462	257.7100

Table 13, continued.

442	-.4400	0.1520	0.2926	9.7353	281.7100
443	-.4621	0.1580	0.2941	9.8147	305.0000
444	-.4437	0.1530	0.2904	9.9069	334.4600
445	-.4547	0.1565	0.2880	9.9734	357.4600
446	-.4923	0.1660	0.2804	10.0914	402.2100
447	-.5077	0.1700	0.2772	10.2539	473.2100
448	-.4733	0.1610	0.2841	10.3965	545.7100
449	-.4771	0.1620	0.2906	10.5581	641.4600
450	-.5155	0.1720	0.2808	10.6388	695.3300
501	-.0023	0.0010	0.4063	0.0000	0.0000
502	-.0047	0.0020	0.3977	3.4340	0.5000
503	-.0382	0.0160	0.3883	4.1109	1.0000
504	-.1433	0.0570	0.3480	4.7958	2.0000
505	-.1679	0.0660	0.3426	5.1985	3.0000
506	-.1903	0.0740	0.3368	5.4848	4.0000
507	-.1790	0.0700	0.3344	5.7071	5.0000
508	-.1487	0.0590	0.3487	5.8889	6.0000
509	-.1569	0.0620	0.3458	6.0426	7.0000
510	-.1166	0.0470	0.3607	6.1759	8.0000
511	-.1061	0.0430	0.3662	6.2943	9.0000
512	-.1989	0.0770	0.3357	6.3986	10.0000
513	-.1192	0.0480	0.3549	6.4938	11.0000
514	-.2046	0.0790	0.3359	6.6349	12.6700
515	-.1487	0.0590	0.3459	6.7813	14.6700
516	-.2075	0.0800	0.3356	6.9090	16.6700
517	-.1819	0.0710	0.3408	7.0173	18.5800
518	-.1166	0.0470	0.3607	7.1238	20.6700
519	-.1932	0.0750	0.3325	7.2161	22.6700
520	-.1679	0.0660	0.3388	7.3006	24.6700
521	-.2103	0.0810	0.3344	7.4508	28.6700
522	-.2278	0.0870	0.3256	7.5182	30.6700
523	-.2607	0.0980	0.3212	7.7498	38.6700
524	-.2367	0.0900	0.3272	7.8482	42.6780
525	-.2367	0.0900	0.3280	7.9378	46.6700
526	-.2885	0.1070	0.3141	8.0587	52.6700
527	-.3202	0.1170	0.3043	8.2251	62.2100
528	-.2161	0.0830	0.3188	8.3172	68.2100
529	-.3106	0.1140	0.3125	8.4015	74.2100
530	-.3267	0.1190	0.3062	8.5743	88.2100
531	-.2885	0.1070	0.3195	8.6985	99.8800
532	-.3267	0.1190	0.3052	8.8208	112.8800
533	-.3431	0.1240	0.3038	8.9218	124.8800
534	-.3365	0.1220	0.3058	9.0136	136.8800
535	-.3563	0.1280	0.3042	9.0948	148.4600
536	-.3732	0.1330	0.3046	9.1751	160.8800
537	-.3800	0.1350	0.2998	9.2344	170.7100
538	-.3732	0.1330	0.2922	9.3132	184.7100
539	-.3766	0.1340	0.2982	9.4354	208.7100
540	-.4008	0.1410	0.2979	9.5485	233.7100

Table 13, continued.

541	-.3800	0.1350	0.2956	9.6462	257.7100
542	-.4220	0.1470	0.2906	9.7353	281.7100
543	-.4184	0.1460	0.2920	9.8147	305.0000
544	-.4400	0.1520	0.2879	9.9069	334.4600
545	-.4292	0.1490	0.2864	9.9734	357.4600
546	-.4584	0.1570	0.2787	10.0914	402.2100
547	-.4808	0.1630	0.2752	10.2539	473.2100
548	-.4584	0.1570	0.2818	10.3965	545.7100
549	-.4733	0.1610	0.2867	10.5581	641.4600
550	-.5038	0.1690	0.2772	10.6388	695.3300
601	-.0118	0.0050	0.4084	0.0000	0.0000
602	0.0000	0.0000	0.4017	3.4340	0.5000
603	-.0406	0.0170	0.3912	4.1109	1.0000
604	-.1569	0.0620	0.3503	4.7958	2.0000
605	-.1514	0.0600	0.3459	5.1985	3.0000
606	-.1487	0.0590	0.3411	5.4848	4.0000
607	-.1433	0.0570	0.3393	5.7071	5.0000
608	-.1299	0.0520	0.3523	5.8889	6.0000
609	-.1406	0.0560	0.3492	6.0426	7.0000
610	-.1061	0.0430	0.3639	6.1759	8.0000
611	-.0906	0.0370	0.3694	6.2943	9.0000
612	-.1569	0.0620	0.3397	6.3986	10.0000
613	-.1272	0.0510	0.3578	6.4938	11.0000
614	-.1847	0.0720	0.3385	6.6349	12.6700
615	-.1379	0.0550	0.3495	6.7813	14.6700
616	-.1651	0.0650	0.3392	6.9090	16.6700
617	-.1406	0.0560	0.3449	7.0173	18.5800
618	-.0728	0.0300	0.3656	7.1238	20.6700
619	-.1735	0.0680	0.3361	7.2161	22.6700
620	-.1352	0.0540	0.3435	7.3006	24.6700
621	-.1790	0.0700	0.3375	7.4508	28.6700
622	-.1847	0.0720	0.3296	7.5182	30.6700
623	-.1960	0.0760	0.3253	7.7498	38.6700
624	-.2132	0.0820	0.3296	7.8482	42.6780
625	-.1819	0.0710	0.3318	7.9378	46.6700
626	-.2337	0.0890	0.3174	8.0587	52.6700
627	-.2853	0.1060	0.3066	8.2251	62.2100
628	-.2191	0.0840	0.3221	8.3172	68.2100
629	-.2427	0.0920	0.3156	8.4015	74.2100
630	-.2486	0.0940	0.3099	8.5743	88.2100
631	-.2516	0.0950	0.3212	8.6985	99.8800
632	-.2668	0.1000	0.3081	8.8208	112.8800
633	-.2822	0.1050	0.3063	8.9218	124.8800
634	-.2885	0.1070	0.3078	9.0136	136.8800
635	-.2947	0.1090	0.3061	9.0948	148.4600
636	-.2822	0.1050	0.3070	9.1751	160.8800
637	-.2979	0.1100	0.3021	9.2344	170.7100
638	-.3170	0.1160	0.2947	9.3132	184.7100
639	-.3042	0.1120	0.3005	9.4354	208.7100

Table 13, continued.

640	-.3365	0.1220	0.2989	9.5485	233.7100
641	-.3332	0.1210	0.2970	9.6462	257.7100
642	-.3365	0.1220	0.2925	9.7353	281.7100
643	-.3299	0.1200	0.2940	9.8147	305.0000
644	-.3664	0.1310	0.2890	9.9069	334.4600
645	-.3904	0.1380	0.2868	9.9734	357.4600
646	-.3869	0.1370	0.2803	10.0914	402.2100
647	-.4078	0.1430	0.2764	10.2539	473.2100
648	-.3973	0.1400	0.2825	10.3965	545.7100
649	-.4008	0.1410	0.2866	10.5581	641.4600
650	-.4584	0.1570	0.2762	10.6388	695.3300
701	-.0237	0.0100	0.4094	0.0000	0.0000
702	-.0309	0.0130	0.4032	3.4340	0.5000
703	-.0382	0.0160	0.3936	4.1109	1.0000
704	-.1433	0.0570	0.3527	4.7958	2.0000
705	-.1460	0.0580	0.3487	5.1985	3.0000
706	-.1847	0.0720	0.3428	5.4848	4.0000
707	-.1763	0.0690	0.3415	5.7071	5.0000
708	-.1166	0.0470	0.3556	5.8889	6.0000
709	-.1325	0.0530	0.3522	6.0426	7.0000
710	-.1035	0.0420	0.3664	6.1759	8.0000
711	-.1140	0.0460	0.3708	6.2943	9.0000
712	-.1624	0.0640	0.3425	6.3986	10.0000
713	-.1114	0.0450	0.3607	6.4938	11.0000
714	-.1707	0.0670	0.3411	6.6349	12.6700
715	-.1460	0.0580	0.3518	6.7813	14.6700
716	-.1819	0.0710	0.3412	6.9090	16.6700
717	-.1514	0.0600	0.3476	7.0173	18.5800
718	-.1087	0.0440	0.3677	7.1238	20.6700
719	-.1763	0.0690	0.3388	7.2161	22.6700
720	-.1847	0.0720	0.3449	7.3006	24.6700
721	-.1960	0.0760	0.3391	7.4508	28.6700
722	-.2220	0.0850	0.3311	7.5182	30.6700
723	-.2161	0.0830	0.3275	7.7498	38.6700
724	-.2161	0.0830	0.3314	7.8482	42.6780
725	-.1624	0.0640	0.3356	7.9378	46.6700
726	-.2397	0.0910	0.3196	8.0587	52.6700
727	-.3010	0.1110	0.3077	8.2251	62.2100
728	-.2547	0.0960	0.3232	8.3172	68.2100
729	-.2638	0.0990	0.3171	8.4015	74.2100
730	-.2916	0.1080	0.3110	8.5743	88.2100
731	-.2427	0.0920	0.3229	8.6985	99.8800
732	-.2885	0.1070	0.3096	8.8208	112.8800
733	-.3010	0.1110	0.3075	8.9218	124.8800
734	-.2853	0.1060	0.3094	9.0136	136.8800
735	-.3010	0.1110	0.3073	9.0948	148.4600
736	-.3042	0.1120	0.3079	9.1751	160.8800
737	-.3074	0.1130	0.3036	9.2344	170.7100
738	-.3497	0.1260	0.2955	9.3132	184.7100

Table 13, continued.

739	-.3267	0.1190	0.3014	9.4354	208.7100
740	-.3299	0.1200	0.2998	9.5485	233.7100
741	-.3431	0.1240	0.2978	9.6462	257.7100
742	-.3563	0.1280	0.2933	9.7353	281.7100
743	-.3664	0.1310	0.2943	9.8147	305.0000
744	-.3869	0.1370	0.2892	9.9069	334.4600
745	-.3973	0.1400	0.2868	9.9734	357.4600
746	-.4292	0.1490	0.2800	10.0914	402.2100
747	-.4658	0.1590	0.2754	10.2539	473.2100
748	-.4292	0.1490	0.2820	10.3965	545.7100
749	-.4184	0.1460	0.2859	10.5581	641.4600
750	-.4510	0.1550	0.2757	10.6388	695.3300
801	-.0213	0.0090	0.4104	0.0000	0.0000
802	-.0165	0.0070	0.4050	3.4340	0.5000
803	-.0285	0.0120	0.3959	4.1109	1.0000
804	-.1460	0.0580	0.3544	4.7958	2.0000
805	-.0984	0.0400	0.3528	5.1985	3.0000
806	-.1542	0.0610	0.3453	5.4848	4.0000
807	-.1219	0.0490	0.3454	5.7071	5.0000
808	-.1140	0.0460	0.3584	5.8889	6.0000
809	-.1219	0.0490	0.3550	6.0426	7.0000
810	-.0881	0.0360	0.3691	6.1759	8.0000
811	-.0653	0.0270	0.3739	6.2943	9.0000
812	-.1596	0.0630	0.3448	6.3986	10.0000
813	-.0779	0.0320	0.3644	6.4938	11.0000
814	-.1325	0.0530	0.3446	6.6349	12.6700
815	-.1140	0.0460	0.3549	6.7813	14.6700
816	-.1325	0.0530	0.3447	6.9090	16.6700
817	-.1219	0.0490	0.3508	7.0173	18.5800
818	-.0504	0.0210	0.3718	7.1238	20.6700
819	-.1406	0.0560	0.3422	7.2161	22.6700
820	-.1219	0.0490	0.3484	7.3006	24.6700
821	-.1679	0.0660	0.3414	7.4508	28.6700
822	-.1569	0.0620	0.3347	7.5182	30.6700
823	-.1819	0.0710	0.3306	7.7498	38.6700
824	-.1763	0.0690	0.3342	7.8482	42.6780
825	-.1679	0.0660	0.3383	7.9378	46.6700
826	-.1989	0.0770	0.3229	8.0587	52.6700
827	-.2220	0.0850	0.3114	8.2251	62.2100
828	-.1989	0.0770	0.3260	8.3172	68.2100
829	-.2075	0.0800	0.3203	8.4015	74.2100
830	-.2427	0.0920	0.3135	8.5743	88.2100
831	-.2103	0.0810	0.3254	8.6985	99.8800
832	-.2278	0.0870	0.3128	8.8208	112.8800
833	-.2791	0.1040	0.3091	8.9218	124.8800
834	-.2427	0.0920	0.3121	9.0136	136.8800
835	-.2760	0.1030	0.3091	9.0948	148.4600
836	-.2791	0.1040	0.3095	9.1751	160.8800
837	-.2822	0.1050	0.3055	9.2344	170.7100

Table 13, continued.

838	-.3042	0.1120	0.2976	9.3132	184.7100
839	-.2885	0.1070	0.3034	9.4354	208.7100
840	-.3138	0.1150	0.3011	9.5485	233.7100
841	-.3042	0.1120	0.2996	9.6462	257.7100
842	-.3332	0.1210	0.2947	9.7353	281.7100
843	-.3170	0.1160	0.2961	9.8147	305.0000
844	-.3332	0.1210	0.2910	9.9069	334.4600
845	-.3398	0.1230	0.2886	9.9734	357.4600
846	-.3631	0.1300	0.2818	10.0914	402.2100
847	-.4043	0.1420	0.2764	10.2539	473.2100
848	-.3563	0.1280	0.2838	10.3965	545.7100
849	-.3973	0.1400	0.2860	10.5581	641.4600
850	-.4113	0.1440	0.2765	10.6388	695.3300

Table 14. Regression data, plot B.

Depth and Reading	ln(θ/θm)	θm-θ	W/z	ln t(min)	t(hr)
101	-.0480	0.0200	0.4070	0.0000	0.0000
102	-.1932	0.0750	0.3520	4.1109	1.0000
103	-.1433	0.0570	0.3700	4.7958	2.0000
104	-.1679	0.0660	0.3610	5.1985	3.0000
105	-.2337	0.0890	0.3380	5.4848	4.0000
106	-.1735	0.0680	0.3590	5.7071	5.0000
107	-.2516	0.0950	0.3320	5.8889	6.0000
108	-.2486	0.0940	0.3330	6.1759	8.0000
109	-.2547	0.0960	0.3310	6.3986	10.0000
110	-.2397	0.0910	0.3360	6.5806	12.0000
111	-.2075	0.0800	0.3470	6.7346	14.0000
112	-.2791	0.1040	0.3230	6.8680	16.0000
113	-.2486	0.0940	0.3330	6.9856	18.0000
114	-.2668	0.1000	0.3270	7.1861	22.0000
115	-.3010	0.1110	0.3160	7.2731	24.0000
116	-.3042	0.1120	0.3150	7.5606	32.0000
117	-.3010	0.1110	0.3160	7.6783	36.0000
118	-.2853	0.1060	0.3210	7.7836	40.0000
119	-.3530	0.1270	0.3000	7.9233	46.0000
120	-.3563	0.1280	0.2990	8.1200	56.0000
121	-.3299	0.1200	0.3070	8.2217	62.0000
122	-.3530	0.1270	0.3000	8.3141	68.0000
123	-.3631	0.1300	0.2970	8.5013	82.0000
124	-.3299	0.1200	0.3070	8.6271	93.0000
125	-.3766	0.1340	0.2930	8.7579	106.0000
126	-.3664	0.1310	0.2960	8.8652	118.0000
127	-.3431	0.1240	0.3030	8.9620	130.0000
128	-.3631	0.1300	0.2970	9.0500	142.0000
129	-.3835	0.1360	0.2910	9.1314	154.0000
130	-.3732	0.1330	0.2940	9.1943	164.0000
131	-.3835	0.1360	0.2910	9.2762	178.0000
132	-.3973	0.1400	0.2870	9.4027	202.0000
133	-.3732	0.1330	0.2940	9.5194	227.0000
134	-.3800	0.1350	0.2920	9.6199	251.0000
135	-.3904	0.1380	0.2890	9.7112	275.0000
136	-.3938	0.1390	0.2880	9.7915	298.0000
137	-.4149	0.1450	0.2820	9.8874	328.0000
138	-.4149	0.1450	0.2820	9.9552	351.0000
139	-.4220	0.1470	0.2800	10.0758	396.0000
140	-.4584	0.1570	0.2700	10.2407	467.0000
141	-.4328	0.1500	0.2770	10.3841	539.0000
142	-.4364	0.1510	0.2760	10.5480	635.0000
143	-.4473	0.1540	0.2730	10.6296	689.0000
201	-.1624	0.0640	0.3938	0.0000	0.0000

Table 14, continued

202	-.1763	0.0690	0.3538	4.1109	1.0000
203	-.1542	0.0610	0.3688	4.7958	2.0000
204	-.1379	0.0550	0.3643	5.1985	3.0000
205	-.2161	0.0830	0.3398	5.4848	4.0000
206	-.1596	0.0630	0.3605	5.7071	5.0000
207	-.2191	0.0840	0.3353	5.8889	6.0000
208	-.2103	0.0810	0.3369	6.1759	8.0000
209	-.2249	0.0860	0.3340	6.3986	10.0000
210	-.2427	0.0920	0.3357	6.5806	12.0000
211	-.1790	0.0700	0.3500	6.7346	14.0000
212	-.2791	0.1040	0.3230	6.8680	16.0000
213	-.2699	0.1010	0.3309	6.9856	18.0000
214	-.2760	0.1030	0.3261	7.1861	22.0000
215	-.2699	0.1010	0.3190	7.2731	24.0000
216	-.3202	0.1170	0.3135	7.5606	32.0000
217	-.3106	0.1140	0.3151	7.6783	36.0000
218	-.2822	0.1050	0.3213	7.7836	40.0000
219	-.3530	0.1270	0.3000	7.9233	46.0000
220	-.3631	0.1300	0.2984	8.1200	56.0000
221	-.3332	0.1210	0.3067	8.2217	62.0000
222	-.3563	0.1280	0.2997	8.3141	68.0000
223	-.3698	0.1320	0.2964	8.5013	82.0000
224	-.3497	0.1260	0.3052	8.6271	93.0000
225	-.3267	0.1190	0.2975	8.7579	106.0000
226	-.3869	0.1370	0.2942	8.8652	118.0000
227	-.3597	0.1290	0.3015	8.9620	130.0000
228	-.3938	0.1390	0.2943	9.0500	142.0000
229	-.4078	0.1430	0.2889	9.1314	154.0000
230	-.3973	0.1400	0.2919	9.1943	164.0000
231	-.4220	0.1470	0.2877	9.2762	178.0000
232	-.4008	0.1410	0.2867	9.4027	202.0000
233	-.3938	0.1390	0.2922	9.5194	227.0000
234	-.3835	0.1360	0.2917	9.6199	251.0000
235	-.4292	0.1490	0.2857	9.7112	275.0000
236	-.4220	0.1470	0.2856	9.7915	298.0000
237	-.4184	0.1460	0.2817	9.8874	328.0000
238	-.4008	0.1410	0.2832	9.9552	351.0000
239	-.4256	0.1480	0.2797	10.0758	396.0000
240	-.4078	0.1430	0.2742	10.2407	467.0000
241	-.4256	0.1480	0.2776	10.3841	539.0000
242	-.4113	0.1440	0.2781	10.5480	635.0000
243	-.4808	0.1630	0.2703	10.6296	689.0000
301	-.1272	0.0510	0.3897	0.0000	0.0000
302	-.1624	0.0640	0.3559	4.1109	1.0000
303	-.0984	0.0400	0.3730	4.7958	2.0000
304	-.1114	0.0450	0.3684	5.1985	3.0000
305	-.2017	0.0780	0.3419	5.4848	4.0000
306	-.1114	0.0450	0.3655	5.7071	5.0000
307	-.2046	0.0790	0.3382	5.8889	6.0000

Table 14, continued.

308	-.1847	0.0720	0.3411	6.1759	8.0000
309	-.2132	0.0820	0.3365	6.3986	10.0000
310	-.1819	0.0710	0.3404	6.5806	12.0000
311	-.1433	0.0570	0.3546	6.7346	14.0000
312	-.2220	0.0850	0.3274	6.8680	16.0000
313	-.2337	0.0890	0.3325	6.9856	18.0000
314	-.2367	0.0900	0.3286	7.1861	22.0000
315	-.2607	0.0980	0.3213	7.2731	24.0000
316	-.2730	0.1020	0.3162	7.5606	32.0000
317	-.2516	0.0950	0.3190	7.6783	36.0000
318	-.2308	0.0880	0.3254	7.7836	40.0000
319	-.2638	0.0990	0.3065	7.9233	46.0000
320	-.3138	0.1150	0.3015	8.1200	56.0000
321	-.2885	0.1070	0.3098	8.2217	62.0000
322	-.3138	0.1150	0.3025	8.3141	68.0000
323	-.3106	0.1140	0.3002	8.5013	82.0000
324	-.2947	0.1090	0.3082	8.6271	93.0000
325	-.3299	0.1200	0.2997	8.7579	106.0000
326	-.3464	0.1250	0.2960	8.8652	118.0000
327	-.3365	0.1220	0.3023	8.9620	130.0000
328	-.3597	0.1290	0.2952	9.0500	142.0000
329	-.3398	0.1230	0.2924	9.1314	154.0000
330	-.3398	0.1230	0.2947	9.1943	164.0000
331	-.3398	0.1230	0.2915	9.2762	178.0000
332	-.3664	0.1310	0.2888	9.4027	202.0000
333	-.3530	0.1270	0.2940	9.5194	227.0000
334	-.3631	0.1300	0.2929	9.6199	251.0000
335	-.4043	0.1420	0.2855	9.7112	275.0000
336	-.3869	0.1370	0.2866	9.7915	298.0000
337	-.3835	0.1360	0.2838	9.8874	328.0000
338	-.4043	0.1420	0.2836	9.9552	351.0000
339	-.4184	0.1460	0.2800	10.0758	396.0000
340	-.4473	0.1540	0.2739	10.2407	467.0000
341	-.4510	0.1550	0.2763	10.3841	539.0000
342	-.4328	0.1500	0.2778	10.5480	635.0000
343	-.4510	0.1550	0.2707	10.6296	689.0000
401	-.0118	0.0050	0.3957	0.0000	0.0000
402	-.1379	0.0550	0.3589	4.1109	1.0000
403	-.0932	0.0380	0.3760	4.7958	2.0000
404	-.0830	0.0340	0.3730	5.1985	3.0000
405	-.1651	0.0650	0.3457	5.4848	4.0000
406	-.1192	0.0480	0.3680	5.7071	5.0000
407	-.1847	0.0720	0.3414	5.8889	6.0000
408	-.1460	0.0580	0.3463	6.1759	8.0000
409	-.1707	0.0670	0.3409	6.3986	10.0000
410	-.1790	0.0700	0.3435	6.5806	12.0000
411	-.1192	0.0480	0.3592	6.7346	14.0000
412	-.2249	0.0860	0.3299	6.8680	16.0000
413	-.1932	0.0750	0.3362	6.9856	18.0000

Table 14, continued.

414	-.2278	0.0870	0.3308	7.1861	22.0000
415	-.2397	0.0910	0.3241	7.2731	24.0000
416	-.2249	0.0860	0.3208	7.5606	32.0000
417	-.2427	0.0920	0.3220	7.6783	36.0000
418	-.2577	0.0970	0.3263	7.7836	40.0000
419	-.2853	0.1060	0.3092	7.9233	46.0000
420	-.3106	0.1140	0.3037	8.1200	56.0000
421	-.2607	0.0980	0.3134	8.2217	62.0000
422	-.3042	0.1120	0.3049	8.3141	68.0000
423	-.3234	0.1180	0.3019	8.5013	82.0000
424	-.3170	0.1160	0.3087	8.6271	93.0000
425	-.3365	0.1220	0.3007	8.7579	106.0000
426	-.3732	0.1330	0.2956	8.8652	118.0000
427	-.3530	0.1270	0.3019	8.9620	130.0000
428	-.3530	0.1270	0.2961	9.0500	142.0000
429	-.3800	0.1350	0.2923	9.1314	154.0000
430	-.3698	0.1320	0.2947	9.1943	164.0000
431	-.3938	0.1390	0.2908	9.2762	178.0000
432	-.3869	0.1370	0.2891	9.4027	202.0000
433	-.4008	0.1410	0.2925	9.5194	227.0000
434	-.3973	0.1400	0.2918	9.6199	251.0000
435	-.4364	0.1510	0.2837	9.7112	275.0000
436	-.4400	0.1520	0.2844	9.7915	298.0000
437	-.4473	0.1540	0.2818	9.8874	328.0000
438	-.4400	0.1520	0.2820	9.9552	351.0000
439	-.4733	0.1610	0.2774	10.0758	396.0000
440	-.5155	0.1720	0.2704	10.2407	467.0000
441	-.4771	0.1620	0.2742	10.3841	539.0000
442	-.4695	0.1600	0.2758	10.5480	635.0000
443	-.5555	0.1820	0.2659	10.6296	689.0000
501	-.0603	0.0250	0.3967	0.0000	0.0000
502	-.0653	0.0270	0.3654	4.1109	1.0000
503	-.0406	0.0170	0.3814	4.7958	2.0000
504	-.0653	0.0270	0.3773	5.1985	3.0000
505	-.1406	0.0560	0.3497	5.4848	4.0000
506	-.0728	0.0300	0.3726	5.7071	5.0000
507	-.1569	0.0620	0.3451	5.8889	6.0000
508	-.1245	0.0500	0.3512	6.1759	8.0000
509	-.1325	0.0530	0.3462	6.3986	10.0000
510	-.1245	0.0500	0.3488	6.5806	12.0000
511	-.0804	0.0330	0.3647	6.7346	14.0000
512	-.1514	0.0600	0.3358	6.8680	16.0000
513	-.1569	0.0620	0.3407	6.9856	18.0000
514	-.1707	0.0670	0.3354	7.1861	22.0000
515	-.1763	0.0690	0.3294	7.2731	24.0000
516	-.1989	0.0770	0.3254	7.5606	32.0000
517	-.1960	0.0760	0.3266	7.6783	36.0000
518	-.1903	0.0740	0.3305	7.7836	40.0000
519	-.1763	0.0690	0.3169	7.9233	46.0000

Table 14, continued.

520	-.2367	0.0900	0.3089	8.1200	56.0000
521	-.2249	0.0860	0.3177	8.2217	62.0000
522	-.2607	0.0980	0.3087	8.3141	68.0000
523	-.2822	0.1050	0.3051	8.5013	82.0000
524	-.2367	0.0900	0.3132	8.6271	93.0000
525	-.2760	0.1030	0.3044	8.7579	106.0000
526	-.2979	0.1100	0.2990	8.8652	118.0000
527	-.2822	0.1050	0.3051	8.9620	130.0000
528	-.2947	0.1090	0.2995	9.0500	142.0000
529	-.3332	0.1210	0.2945	9.1314	154.0000
530	-.3202	0.1170	0.2972	9.1943	164.0000
531	-.3398	0.1230	0.2929	9.2762	178.0000
532	-.3398	0.1230	0.2914	9.4027	202.0000
533	-.3398	0.1230	0.2943	9.5194	227.0000
534	-.3332	0.1210	0.2941	9.6199	251.0000
535	-.3938	0.1390	0.2844	9.7112	275.0000
536	-.3766	0.1340	0.2858	9.7915	298.0000
537	-.3597	0.1290	0.2844	9.8874	328.0000
538	-.3904	0.1380	0.2831	9.9552	351.0000
539	-.4008	0.1410	0.2787	10.0758	396.0000
540	-.4149	0.1450	0.2722	10.2407	467.0000
541	-.4149	0.1450	0.2754	10.3841	539.0000
542	-.4220	0.1470	0.2765	10.5480	635.0000
543	-.4733	0.1610	0.2659	10.6296	689.0000
601	-.0406	0.0170	0.3985	0.0000	0.0000
602	-.0309	0.0130	0.3720	4.1109	1.0000
603	-.0309	0.0130	0.3858	4.7958	2.0000
604	-.0358	0.0150	0.3820	5.1985	3.0000
605	-.0906	0.0370	0.3552	5.4848	4.0000
606	-.0804	0.0330	0.3755	5.7071	5.0000
607	-.0984	0.0400	0.3508	5.8889	6.0000
608	-.0906	0.0370	0.3565	6.1759	8.0000
609	-.1192	0.0480	0.3506	6.3986	10.0000
610	-.0830	0.0340	0.3548	6.5806	12.0000
611	-.0455	0.0190	0.3706	6.7346	14.0000
612	-.1140	0.0460	0.3420	6.8680	16.0000
613	-.1140	0.0460	0.3462	6.9856	18.0000
614	-.1433	0.0570	0.3401	7.1861	22.0000
615	-.1433	0.0570	0.3350	7.2731	24.0000
616	-.1460	0.0580	0.3314	7.5606	32.0000
617	-.1790	0.0700	0.3307	7.6783	36.0000
618	-.1487	0.0590	0.3356	7.7836	40.0000
619	-.1763	0.0690	0.3225	7.9233	46.0000
620	-.1960	0.0760	0.3147	8.1200	56.0000
621	-.1487	0.0590	0.3246	8.2217	62.0000
622	-.2249	0.0860	0.3131	8.3141	68.0000
623	-.2397	0.0910	0.3093	8.5013	82.0000
624	-.2046	0.0790	0.3179	8.6271	93.0000
625	-.2191	0.0840	0.3096	8.7579	106.0000

Table 14, continued.

626	-.2885	0.1070	0.3019	8.8652	118.0000
627	-.2397	0.0910	0.3093	8.9620	130.0000
628	-.2486	0.0940	0.3041	9.0500	142.0000
629	-.2516	0.0950	0.2996	9.1314	154.0000
630	-.2730	0.1020	0.3010	9.1943	164.0000
631	-.2853	0.1060	0.2967	9.2762	178.0000
632	-.2760	0.1030	0.2959	9.4027	202.0000
633	-.3042	0.1120	0.2971	9.5194	227.0000
634	-.2853	0.1060	0.2977	9.6199	251.0000
635	-.3106	0.1140	0.2883	9.7112	275.0000
636	-.3299	0.1200	0.2887	9.7915	298.0000
637	-.3074	0.1130	0.2884	9.8874	328.0000
638	-.3365	0.1220	0.2861	9.9552	351.0000
639	-.3464	0.1250	0.2819	10.0758	396.0000
640	-.3800	0.1350	0.2749	10.2407	467.0000
641	-.3631	0.1300	0.2784	10.3841	539.0000
642	-.3869	0.1370	0.2783	10.5480	635.0000
643	-.4292	0.1490	0.2675	10.6296	689.0000
701	-.0628	0.0260	0.3988	0.0000	0.0000
702	-.0603	0.0250	0.3756	4.1109	1.0000
703	-.0431	0.0180	0.3886	4.7958	2.0000
704	-.0333	0.0140	0.3857	5.1985	3.0000
705	-.1245	0.0500	0.3578	5.4848	4.0000
706	-.0504	0.0210	0.3792	5.7071	5.0000
707	-.1061	0.0430	0.3548	5.8889	6.0000
708	-.0804	0.0330	0.3610	6.1759	8.0000
709	-.1272	0.0510	0.3537	6.3986	10.0000
710	-.0932	0.0380	0.3589	6.5806	12.0000
711	-.0189	0.0080	0.3764	6.7346	14.0000
712	-.1272	0.0510	0.3460	6.8680	16.0000
713	-.0881	0.0360	0.3516	6.9856	18.0000
714	-.1299	0.0520	0.3443	7.1861	22.0000
715	-.1433	0.0570	0.3392	7.2731	24.0000
716	-.1379	0.0550	0.3362	7.5606	32.0000
717	-.1192	0.0480	0.3365	7.6783	36.0000
718	-.0906	0.0370	0.3421	7.7836	40.0000
719	-.1707	0.0670	0.3270	7.9233	46.0000
720	-.1960	0.0760	0.3190	8.1200	56.0000
721	-.1379	0.0550	0.3303	8.2217	62.0000
722	-.2046	0.0790	0.3173	8.3141	68.0000
723	-.2191	0.0840	0.3133	8.5013	82.0000
724	-.1707	0.0670	0.3230	8.6271	93.0000
725	-.2161	0.0830	0.3138	8.7579	106.0000
726	-.2278	0.0870	0.3064	8.8652	118.0000
727	-.2132	0.0820	0.3136	8.9620	130.0000
728	-.2249	0.0860	0.3085	9.0500	142.0000
729	-.2547	0.0960	0.3034	9.1314	154.0000
730	-.2607	0.0980	0.3043	9.1943	164.0000
731	-.2822	0.1050	0.2998	9.2762	178.0000

Table 14, continued.

732	-.2668	0.1000	0.2996	9.4027	202.0000
733	-.2822	0.1050	0.3001	9.5194	227.0000
734	-.2853	0.1060	0.3005	9.6199	251.0000
735	-.3170	0.1160	0.2910	9.7112	275.0000
736	-.3042	0.1120	0.2918	9.7915	298.0000
737	-.3267	0.1190	0.2908	9.8874	328.0000
738	-.3074	0.1130	0.2894	9.9552	351.0000
739	-.3299	0.1200	0.2849	10.0758	396.0000
740	-.3664	0.1310	0.2774	10.2407	467.0000
741	-.3766	0.1340	0.2801	10.3841	539.0000
742	-.3631	0.1300	0.2806	10.5480	635.0000
743	-.3835	0.1360	0.2704	10.6296	689.0000
801	-.1009	0.0410	0.3975	0.0000	0.0000
802	-.1087	0.0440	0.3764	4.1109	1.0000
803	-.0779	0.0320	0.3893	4.7958	2.0000
804	-.0804	0.0330	0.3866	5.1985	3.0000
805	-.1460	0.0580	0.3590	5.4848	4.0000
806	-.0529	0.0220	0.3819	5.7071	5.0000
807	-.1192	0.0480	0.3574	5.8889	6.0000
808	-.1166	0.0470	0.3630	6.1759	8.0000
809	-.1087	0.0440	0.3568	6.3986	10.0000
810	-.1114	0.0450	0.3614	6.5806	12.0000
811	-.0603	0.0250	0.3791	6.7346	14.0000
812	-.1219	0.0490	0.3495	6.8680	16.0000
813	-.1325	0.0530	0.3540	6.9856	18.0000
814	-.1487	0.0590	0.3468	7.1861	22.0000
815	-.1763	0.0690	0.3412	7.2731	24.0000
816	-.1763	0.0690	0.3386	7.5606	32.0000
817	-.1790	0.0700	0.3387	7.6783	36.0000
818	-.1299	0.0520	0.3456	7.7836	40.0000
819	-.1903	0.0740	0.3298	7.9233	46.0000
820	-.2249	0.0860	0.3214	8.1200	56.0000
821	-.1989	0.0770	0.3324	8.2217	62.0000
822	-.2308	0.0880	0.3196	8.3141	68.0000
823	-.2486	0.0940	0.3154	8.5013	82.0000
824	-.2249	0.0860	0.3249	8.6271	93.0000
825	-.2638	0.0990	0.3153	8.7579	106.0000
826	-.2577	0.0970	0.3090	8.8652	118.0000
827	-.2337	0.0890	0.3162	8.9620	130.0000
828	-.2638	0.0990	0.3106	9.0500	142.0000
829	-.2607	0.0980	0.3061	9.1314	154.0000
830	-.2822	0.1050	0.3062	9.1943	164.0000
831	-.3010	0.1110	0.3015	9.2762	178.0000
832	-.3074	0.1130	0.3011	9.4027	202.0000
833	-.2979	0.1100	0.3019	9.5194	227.0000
834	-.3170	0.1160	0.3016	9.6199	251.0000
835	-.3299	0.1200	0.2927	9.7112	275.0000
836	-.3202	0.1170	0.2938	9.7915	298.0000
837	-.3664	0.1310	0.2913	9.8874	328.0000

Table 14, continued.

838	-.3766	0.1340	0.2898	9.9552	351.0000
839	-.3732	0.1330	0.2859	10.0758	396.0000
840	-.4184	0.1460	0.2778	10.2407	467.0000
841	-.4149	0.1450	0.2803	10.3841	539.0000
842	-.3938	0.1390	0.2814	10.5480	635.0000
843	-.4256	0.1480	0.2713	10.6296	689.0000