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AGRICULTURAL SOIL MOISTURE EXPERIMENT, COLBY, KANSAS, 1978: MEASURED AND PREDICTED HYDROLOGIC PROPERTIES OF THE SOIL

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3. L. M. Arya

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L. M. Arya
Lockheed Engineering and Management Services Company, Inc.

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16. Abstract

Predictive procedures for developing soil hydrologic properties (i.e., relationships of soil water pressure and hydraulic conductivity to soil water content) are presented in this report.

Three models of the soil water pressure-water content relationship and one model of the hydraulic conductivity-water content relationship are discussed. Input requirements for the models are indicated, and computational procedures are outlined.

Computed hydrologic properties for Keith silt loam, a soil type near Colby, Kansas, on which the 1978 Agricultural Soil Moisture Experiment was conducted, are presented.

A comparison of computed results with experimental data in the dry range shows that analytical models utilizing a few basic hydrophysical parameters can produce satisfactory data for large-scale applications.

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AGRICULTURAL SOIL MOISTURE EXPERIMENT, COLBY, KANSAS, 1978: MEASURED AND PREDICTED HYDROLOGIC PROPERTIES OF THE SOIL

Job Order 73-322

This report describes the activities of the
Soil Moisture project of the AgRISTARS program.

PREPARED BY

L. M. Arya

APPROVED BY

Dale E Phinney
D. E. Phinney, Supervisor
Agricultural Technology Section

John E Wainwright
J. E. Wainwright, Manager
Development and Evaluation Department

LOCKHEED ENGINEERING AND MANAGEMENT SERVICES COMPANY, INC.

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For

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
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October 1980

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PREFACE

The research which is the subject of this report was conducted to support the Soil Moisture project of the Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing program. Under Contract NAS 9-15800, personnel of Lockheed Engineering and Management Services Company, Inc., completed this work for the Earth Observations Division, Space and Life Sciences Directorate, National Aeronautics and Space Administration, at the Lyndon B. Johnson Space Center.

W. W. Hildreth of Lockheed wrote the computer program for computation of unsaturated hydraulic conductivity.

J. F. Paris and R. R. Baldwin of the National Aeronautics and Space Administration reviewed the final report and made useful suggestions for improvement.

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FIGURES

1. INTRODUCTION

The 1978 Agricultural Soil Moisture Experiment (ASME) conducted at a site near Colby, Kansas, was designed to acquire field data for use in testing and evaluation of soil moisture profile models. Weekly measurements of soil water content as a function of depth were made by a combination of gravimetric sampling and neutron-meter techniques. Four locations in each of fourteen 16.2-hectare (40-acre) fields were monitored from May 20 to the end of August 1978. The soil type for all fields is reported to be Keith silt loam (refs. 1, 2).

Most of the soil moisture models selected for testing and evaluation require data on soil hydrologic properties.[1] A detailed knowledge of these properties is essential for the analysis of soil water movement. Although field-measured soil hydrologic properties are emphasized in soil moisture studies, laboratory data on undisturbed core samples are relatively easier to obtain. In some instances (e.g., Rogowski, ref. 3; Nielsen et al., ref. 4), predictive models utilizing limited measurements and soil structural properties have been found to give satisfactory results.

Colby soils data that were collected on the physical properties include: bulk density, saturated hydraulic conductivity, and a few data points for the relationship between soil water pressure and soil water content measured on disturbed (crushed and sieved) soil samples. Since hydrologic properties determined on disturbed soil samples are not considered suitable and saturated hydraulic conductivity represents only one data point for the relationship between hydraulic conductivity and soil water content, information available on Colby soils was considered inadequate. Consequently, predictive procedures were adopted to develop the needed information. In predicting the hydrologic

[1]The relationships between (a) soil water pressure and soil water content and (b) hydraulic conductivity and soil water pressure or soil water content. These relationships are typically described by curves which span over the range of wetness of interest.

properties of Keith silt loam, use was made of the available data (refs. 1, 2) on some of the basic characteristics of the soil.

This report presents the hydrologic properties of Keith silt loam soil obtained from predictive models. Characteristics of the models which were used are discussed, and input requirements and computation procedures are outlined. The relative merits of the regression and analytical approaches are commented upon. Additional efforts for developing and testing predictive procedures are recommended.

2. AVAILABLE DATA

2.1 AGRICULTURAL TECHNOLOGY COMPANY

Bulk density, soil water pressure versus soil water content relationship, and saturated hydraulic conductivity data for Keith silt loam collected by the Agricultural Technology Company, McCook, Nebraska, are shown respectively in tables 2-1, 2-2, and 2-3.

Bulk density data were single values for the various depths in each of the 14 fields and showed wide variations between fields and depths (see fig. 2-1). Since bulk densities are known to vary over short spaces, more representative values for each field were obtained by pooling the data on the basis of similarity. Assuming all fields were in Keith silt loam, it was argued that differences in surface bulk densities would be more a result of historical cultural treatments (e.g., tillage and cropping) and that differences in the lower layers would reflect the effects of spatial variabilities in the factors of soil formation. On this basis, bulk densities from the surface down to a depth of 38 centimeters (15 inches) for all fields of one type — corn, pasture, wheat, or fallow — were pooled together, forming a separate group for each type of field. For each group, a single smooth curve was hand drawn to represent the bulk density profile for the 38 centimeters (15 inches) of surface soil. For the lower layers, fields were grouped together on the basis of similarity in the pattern of bulk density changes with depth, and smooth curves were drawn through the pooled data.

Field bulk density data were limited to a depth of 137 centimeters (54 inches), whereas the water content measurements extended down to a depth of 183 centimeters (72 inches). This necessitated extrapolation of bulk density profiles below the 137-centimeter (54-inch) depth. Bulk density data interpolated from smooth curves are shown in table 2-4.

Data for soil water pressure versus soil water content relationships (table 2-2) were obtained on disturbed (crushed and sieved) soil samples; hence, they were not considered entirely satisfactory. Numerous studies (e.g., Croney and Coleman, ref. 5; Sharma and Uehara, ref. 6) have shown that water retention in the wet range is strongly influenced by soil structure. In the dry range, the influence of soil texture is more dominant. Since crushing destroys the soil structure, data obtained on such samples cannot approximate field conditions. They are useful, however, in the range of soil dryness where soil structure has least influence. The range of wetness over which the influence of soil structure is significant is somewhat difficult to define, for it varies from soil to soil and is modified by the sample history. Typically, however, soil water pressures from 0 down to -3000 centimeters can be considered to represent the wet range for most soils. Thus, only Colby data for lower pressures could be considered useful.

Saturated hydraulic conductivities (table 2-3) were obtained at various times during a 48-hour flow. The data show fluctuating conductivity values, but such fluctuations are not uncommon. Incomplete saturation and structural changes during the prolonged wetting and flow process can have both negative and positive influences on the flow rate. It is doubtful, therefore, whether a mean of all observations for the 48-hour period would be a more reasonable value than that of the first few observations.

Since the objective of the experiment is to closely approximate the field structural condition, it is generally recommended (e.g., Klute, ref. 7) that, after complete saturation, conductivity should be obtained when approximately 100 milliliters of water has passed. In the case of Colby data, the length of saturation time and the amount of water collected for each observation are not known. However, in view of the probable structural disturbance that could have taken place, a mean of the first three observations (a 4-hour flow) was considered appropriate.

2.2 SOIL CONSERVATION SERVICE SOIL SURVEY LABORATORY

In addition to data supplied by the Agricultural Technology Company, descriptions of two Keith silt loam profiles (ref. 8) were available from the Soil Conservation Service (SCS) Soil Survey Laboratory, Lincoln, Nebraska.[1] These profile surveys were made in 1958. From these surveys, soil texture, organic carbon, bulk density, and 15-atmosphere water content data were extracted and are reported in table 2-5. For the two profiles, variations in soil texture with depth appeared very similar; therefore, particle-size data were combined to reflect the variations with respect to soil horizons only. Particle-size distributions for the A, B, and C horizons are shown in figure 2-2. The data show that the C-horizon [i.e., soil below the 102-centimeter (40-inch) depth] is distinctly coarser than the A and B horizons. Although the textural compositions of A and B horizons appear somewhat similar, owing to variations in structure and organic matter content, water retention characteristics of the two horizons can be significantly different. Therefore, treating the two horizons separately would be appropriate.

As expected, organic carbon decreased with depth. These data are plotted in figure 2-3, and a smooth curve is hand drawn.

[1]An agency of the U.S. Department of Agriculture (USDA).

TABLE 2-1.- BULK DENSITY DATA FOR KEITH SILT LOAM

[As reported by the Agricultural Technology Company]

Field	Depth, in.	Bulk density, gcm^{-3}	Field	Depth, in.	Bulk density, gcm^{-3}	Field	Depth, in.	Bulk density, gcm^{-3}
1	3	1.05	6	3	1.07	11	3	1.12
	3*	1.30		3*	1.24		3*	1.31
	5*	1.44		5*	1.39		5*	1.45
	8	1.17		8	1.03		8	1.13
	9*	1.34		9*	1.40		9*	1.43
	15*	1.45		15*	1.43		15*	1.46
	28	1.22		24	1.10		28	1.31
	54	1.09		52	1.51		52	1.11
2	3	1.26	7	3	1.39	12	3	1.12
	3*	1.15		3*	1.25		3*	1.27
	5*	1.17		5*	1.29		5*	1.42
	8	1.22		8	1.25		8	1.03
	9*	1.23		9*	1.36		9*	1.40
	15*	1.43		15*	1.35		15*	1.37
	28	1.40		28	1.27		28	1.47
	54	1.27		52	1.29		52	1.39
3	3	1.34	8	3	0.94	13	3	1.29
	3*	1.20		3*	1.17		3*	1.12
	5*	1.29		5*	1.15		5*	1.21
	8	1.22		8	1.14		8	1.10
	9*	1.36		9*	1.27		9*	1.34
	15*	1.38		15*	1.34		15*	1.36
	28	1.59		26	1.51		28	1.34
	54	1.25		54	1.47		52	1.23
4	3	1.09	9	3	1.39	14	3	1.06
	3*	1.18		3*	1.25		3*	1.23
	5*	1.23		5*	1.35		5*	1.20
	8	1.29		8	1.27		8	1.28
	9*	1.39		9*	1.37		9*	1.25
	15*	1.31		15*	1.39		15*	1.24
	28	1.43		28	1.38		28	1.20
	54	1.31		52	1.34		52	1.20
5	3	1.29	10	3	1.14			
	3*	1.29		3*	1.24			
	5*	1.30		5*	1.28			
	8	1.36		8	1.13			
	9*	1.38		9*	1.28			
	15*	1.48		15*	1.39			
	28	1.28		26	1.31			
	54	1.31		52	1.11			

*From bulk density data set obtained for the microwave remote sensing experiment.

TABLE 2-2.- SOIL WATER PRESSURE VERSUS SOIL WATER CONTENT RELATIONSHIPS* FOR KEITH SILT LOAM

[As reported by the Agricultural Technology Company]

(a) Set I

Field	Depth, in.	Pressure, -bars 1/3	Pressure, -bars 15	Field	Depth, in.	Pressure, -bars 1/3	Pressure, -bars 15
		Water content, gg^{-1}				Water content, gg^{-1}	
1	3	0.243	0.116	8	3	0.252	0.116
	8	0.250	0.122		8	0.223	0.105
	28	0.250	0.120		26	0.265	0.124
	54	0.261	0.127		54	0.292	0.159
2	3	0.251	0.108	9	3	0.253	0.106
	8	0.259	0.121		8	0.236	0.011
	28	0.262	0.113		28	0.258	0.122
	54	0.263	0.132		52	0.262	0.115
3	3	0.245	0.104	10	3	0.216	0.089
	8	0.236	0.107		8	0.211	0.091
	28	0.258	0.112		26	0.239	0.102
	54	0.262	0.117		52	0.251	0.115
4	3	0.253	0.112	11	3	0.239	0.098
	8	0.270	0.133		8	0.247	0.133
	28	0.277	0.127		28	0.249	0.128
	54	0.274	0.122		52	0.254	0.123
5	3	0.267	0.121	12	3	0.270	0.101
	8	0.257	0.122		8	0.268	0.112
	28	0.278	0.124		28	0.259	0.120
	54	0.278	0.144		52	0.258	0.118
6	3	0.281	0.138	13	3	0.262	0.100
	8	0.278	0.141		8	0.259	0.125
	24	0.277	0.144		28	0.257	0.119
	54	0.279	0.153		52	0.262	0.121
7	3	0.240	0.099	14	3	0.280	0.107
	8	0.246	0.118		8	0.262	0.114
	28	0.262	0.122		28	0.268	0.115
	52	0.254	0.116		52	0.269	0.106

*Determined on crushed, sieved samples using a pressure plate apparatus.

TABLE 2-2.- Concluded.

(b) Set II

Field and location	Depth, in.	Pressure, -bars					
		1/3	1	3	6	10	15
		Water content, gg^{-1}					
2-3	8	0.333	0.248	0.198	0.160	0.150	0.148
2-3	25	0.328	0.238	0.189	0.160	0.153	0.149
2-3	48	0.279	0.218	0.161	0.138	0.133	0.119
6-3	8	0.356	0.274	0.216	0.203	0.185	0.183
6-3	25	0.298	0.217	0.164	0.142	0.139	0.134
6-3	48	0.284	0.198	0.141	0.123	0.117	0.113
11-4	8	0.328	0.246	0.198	0.181	0.139	0.135
11-4	25	0.326	0.236	0.187	0.156	0.151	0.146
11-4	48	0.279	0.215	0.158	0.139	0.124	0.118
14-1	8	0.298	0.227	0.176	0.174	0.147	0.142
14-1	25	0.309	0.245	0.193	0.170	0.135	0.134
14-1	48	0.279	0.218	0.159	0.136	0.130	0.125

TABLE 2-3.- SATURATED HYDRAULIC CONDUCTIVITY (INCHES PER HOUR) IN KEITH SILT LOAM

[As reported by the Agricultural Technology Company]

Field and location	Depth, in.	Flow time, hr						Mean	
		1	2	4	8	24	48	All	First three
2-3	8	0.40	0.36	0.46	0.45	0.45	0.31	0.41	0.41
2-3	25	1.15	0.93	1.08	1.03	1.07	1.15	1.07	1.05
2-3	48	0.48	0.41	0.48	0.48	0.46	0.37	0.47	0.46
6-3	8	1.98	1.72	2.06	1.94	2.11	1.51	1.87	1.92
6-3	25	0.26	0.22	0.26	0.26	0.29	0.33	0.27	0.25
6-3	48	0.95	0.79	1.03	1.00	1.07	1.08	0.98	0.92
11-4	8	0.69	0.55	0.65	0.55	0.67	0.77	0.65	0.63
11-4	25	0.40	--	0.43	0.40	0.46	0.48	0.43	0.42
11-4	48	0.43	0.40	0.52	0.46	0.48	0.48	0.46	0.45
14-1	8	0.72	0.64	0.77	0.77	1.03	1.19	0.85	0.71
14-1	25	1.38	1.20	1.46	1.43	1.44	1.62	1.42	1.35
14-1	48	0.41	0.38	0.43	--	--	0.33	0.39	0.41

Results:

Overall mean = 1.90 cm/hr (0.748 in/hr) = 3.17×10^{-2} cm/min
Mean for A-horizon [20-cm (8-in.) depth] = 3.88×10^{-2} cm/min
Mean for B-horizon [64-cm (25-in.) depth] = 3.25×10^{-2} cm/min
Mean for C-horizon [122-cm (48-in.) depth] = 2.37×10^{-2} cm/min

TABLE 2-4.- SMOOTH BULK DENSITY VALUES FOR DEPTHS OF WATER CONTENT MEASUREMENT IN VARIOUS FIELDS

Depth,		Bulk density, gcm^{-3}, for field —													
Cm	In.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
3.8	1.5	1.00	1.00	1.00	1.00	0.95	0.95	1.00	0.95	0.95	1.00	1.00	0.95	0.95	0.95
11.4	4.5	1.22	1.22	1.22	1.24	1.17	1.28	1.24	1.17	1.28	1.24	1.24	1.28	1.28	1.17
30.5	12	1.41	1.41	1.41	1.39	1.36	1.39	1.39	1.36	1.39	1.39	1.39	1.39	1.39	1.36
45.7	18	1.45	1.45	1.45	1.43	1.39	1.40	1.43	1.39	1.40	1.43	1.43	1.40	1.40	1.39
61.0	24	1.35	1.40	1.47	1.40	1.27	1.27	1.27	1.47	1.47	1.35	1.35	1.47	1.40	1.27
76.2	30	1.26	1.38	1.49	1.38	1.22	1.22	1.22	1.49	1.49	1.26	1.26	1.49	1.38	1.22
91.4	36	1.20	1.36	1.47	1.36	1.24	1.24	1.24	1.47	1.47	1.20	1.20	1.47	1.36	1.24
106.7	42	1.16	1.33	1.44	1.33	1.27	1.27	1.27	1.44	1.44	1.16	1.16	1.44	1.33	1.27
121.9	48	1.12	1.30	1.40	1.30	1.30	1.30	1.30	1.40	1.40	1.12	1.12	1.40	1.30	1.30
137.2	54	1.10	1.27	1.36	1.27	1.33	1.33	1.33	1.36	1.36	1.10	1.10	1.36	1.27	1.33
152.4*	60*	1.09	1.24	1.32	1.24	1.36	1.36	1.36	1.32	1.32	1.09	1.09	1.32	1.24	1.36
167.6*	66*	1.08	1.21	1.27	1.21	1.38	1.38	1.38	1.27	1.27	1.08	1.08	1.27	1.21	1.38
182.9*	72*	1.07	1.18	1.23	1.18	1.41	1.41	1.41	1.23	1.23	1.07	1.07	1.23	1.18	1.41

*Data for these depths are extrapolated.

TABLE 2-5.- SOME IMPORTANT CHARACTERISTICS OF KEITH SILT LOAM, LOGAN COUNTY, KANSAS

[SCS description of Keith silt loam soil profiles; data obtained in 1958]

Depth, in.	Horizon	Particle-size distribution, mm, percentage by weight										Organic carbon, percent	Bulk density, gcm^{-3}	15-atm. water content, gg^{-1}
		Gravel >2	Very coarse sand 2-1	Coarse sand 1-0.5	Medium sand 0.5-0.25	Fine sand 0.25-0.10	Very fine sand 0.1-0.05	Silt 0.05-0.002	Clay <0.002	0.20-0.02	0.02-0.002			
Profile 1														
0-4	Ap1	--	0.2	0.2	0.1	0.3	10.4	58.6	30.2	50.0	19.2	2.05		0.131
4-6	Ap2	--	0.2	0.2	0.1	0.2	10.3	62.4	26.6	53.4	19.4	2.12		0.126
6-10	A1	--	--	--	--	0.1	8.6	62.5	28.8	52.0	19.2	1.36	1.21	0.131
10-16	A3	--	--	--	--	1.6	8.2	59.4	30.8	51.0	18.2	0.91		0.137
16-22	B21t	--	--	0.3	0.1	0.4	7.0	62.1	30.1	51.1	18.3	0.74		0.139
22-36	B22t	--	--	--	--	0.1	6.0	60.5	33.4	47.2	19.4	0.51	1.33	0.149
36-46	B3 Ca	--	--	0.1	--	0.1	7.8	57.6	34.4	42.8	22.7	0.36		0.152
46-57	Cca	--	--	--	--	0.1	9.7	66.6	23.6	52.9	23.5	0.22	1.17	0.118
57-70+	C	--	--	--	--	0.1	11.1	70.4	18.4	56.1	25.5	0.15		0.109
Profile 2														
0-4	Ap1	--	0.2	0.1	--	0.3	7.5	67.1	24.8	55.0	19.8	1.54		0.114
4-6	Ap2	--	0.1	0.1	--	0.1	8.9	64.0	26.8	52.3	20.7	1.50		0.123
6-11	A1	--	0.1	0.1	--	0.2	9.6	60.4	29.6	51.3	18.8	1.16	1.30	0.134
11-17	A3	--	--	--	--	0.1	9.1	61.5	29.3	53.0	17.7	0.76		0.133
17-21	B21t	--	--	--	--	0.1	9.1	63.6	27.2	54.5	18.3	0.59		0.128
21-33	B22t	--	--	--	--	0.1	8.3	61.9	29.7	50.2	20.1	0.39	1.35	0.139
33-41	B2 Ca	--	--	--	--	0.2	9.3	60.1	30.4	48.4	21.2	0.32		0.136
41-57	Cca	--	--	--	--	0.1	11.4	65.7	22.8	53.7	23.5	0.21	1.20	0.120

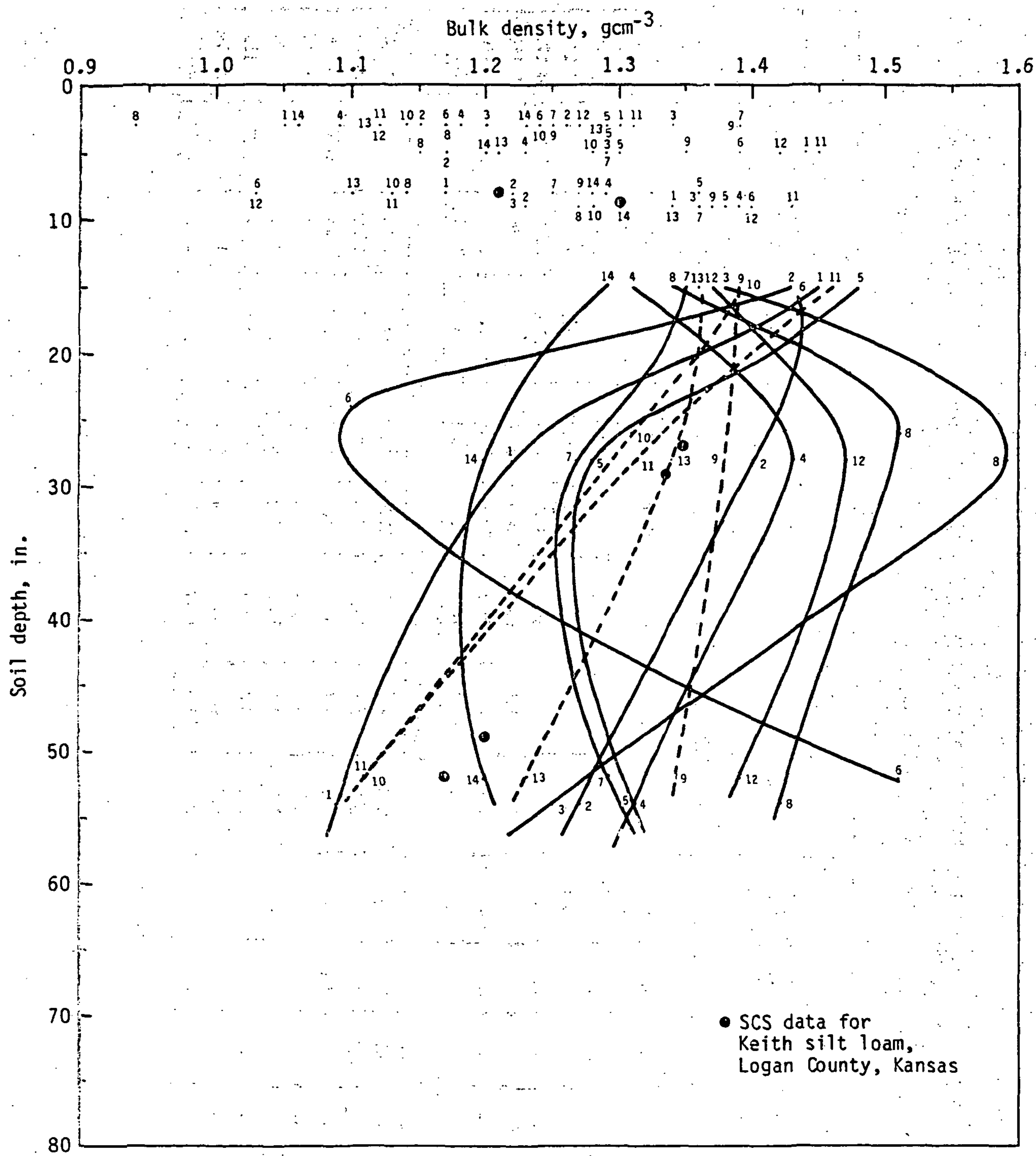


Figure 2-1.- Bulk density profiles for Colby fields. Data for various fields are identified by field numbers.

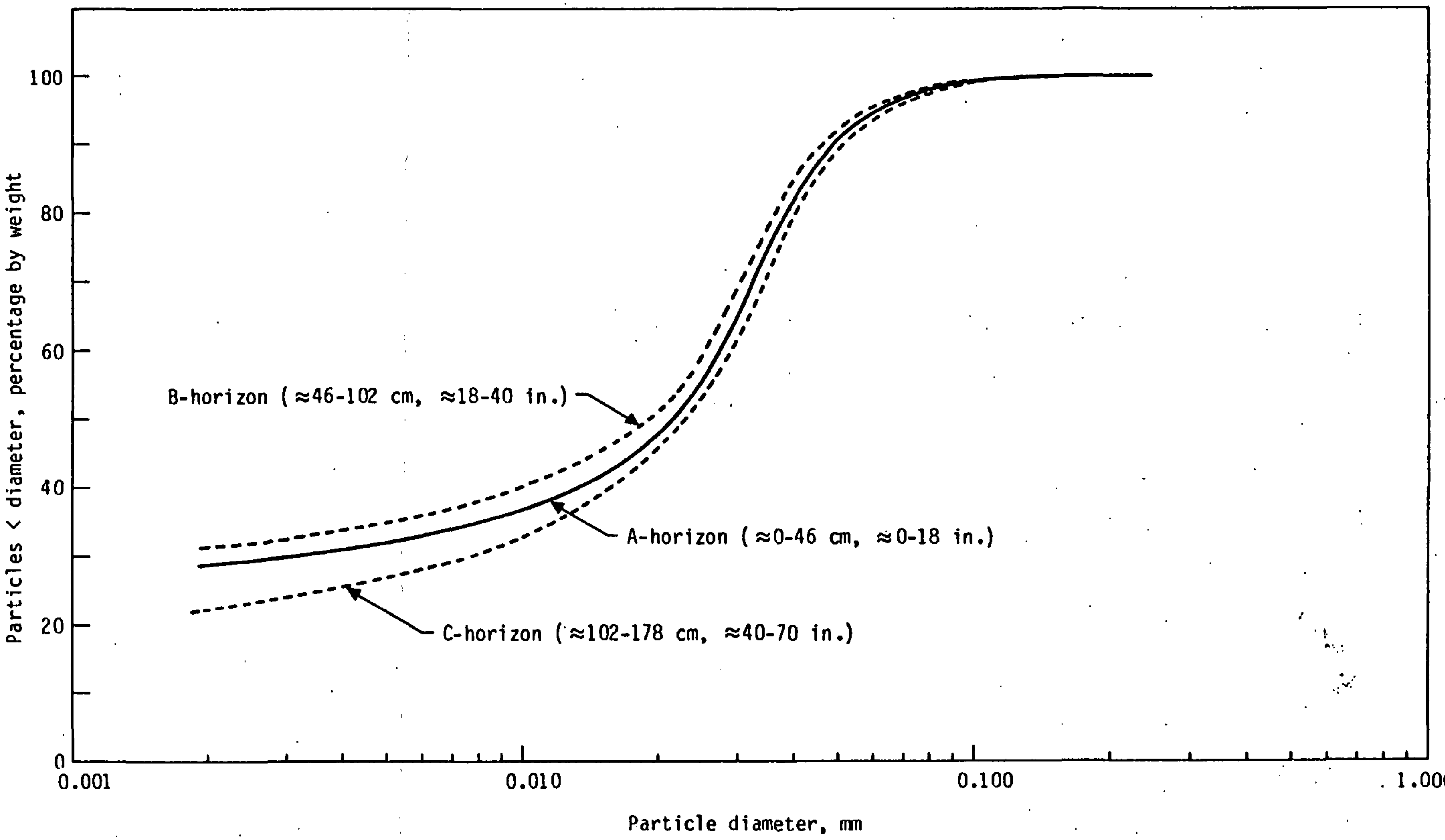


Figure 2-2.- Particle-size distribution in Keith silt loam, Logan County, Kansas. Data represent the mean of two soil profiles.

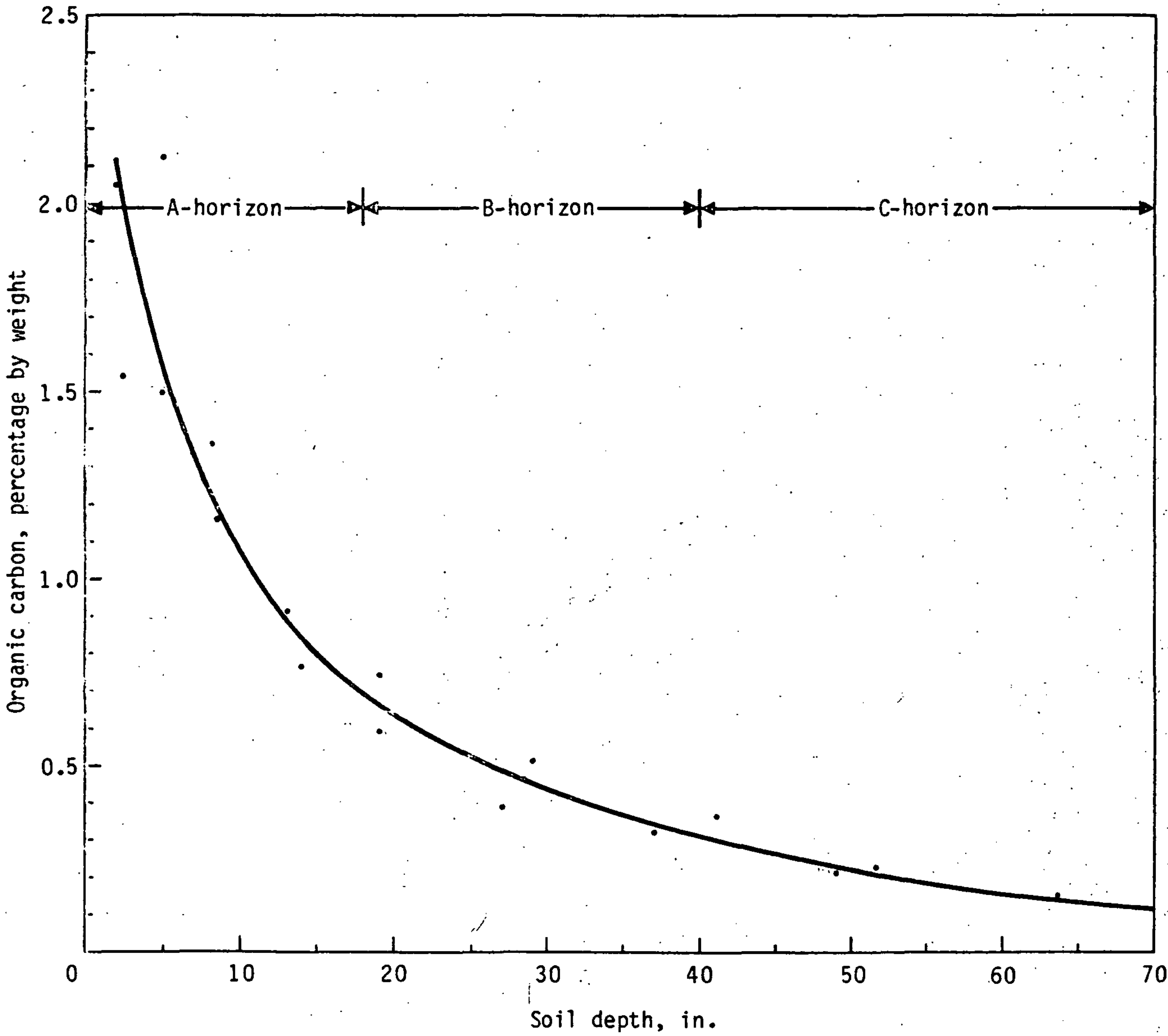


Figure 2-3.- Organic carbon distribution in Keith silt loam, Logan County, Kansas. Data from two soil profiles. The curve is hand drawn.

3. ESTIMATION OF HYDROLOGIC PROPERTIES

3.1 SOIL WATER PRESSURE VERSUS SOIL WATER CONTENT RELATIONSHIPS

Three different models were considered for estimating the relationship of soil water pressure to soil water content for Keith silt loam. These were:

a. Regression model

b. Rogowski model

c. Ghosh model

3.1.1 REGRESSION MODEL

The regression model was developed by Hall et al. (ref. 9) in 1977 at the Rothamsted Experimental Station, England. A family of regression equations relates the volumetric water content at different pressures to particle-size composition, organic carbon, and bulk density. The equations are:

Topsoils:

$$\theta_v(0.05) = 47.00 + 0.25C + 0.10Z + 1.12X - 16.52D_b \tag{1}$$

$$\theta_v(0.10) = 37.47 + 0.32C + 0.12Z + 1.15X - 12.5D_b \tag{2}$$

$$\theta_v(0.40) = 26.66 + 0.36C + 0.12Z + 1.00X - 7.64D_b \tag{3}$$

$$\theta_v(2) = 8.70 + 0.45C + 0.11Z + 1.03X \tag{4}$$

$$\theta_v(15) = 2.94 + 0.83C - 0.0054C^2 \tag{5}$$

Subsoils:

$$\theta_v(0.05) = 37.20 + 0.35C + 0.12Z - 11.73D_b \tag{6}$$

$$\theta_v(0.10) = 27.87 + 0.41C + 0.15Z - 8.32D_b \tag{7}$$

$$\theta_v(0.40) = 20.81 + 0.45C + 0.13Z - 5.96D_b \tag{8}$$

$$\theta_v(2) = 7.57 + 0.48C + 0.11Z \tag{9}$$

$$\theta_v(15) = 1.48 + 0.84C - 0.0054C^2 \tag{10}$$

where

θ_v = percentage of volumetric water content at different pressures (in bars) indicated in parentheses (One bar = 1000-centimeter height of a water column.)

C = particles <0.002 millimeters, percentage by weight

Z = particles 0.002 to 0.06 millimeters, percentage by weight

X = organic carbon, percentage by weight

D_b = dry bulk density of the soil, grams per cubic centimeter

For the various horizons of Keith silt loam, mean values of C, Z, X, and D_b and applicable equations are as follows:

Horizon	C	Z	X	D_b	Equations
A	28.5	65.5	1.30	1.30	1 through 5
B	31.0	64.0	--	1.35	6 through 10
C	22.0	71.0	--	1.28	6 through 10
Reference	Fig. 2-2	Fig. 2-2	Fig. 2-3	Fig. 2-1	

The relationships of soil water pressure to soil water content computed from equations (1) through (10) are plotted in figure 3-1. The soil water pressures for which water contents can be calculated from the regression equations are limited to -50 centimeters in the wet range and -15 000 centimeters in the dry range. Most soil moisture models and hydraulic conductivity calculations, however, require data beyond these limits. Thus, the utility of the regression model appears to be limited. With this model, therefore, extrapolation of computed soil water pressure versus soil water content relationships may become necessary. In the dry range, the pressure versus water content relationships for most soils, when plotted on semilog graphs, are very nearly linear, and extrapolation may not be too critical (see model comparisons by Rogowski, ref. 3; Baver et al., ref. 10, p. 296). In the wet range, however, extrapolation may not be simple; and, as an aid, knowledge of other hydrologic parameters such as pressure and water content at the air-entry point and effective saturation may be required. For the purpose of comparative testing of soil moisture profile models, computed data were extrapolated to a water content value equivalent to 85 percent of the theoretical porosity,[1] which appeared to approximate effective saturation. This was done merely to fill in the gap and is not recommended as a rule.

The data in figure 3-1 show that the water retention characteristics of A and B horizons are similar and can be grouped together. Those for the C-horizon show substantially lower water retention. Thus, it appears that two distinctly different soil water pressure versus soil water content relationships, one for the combined A and B horizons and the other for the C-horizon, are applicable to Keith silt loam at Colby. This pattern of separation between horizons is also shown by the experimental data plotted in figure 3-1.

Because experimental data were obtained on disturbed samples, only the pressure versus water content values in the dry range should be considered valid. In this range, a comparison between experimental and predicted data shows that, on an average, predicted water contents are 15 percent higher. A similar comparison of data in the wet range is not possible because (1) the regression model does not provide for computation of water contents in the wet range and (2) valid experimental data are not available.

For ease in applying data to soil moisture models and in computing hydraulic conductivity, pressure-water content values for small increments of water content are presented in table 3-1.

3.1.2 ROGOWSKI MODEL

The Rogowski model (ref. 3) describes an analytic form of the soil water pressure versus soil water content relationship. The essential soil hydrologic parameters are water content at a soil water pressure of -15 000 centimeters, soil water pressure and water content at the air-entry point, and saturated water content. The model is of the following form.

---

[1] $f = [1 - (D_b/D_p)]$, where f is the theoretical porosity, D_b is the bulk density, and D_p is the particle density assumed to be 2.65 grams per cubic centimeter.

$$\theta_v = (\theta_v)_e + \alpha \, \ln(\psi - \psi_e + 1) \quad ; \quad \psi > \psi_e \tag{11}$$

$$\theta_v = (\theta_v)_e \quad ; \quad \psi < \psi_e \tag{12}$$

$$\alpha = [(\theta_v)_{15} - (\theta_v)_e]/\ln(\psi_{15} - \psi_e + 1) \tag{13}$$

where θ_v is the volumetric water content in cubic centimeter per cubic centimeter and ψ is the soil water pressure in centimeters (in terms of magnitude only). Subscripts e and 15 denote air entry and 15 000 centimeters pressure, respectively.

For Keith silt loam at Colby, experimentally measured $(\theta_v)_{15}$ values (i.e., volumetric water content at a pressure of -15 000 centimeters) can be accepted. Values are given in table 2-2 and are plotted in figure 3-1. Parameters $(\theta_v)_e$ and ψ_e were not measured and must be estimated based on data in the literature. Some data compiled by Rogowski (ref. 11) are summarized in table 3-2. These data show that, on an average, the ratio of air-entry water content to saturated water content is approximately 0.9 and the air-entry pressure is approximately 23 centimeters. Assuming these values are applicable to the Keith silt loam at Colby, relevant hydrologic parameters for computing pressure-water content relationships can be developed. Important parameters for Keith silt loam are shown below.

Horizon	D_p, gcm^{-3}	D_b, gcm^{-3}	$(\theta_v)_o$, cm^3cm^{-3}	$(\theta_v)_e/(\theta_v)_o$	$(\theta_v)_e$, cm^3cm^{-3}	ψ_e, cm	$(\theta_v)_{15}$, cm^3cm^{-3}	$-\alpha$
A	2.65	1.30	0.509	0.90	0.458	23.0	0.198	0.02704
B	2.65	1.35	0.491	0.90	0.442	23.0	0.190	0.02621
C	2.65	1.28	0.517	0.90	0.465	23.0	0.152	0.03255

Volumetric water contents as a function of soil water pressure, computed from equations (11) through (13), are shown in figure 3-2. These equations allow computation of water content at pressures below the air-entry point only. For soil water pressures above the air-entry point, Rogowski suggests an alternative formulation in the form:

$$\theta_v = (\theta_v)_e + \beta \, \ln(\psi_e - \psi + 1) \quad ; \quad \psi < \psi_e \tag{14}$$

$$\theta_v > (\theta_v)_e \tag{15}$$

$$\beta = [(\theta_v)_o - (\theta_v)_e]/\ell n(\psi_e - \psi_o + 1) \tag{16}$$

where ψ_o and $(\theta_v)_o$ are saturation soil water pressure and water content, respectively. By using equations (14) through (16), the pressure-water content relationships were extended to the saturation point.

The Colby experimental data are shown also in figure 3-2. Agreement between experimental and predicted water contents appears reasonable in the pressure range of -3000 to -15 000 centimeters. At higher pressures, experimental data show significantly higher water contents. However, because Colby data were obtained on disturbed samples, it would be inappropriate to use them for verifying the predicted results. Rogowski compared the predicted and experimental soil water pressure versus soil water content relationships for a number of soils and concluded that, in view of field variabilities, results obtained from equations (11) through (16) are quite adequate.

Table 3-3 shows the pressure-water content values for small increments of water content.

3.1.3 GHOSH MODEL

The Ghosh model (ref. 12) describes the pressure-water content relationship of soils in the following manner:

$$\psi = \psi_e[\theta_v/(\theta_v)_o]^{-\beta} \tag{17}$$

where ψ is any soil water pressure, ψ_e is the soil water pressure at air entry, θ_v is the water content corresponding to soil water pressure ψ, $(\theta_v)_o$ is the water content at saturation, and β is an empirically determined constant. For application of this model, at least one measurement of θ_v at ψ and knowledge of ψ_e, particle-size distribution, and bulk density are necessary. The value of $(\theta_v)_o$ can be estimated from a knowledge of bulk density, while β is given by the following formulation:

$$\beta = 26.5(\lambda_2/\lambda_1)^{1.786} \tag{18}$$

where λ_1 and λ_2 are the percentages by weight of sand[2] and silt[3] content of the soil.

For Keith silt loam, bulk density and particle-size distribution can be inferred from figures 2-1 and 2-2, respectively.

Measured water content values at pressures ranging from -3000 to -15 000 centimeters are accepted as being reliable. These values can be inferred from figure 3-1 or 3-2.

Relative to the Ghosh model, various parameters for Keith silt loam are as follows:

Horizon	D_p, gcm^{-3}	D_b, gcm^{-3}	$(\theta_v)_o$, cm^3cm^{-3}	$(\theta_v)_{15}$, cm^3cm^{-3}	ψ_e,[4] -cm	λ_1, %	λ_2, %	β[5]
A	2.65	1.30	0.509	0.198	255	52.5	19.0	4.314
B	2.65	1.35	0.491	0.190	94	49.0	20.0	5.348
C	2.65	1.28	0.517	0.152	11	54.5	23.5	5.899

The computed values of ψ_e for the A and B horizons, although not impossible, appear too high when compared with published experimental data (see table 3-2). The empirical formulation for β in the Ghosh model [equation (18)] was developed from data on sandy materials; it may not be adequate for heavier textured soils. Furthermore, variabilities associated with soil density, estimates of saturated water content, and the choice of a pair of measured ψ-θ_v values as inputs to the model should be expected to have an influence on ψ_e.

[2]Particles ranging in size from 2.0 to 0.02 millimeters.
[3]Particles ranging in size from 0.02 to 0.002 millimeters.
[4]Computed on the basis of water content at a pressure of -15 000 centimeters, β, and $(\theta_v)_o$ as shown.
[5]Computed on the basis of particle-size parameters λ_1 and λ_2.

An alternative approach is to estimate both ψ_e and β from a pair of simultaneous equations. However, this approach requires at least two pairs of measured ψ-θ_v values, in addition to saturated water content.

For Keith silt loam at Colby, measured water contents at soil water pressures of -3000 and -15 000 centimeters (see figs. 3-1 and 3-2) were used for estimating ψ_e and β from equation (17). The substitution of appropriate values for ψ, θ_v, and $(\theta_v)_0$ in equation (17) resulted in the following revised values of ψ_e and β for the various horizons.

Horizon	ψ_e, -cm	β
A	37	6.362
B	44	6.134
C	9	6.088

Computed soil water pressure versus soil water content relationships based on revised ψ_e and β values and equation (17) are shown in figure 3-3. The data in figure 3-3 show that the A and B horizons have very nearly identical soil water pressure versus soil water content relationships and that water retention for these two horizons is substantially higher than for the C-horizon.

Table 3-4 shows the pressure-water content values for small increments of water content.

3.2 HYDRAULIC CONDUCTIVITY VERSUS SOIL WATER CONTENT RELATIONSHIPS

A knowledge of hydraulic conductivity as a function of soil water content is important in analyses of water movement. Although experimental data obtained in the field or on undisturbed core samples are preferred, soil variability is often so large that experimental efforts needed for large-scale application become prohibitive. As a result, predictive methods have gained popularity; in many instances (e.g., Nielsen et al., ref. 4), satisfactory estimates of hydraulic conductivity have been obtained.

For Keith silt loam at Colby, saturated hydraulic conductivity for selected depths in four fields was measured. These data are reported in table 2-3. Unsaturated hydraulic conductivity was not measured but was predicted by Jackson's (ref. 13) modification of Marshall's (ref. 14) pore-interaction model.[6] The necessary input for Jackson's method is the soil water pressure versus soil water content relationship for the soil. The curve describing this relationship is divided into n equal water content increments, and the conductivity is calculated by the following equation:

$$K_i = K_s\left[\frac{(\theta_v)_i}{(\theta_v)_1}\right]^p \frac{\sum_{j=i}^{n}\left[(2j + 1 - 2i)\psi_j^{-2}\right]}{\sum_{j=1}^{n}\left[(2j - 1)\psi_j^{-2}\right]} \quad ; \quad i = 1,2,\cdots,n \qquad (19)$$

where

K_i = hydraulic conductivity (centimeters per minute) of water content at the upper end of the i^{th} water content interval

K_s = measured saturated hydraulic conductivity (centimeters per minute)

θ_i = water content at the upper end of the i^{th} water content interval (cubic centimeter per cubic centimeter)

θ_1 = highest or saturated water content (cubic centimeter per cubic centimeter)

p = an empirical constant [The value depends on the method of computation; for equation (19), p = 1.]

ψ_j = soil water pressure at the midpoint of j^{th} water content interval (minus centimeters of water)

[6]The computer program for computation of unsaturated hydraulic conductivity is given in the appendix.

For the combined A and B horizons of Keith silt loam, hydraulic conductivity data computed from equation (19) are shown in figure 3-4. Those for the C-horizon are shown in figure 3-5. Hydraulic conductivities for each of the two sections of the soil profile are based on soil water pressure versus water content relationships predicted from the regression, Rogowski, and Ghosh models. Table 3-5 shows the hydraulic conductivities for small increments of water content.

TABLE 3-1.- SOIL WATER PRESSURE VERSUS SOIL WATER CONTENT RELATIONSHIPS* FOR KEITH SILT LOAM COMPUTED FROM THE REGRESSION MODEL

Soil horizon							
A + B [0 to 102-cm (40-in.) depth]				C [below 102-cm (40-in.) depth]			
Water content, cm^3cm^{-3}	Pressure, -cm	Water content, cm^3cm^{-3}	Pressure, -cm	Water content, cm^3cm^{-3}	Pressure, -cm	Water content, cm^3cm^{-3}	Pressure, -cm
0.43	1.00×10^0	0.23	1.30×10^4	0.43	1.00×10^0	0.23	4.20×10^3
0.42	9.00×10^0	0.22	1.65×10^4	0.42	4.00×10^0	0.22	5.40×10^3
0.41	3.00×10^1	0.21	2.25×10^4	0.41	1.30×10^1	0.21	6.80×10^3
0.40	6.60×10^1	0.20	2.95×10^4	0.40	2.50×10^1	0.20	8.60×10^3
0.39	1.20×10^2	0.19	3.80×10^4	0.39	4.20×10^1	0.19	1.07×10^4
0.38	1.90×10^2	0.18	4.90×10^4	0.38	6.30×10^1	0.18	1.35×10^4
0.37	2.60×10^2	0.17	6.40×10^4	0.37	9.60×10^1	0.17	1.70×10^4
0.36	3.60×10^2	0.16	8.60×10^4	0.36	1.35×10^2	0.16	2.10×10^4
0.35	5.00×10^2	0.15	1.15×10^5	0.35	1.90×10^2	0.15	2.60×10^4
0.34	6.60×10^2	0.14	1.50×10^5	0.34	2.55×10^2	0.14	3.30×10^4
0.33	7.70×10^2	0.13	1.95×10^5	0.33	3.30×10^2	0.13	4.10×10^4
0.32	1.15×10^3	0.12	2.50×10^5	0.32	4.35×10^2	0.12	5.00×10^4
0.31	1.50×10^3	0.11	3.40×10^5	0.31	5.60×10^2	0.11	6.40×10^4
0.30	2.00×10^3	0.10	4.40×10^5	0.30	7.40×10^2	0.10	8.00×10^4
0.29	2.50×10^3	0.09	5.70×10^5	0.29	9.60×10^2	0.09	9.80×10^4
0.28	3.30×10^3	0.08	7.40×10^5	0.28	1.23×10^3	0.08	1.23×10^5
0.27	4.30×10^3	0.07	9.50×10^5	0.27	1.60×10^3	0.07	1.55×10^5
0.26	5.70×10^3	0.06	1.30×10^6	0.26	2.00×10^3	0.06	1.95×10^5
0.25	7.50×10^3	0.05	1.65×10^6	0.25	2.60×10^3	0.05	2.45×10^5
0.24	9.70×10^3	0.04	2.20×10^6	0.24	3.30×10^3	0.04	3.00×10^5

TABLE 3-2.- NUMERICAL VALUES OF IMPORTANT PHYSICAL AND HYDROLOGIC PARAMETERS FOR SEVERAL SOILS

[From prepublication copy of Watershed Physics: Moisture Characteristics and Variability Criteria by A. S. Rogowski, USDA Agricultural Research Service, Beltsville, Maryland]

(a) 15-bar* and air-entry values

Soil series	$(\theta_v)_{15}$, cm^3cm^{-3}	ψ_e,† -cm	$(\theta_v)_e$, cm^3cm^{-3}
Watson S.	--	39.8	0.350
Adelanto c.l.	0.174	12.0	0.414
Adelanto c.l.	0.110	10.0	0.402
Panoche c.l.	0.213	35.0	0.448
Panoche c.l.	0.275	25.0	0.431
Panoche c.l.	0.199	32.0	0.428
Panoche c.l.	0.196	47.0	0.476
Panoche c.l.	--	32.0	0.491
Panoche c.l.	--	32.0	0.522
Yolo l.	0.167	10.0	0.482
Yolo l.	0.167	20.0	0.482
Miller Si.c.	--	10.0	0.357
Miller Si.c.	0.200	15.0	0.340
Miller Si.c.	0.135	30.0	0.333
Miller Si.c.	0.112	30.0	0.340
Monona Si.l	0.125	9.0	0.476
Adams F.s.l.	0.102	10.0	0.519
Cecil C.	0.299	100.0	0.422
Houston C.	0.317	200.0	0.428

(b) Density and $[(\theta_v)_e/(\theta_v)_o]$ ratios

Soil series	D_p, gcm^{-3}	D_b, gcm^{-3}	$(\theta_v)_o$, cm^3cm^{-3}	$(\theta_v)_e$, cm^3cm^{-3}	$[(\theta_v)_e/(\theta_v)_o]$‡
Panoche	2.65	1.31	0.506	0.479	0.95
Panoche	2.65	1.25	0.528	0.435	0.82
Adelanto	2.72	1.47	0.460	0.408	0.89
Yolo	2.65	1.23	0.536	0.474	0.89
Miller	2.65	1.61	0.393	0.334	0.85
Webster	2.58	1.28	0.504	0.419	0.83
Webster	2.58	1.20	0.535	0.513	0.96

*Represents a soil water pressure of -15 000 cm.

†Mean ψ_e = 23 cm for all soils except sand and clay.

‡Mean $[(\theta_v)_e/(\theta_v)_o]$ = 0.90.

TABLE 3-3.- SOIL WATER PRESSURE VERSUS SOIL WATER CONTENT RELATIONSHIPS*
FOR KEITH SILT LOAM COMPUTED FROM THE ROGOWSKI MODEL

Soil horizon							
A + B [0 to 102-cm (40-in.) depth]				C [below 102-cm (40-in.) depth]			
Water content, cm^3cm^{-3}	Pressure, -cm	Water content, cm^3cm^{-3}	Pressure, -cm	Water content, cm^3cm^{-3}	Pressure, -cm	Water content, cm^3cm^{-3}	Pressure, -cm
0.50	1.00×10^{0}	0.27	9.60×10^{2}	0.52	1.00×10^{0}	0.27	4.30×10^{2}
0.49	1.20×10^{1}	0.26	1.35×10^{3}	0.51	9.00×10^{0}	0.26	5.80×10^{2}
0.48	1.80×10^{1}	0.25	2.00×10^{3}	0.50	1.60×10^{1}	0.25	7.90×10^{2}
0.47	2.00×10^{1}	0.24	2.85×10^{3}	0.49	1.95×10^{1}	0.24	1.03×10^{3}
0.46	2.20×10^{1}	0.23	4.15×10^{3}	0.48	2.10×10^{1}	0.23	1.45×10^{3}
0.45	2.30×10^{1}	0.22	6.00×10^{3}	0.47	2.20×10^{1}	0.22	1.90×10^{3}
0.44	2.40×10^{1}	0.21	8.60×10^{3}	0.46	2.30×10^{1}	0.21	2.60×10^{3}
0.43	2.60×10^{1}	0.20	1.25×10^{4}	0.45	2.40×10^{1}	0.20	3.60×10^{3}
0.42	2.80×10^{1}	0.19	1.80×10^{4}	0.44	2.53×10^{1}	0.19	4.80×10^{3}
0.41	3.00×10^{1}	0.18	2.60×10^{4}	0.43	2.65×10^{1}	0.18	6.50×10^{3}
0.40	3.30×10^{1}	0.17	3.80×10^{4}	0.42	2.80×10^{1}	0.17	8.90×10^{3}
0.39	3.60×10^{1}	0.16	5.37×10^{4}	0.41	3.00×10^{1}	0.16	1.20×10^{4}
0.38	4.00×10^{1}	0.15	7.81×10^{4}	0.40	3.20×10^{1}	0.15	1.65×10^{4}
0.37	4.60×10^{1}	0.14	1.14×10^{5}	0.39	3.50×10^{1}	0.14	2.25×10^{4}
0.36	5.30×10^{1}	0.13	1.65×10^{5}	0.38	3.85×10^{1}	0.13	3.00×10^{4}
0.35	6.50×10^{1}	0.12	2.41×10^{5}	0.37	4.30×10^{1}	0.12	4.10×10^{4}
0.34	8.60×10^{1}	0.11	3.51×10^{5}	0.36	4.80×10^{1}	0.11	5.40×10^{4}
0.33	1.15×10^{2}	0.10	5.11×10^{5}	0.35	5.60×10^{1}	0.10	7.41×10^{4}
0.32	1.55×10^{2}	0.09	7.43×10^{5}	0.34	6.80×10^{1}	0.09	1.01×10^{5}
0.31	2.20×10^{2}	0.08	1.08×10^{6}	0.33	8.60×10^{1}	0.08	1.37×10^{5}
0.30	3.15×10^{2}	0.07	1.57×10^{6}	0.32	1.10×10^{2}	0.07	1.86×10^{5}
0.29	4.60×10^{2}	0.06	1.57×10^{6}	0.31	1.40×10^{2}	0.06	2.53×10^{5}
0.28	6.60×10^{2}	0.05	3.34×10^{6}	0.30	1.85×10^{2}	0.05	3.44×10^{5}
		0.04	4.86×10^{6}	0.29	2.40×10^{2}	0.04	4.68×10^{5}
				0.28	3.20×10^{2}		

*Interpolated from figure 3-2.

TABLE 3-4.- SOIL WATER PRESSURE VERSUS SOIL WATER CONTENT RELATIONSHIPS* FOR KEITH SILT LOAM COMPUTED FROM GHOSH MODEL

Soil horizon							
A + B [0 to 102-cm (40-in.) depth]				C [below 102-cm (40-in.) depth]			
Water content, cm^3cm^{-3}	Pressure, -cm	Water content, cm^3cm^{-3}	Pressure, -cm	Water content, cm^3cm^{-3}	Pressure, -cm	Water content, cm^3cm^{-3}	Pressure, -cm
0.50	1.00×10^{0}	0.27	1.95×10^{3}	0.52	1.00×10^{0}	0.27	4.80×10^{2}
0.49	4.50×10^{1}	0.26	2.45×10^{3}	0.51	9.80×10^{0}	0.26	6.00×10^{2}
0.48	5.20×10^{1}	0.25	3.20×10^{3}	0.50	1.10×10^{1}	0.25	7.70×10^{2}
0.47	6.00×10^{1}	0.24	4.00×10^{3}	0.49	1.24×10^{1}	0.24	9.80×10^{2}
0.46	6.80×10^{1}	0.23	5.30×10^{3}	0.48	1.40×10^{1}	0.23	1.25×10^{3}
0.45	7.90×10^{1}	0.22	6.80×10^{3}	0.47	1.60×10^{1}	0.22	1.65×10^{3}
0.44	9.10×10^{1}	0.21	9.00×10^{3}	0.46	1.84×10^{1}	0.21	2.20×10^{3}
0.43	1.05×10^{2}	0.20	1.25×10^{4}	0.45	2.10×10^{1}	0.20	3.00×10^{3}
0.42	1.22×10^{2}	0.19	1.74×10^{4}	0.44	2.40×10^{1}	0.19	4.10×10^{3}
0.41	1.40×10^{2}	0.18	2.40×10^{4}	0.43	2.75×10^{1}	0.18	5.80×10^{3}
0.40	1.64×10^{2}	0.17	3.60×10^{4}	0.42	3.15×10^{1}	0.17	8.20×10^{3}
0.39	1.92×10^{2}	0.16	5.30×10^{4}	0.41	3.65×10^{1}	0.16	1.15×10^{4}
0.38	2.25×10^{2}	0.15	7.58×10^{4}	0.40	4.30×10^{1}	0.15	1.65×10^{4}
0.37	2.70×10^{2}	0.14	1.17×10^{5}	0.39	5.00×10^{1}	0.14	2.55×10^{4}
0.36	3.20×10^{2}	0.13	1.85×10^{5}	0.38	5.80×10^{1}	0.13	4.15×10^{4}
0.35	3.80×10^{2}	0.12	3.06×10^{5}	0.37	7.00×10^{1}	0.12	6.54×10^{4}
0.34	4.60×10^{2}	0.11	5.27×10^{5}	0.36	8.00×10^{1}	0.11	1.11×10^{5}
0.33	5.50×10^{2}	0.10	9.55×10^{5}	0.35	9.70×10^{1}	0.10	1.99×10^{5}
0.32	6.70×10^{2}	0.09	1.84×10^{6}	0.34	1.15×10^{2}	0.09	3.77×10^{5}
0.31	7.40×10^{2}	0.08	3.85×10^{6}	0.33	1.40×10^{2}	0.08	7.73×10^{5}
0.30	1.00×10^{3}	0.07	8.87×10^{6}	0.32	1.68×10^{2}	0.07	1.74×10^{6}
0.29	1.25×10^{3}	0.06	2.32×10^{7}	0.31	2.04×10^{2}	0.06	4.45×10^{6}
0.28	1.55×10^{3}	0.05	7.26×10^{7}	0.30	2.50×10^{2}	0.05	1.35×10^{7}
		0.04	2.93×10^{8}	0.29	3.05×10^{2}	0.04	5.26×10^{7}
				0.28	3.85×10^{2}		

*Interpolated from figure 3-3.

TABLE 3-5.- SOIL WATER CONTENT VERSUS HYDRAULIC CONDUCTIVITY* RELATIONSHIPS FOR KEITH SILT LOAM, BASED ON DIFFERENT MODELS FOR PRESSURE-WATER CONTENT RELATIONSHIPS

Water content, cm^3cm^{-3}	Hydraulic conductivity, cm/hr						Water content, cm^3cm^{-3}	Hydraulic conductivity, cm/hr					
	Regression model		Rogowski model		Ghosh model			Regression model		Rogowski model		Ghosh model	
	A + B horizons	C-horizon	A + B horizons	C-horizon	A + B horizons	C-horizon		A + B horizons	C-horizon	A + B horizons	C-horizon	A + B horizons	C-horizon
0.52	--	--	--	1.44×10^{0}	--	1.44×10^{0}	0.25	9.70×10^{-6}	1.20×10^{-5}	4.60×10^{-6}	2.00×10^{-5}	5.30×10^{-5}	2.20×10^{-5}
0.51	--	--	--	1.24×10^{0}	--	1.05×10^{0}	0.24	5.40×10^{-6}	7.20×10^{-6}	2.10×10^{-6}	1.03×10^{-5}	2.80×10^{-5}	1.20×10^{-5}
0.50	--	--	2.14×10^{0}	9.80×10^{-1}	2.14×10^{0}	8.00×10^{-1}	0.23	2.80×10^{-6}	4.30×10^{-6}	9.60×10^{-7}	5.10×10^{-6}	1.40×10^{-5}	6.20×10^{-6}
0.49	--	--	1.70×10^{0}	8.00×10^{-1}	1.50×10^{0}	5.80×10^{-1}	0.22	1.60×10^{-6}	2.55×10^{-6}	4.50×10^{-7}	2.55×10^{-6}	7.00×10^{-6}	3.20×10^{-6}
0.48	--	--	1.35×10^{0}	6.20×10^{-1}	1.10×10^{0}	4.30×10^{-1}	0.21	8.60×10^{-7}	1.50×10^{-6}	2.00×10^{-7}	1.35×10^{-6}	3.60×10^{-6}	1.55×10^{-6}
0.47	--	--	1.05×10^{0}	5.00×10^{-1}	8.20×10^{-1}	3.10×10^{-1}	0.20	4.50×10^{-7}	8.40×10^{-7}	9.00×10^{-8}	7.20×10^{-7}	1.70×10^{-6}	7.60×10^{-7}
0.46	--	--	7.20×10^{-1}	3.90×10^{-1}	5.80×10^{-1}	2.20×10^{-1}	0.19	2.50×10^{-7}	5.00×10^{-7}	4.20×10^{-8}	3.80×10^{-7}	7.50×10^{-7}	3.30×10^{-7}
0.45	--	--	6.20×10^{-1}	3.00×10^{-1}	4.10×10^{-1}	1.60×10^{-1}	0.18	1.30×10^{-7}	3.00×10^{-7}	2.00×10^{-8}	1.95×10^{-7}	3.00×10^{-7}	1.50×10^{-7}
0.44	--	--	4.70×10^{-1}	2.40×10^{-1}	2.95×10^{-1}	1.15×10^{-1}	0.17	7.00×10^{-8}	1.70×10^{-7}	9.00×10^{-9}	1.00×10^{-7}	1.20×10^{-7}	6.40×10^{-8}
0.43	2.15×10^{0}	1.44×10^{0}	3.55×10^{-1}	1.80×10^{-1}	2.05×10^{-1}	8.20×10^{-2}	0.16	3.60×10^{-8}	1.00×10^{-7}	4.20×10^{-9}	4.80×10^{-8}	4.90×10^{-8}	2.80×10^{-8}
0.42	4.00×10^{-1}	1.85×10^{-1}	2.60×10^{-1}	1.30×10^{-1}	1.45×10^{-1}	5.80×10^{-2}	0.15	1.85×10^{-8}	5.70×10^{-8}	1.85×10^{-9}	2.60×10^{-8}	1.90×10^{-8}	1.15×10^{-8}
0.41	1.60×10^{-1}	8.00×10^{-2}	1.85×10^{-1}	9.60×10^{-2}	1.00×10^{-1}	4.00×10^{-2}	0.14	1.05×10^{-8}	3.35×10^{-8}	8.50×10^{-10}	1.35×10^{-8}	6.40×10^{-9}	5.00×10^{-9}
0.40	7.00×10^{-2}	4.10×10^{-2}	1.30×10^{-1}	7.00×10^{-2}	6.80×10^{-2}	2.75×10^{-2}	0.13	5.70×10^{-9}	1.95×10^{-8}	3.90×10^{-10}	6.80×10^{-9}	2.70×10^{-9}	2.20×10^{-9}
0.39	3.50×10^{-2}	2.10×10^{-2}	8.50×10^{-2}	4.90×10^{-2}	4.70×10^{-2}	1.90×10^{-2}	0.12	3.00×10^{-9}	1.15×10^{-8}	1.80×10^{-10}	3.30×10^{-9}	9.50×10^{-10}	9.00×10^{-10}
0.38	2.00×10^{-2}	1.25×10^{-2}	5.10×10^{-2}	3.35×10^{-2}	3.10×10^{-2}	1.25×10^{-2}	0.11	1.50×10^{-9}	6.80×10^{-9}	8.50×10^{-11}	1.85×10^{-9}	3.50×10^{-10}	3.50×10^{-10}
0.37	1.10×10^{-2}	7.00×10^{-3}	2.65×10^{-2}	2.25×10^{-2}	2.05×10^{-2}	8.50×10^{-3}	0.10	8.20×10^{-10}	4.00×10^{-9}	3.90×10^{-10}	9.60×10^{-10}	1.25×10^{-10}	1.60×10^{-10}
0.36	6.20×10^{-3}	4.00×10^{-3}	1.40×10^{-2}	1.45×10^{-2}	1.40×10^{-2}	5.50×10^{-3}	0.09	4.50×10^{-10}	2.35×10^{-9}	1.80×10^{-11}	4.90×10^{-10}	5.30×10^{-11}	7.40×10^{-11}
0.35	3.40×10^{-3}	2.50×10^{-3}	7.80×10^{-3}	8.80×10^{-3}	8.80×10^{-3}	3.60×10^{-3}	0.08	2.30×10^{-10}	1.35×10^{-9}	8.30×10^{-12}	2.60×10^{-10}	1.85×10^{-11}	3.20×10^{-11}
0.34	1.90×10^{-3}	1.40×10^{-3}	4.50×10^{-3}	5.20×10^{-3}	5.60×10^{-3}	2.35×10^{-3}	0.07	1.25×10^{-10}	8.00×10^{-10}	4.00×10^{-12}	1.35×10^{-10}	7.00×10^{-12}	1.35×10^{-11}
0.33	1.05×10^{-3}	8.00×10^{-4}	2.20×10^{-3}	3.00×10^{-3}	3.60×10^{-3}	1.45×10^{-3}	0.06	6.70×10^{-11}	4.70×10^{-10}	1.85×10^{-12}	7.00×10^{-11}	2.70×10^{-12}	6.00×10^{-12}
0.32	5.80×10^{-4}	4.80×10^{-4}	1.10×10^{-3}	1.65×10^{-3}	2.20×10^{-3}	9.20×10^{-4}	0.05	3.60×10^{-11}	2.70×10^{-10}	9.00×10^{-13}	3.60×10^{-11}	9.00×10^{-13}	2.60×10^{-12}
0.31	3.00×10^{-4}	2.70×10^{-4}	5.00×10^{-4}	9.00×10^{-4}	1.35×10^{-3}	5.80×10^{-4}	0.04	1.90×10^{-11}	1.65×10^{-10}	4.00×10^{-13}	1.90×10^{-11}	4.00×10^{-13}	1.10×10^{-12}
0.30	1.90×10^{-4}	1.65×10^{-4}	2.20×10^{-4}	5.00×10^{-4}	8.20×10^{-4}	3.55×10^{-4}	0.03	1.05×10^{-11}	9.60×10^{-11}	1.90×10^{-13}	1.00×10^{-11}	1.35×10^{-13}	4.70×10^{-13}
0.29	1.10×10^{-4}	1.00×10^{-4}	1.20×10^{-4}	2.70×10^{-4}	5.30×10^{-4}	2.15×10^{-4}	0.02	5.60×10^{-12}	5.60×10^{-11}	8.80×10^{-14}	5.20×10^{-12}	5.50×10^{-14}	2.10×10^{-13}
0.28	6.00×10^{-5}	6.20×10^{-5}	4.60×10^{-5}	1.35×10^{-4}	3.10×10^{-4}	1.25×10^{-4}	0.01	3.00×10^{-12}	3.40×10^{-11}	4.50×10^{-14}	2.70×10^{-12}	2.00×10^{-14}	9.00×10^{-14}
0.27	3.20×10^{-5}	3.30×10^{-5}	2.10×10^{-5}	7.60×10^{-5}	1.65×10^{-4}	7.50×10^{-5}	0.00	1.75×10^{-12}	2.00×10^{-11}	2.10×10^{-14}	1.40×10^{-12}	1.00×10^{-14}	4.00×10^{-14}
0.26	1.75×10^{-5}	2.00×10^{-5}	1.03×10^{-5}	3.80×10^{-5}	9.50×10^{-5}	4.20×10^{-5}							

*Interpolated from figures 3-4 and 3-5.

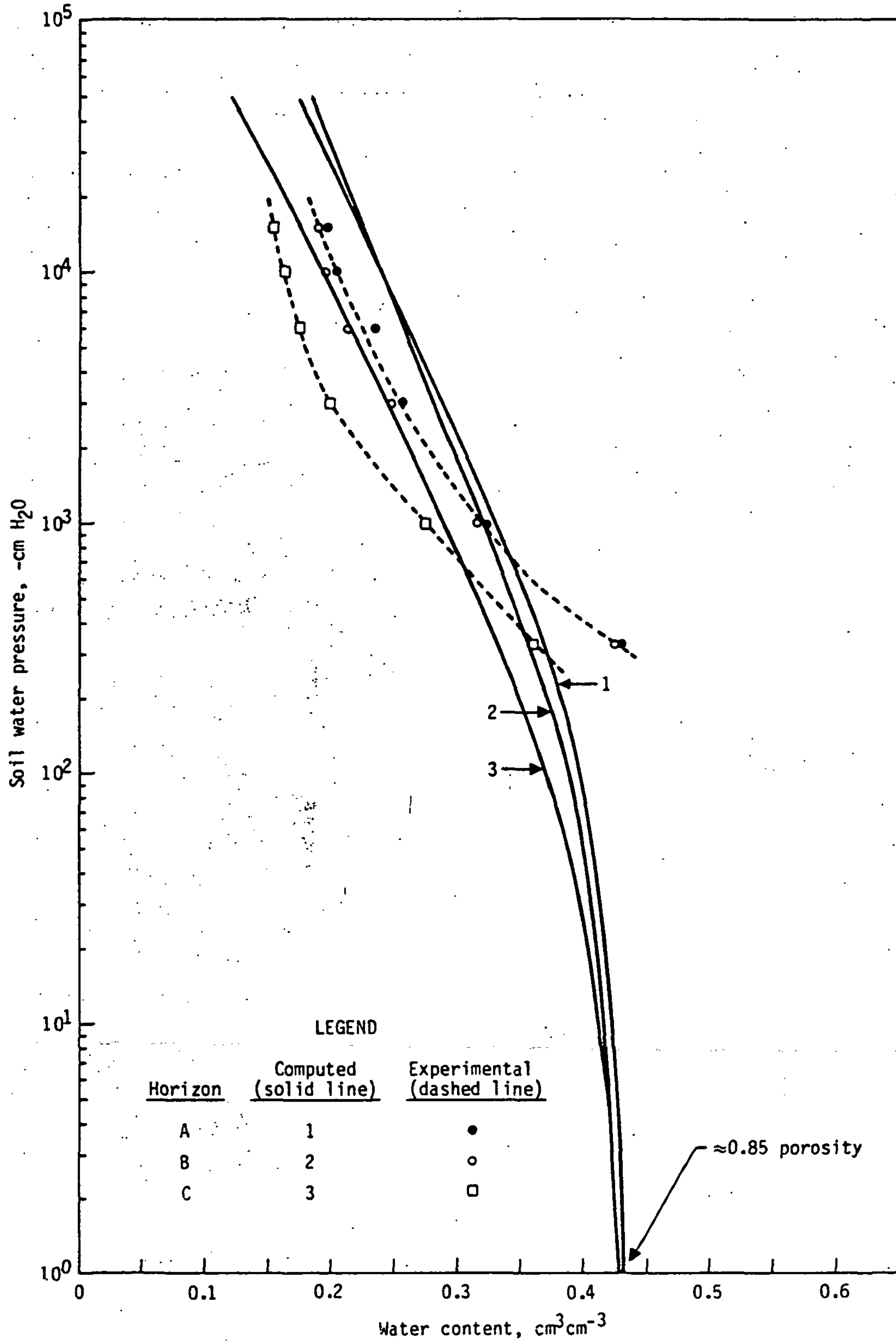
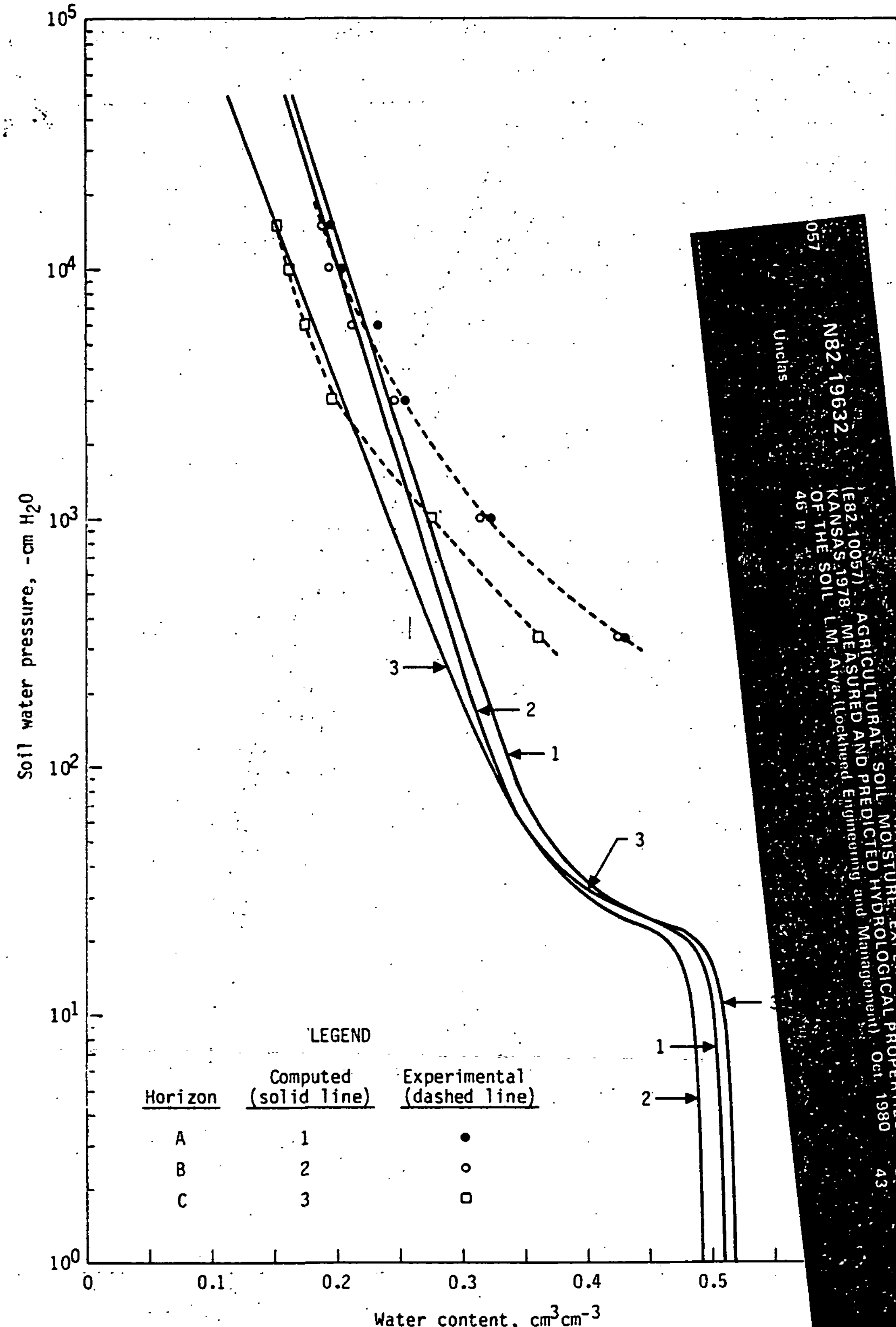


Figure 3-1.- Soil water pressure versus soil water content relationships for Keith silt loam computed from the regression model.



Horizon	Computed (solid line)	Experimental (dashed line)
A	1	●
B	2	○
C	3	□

Figure 3-2.- Soil water pressure versus soil water content r
for Keith silt loam computed from the Rogowski mode

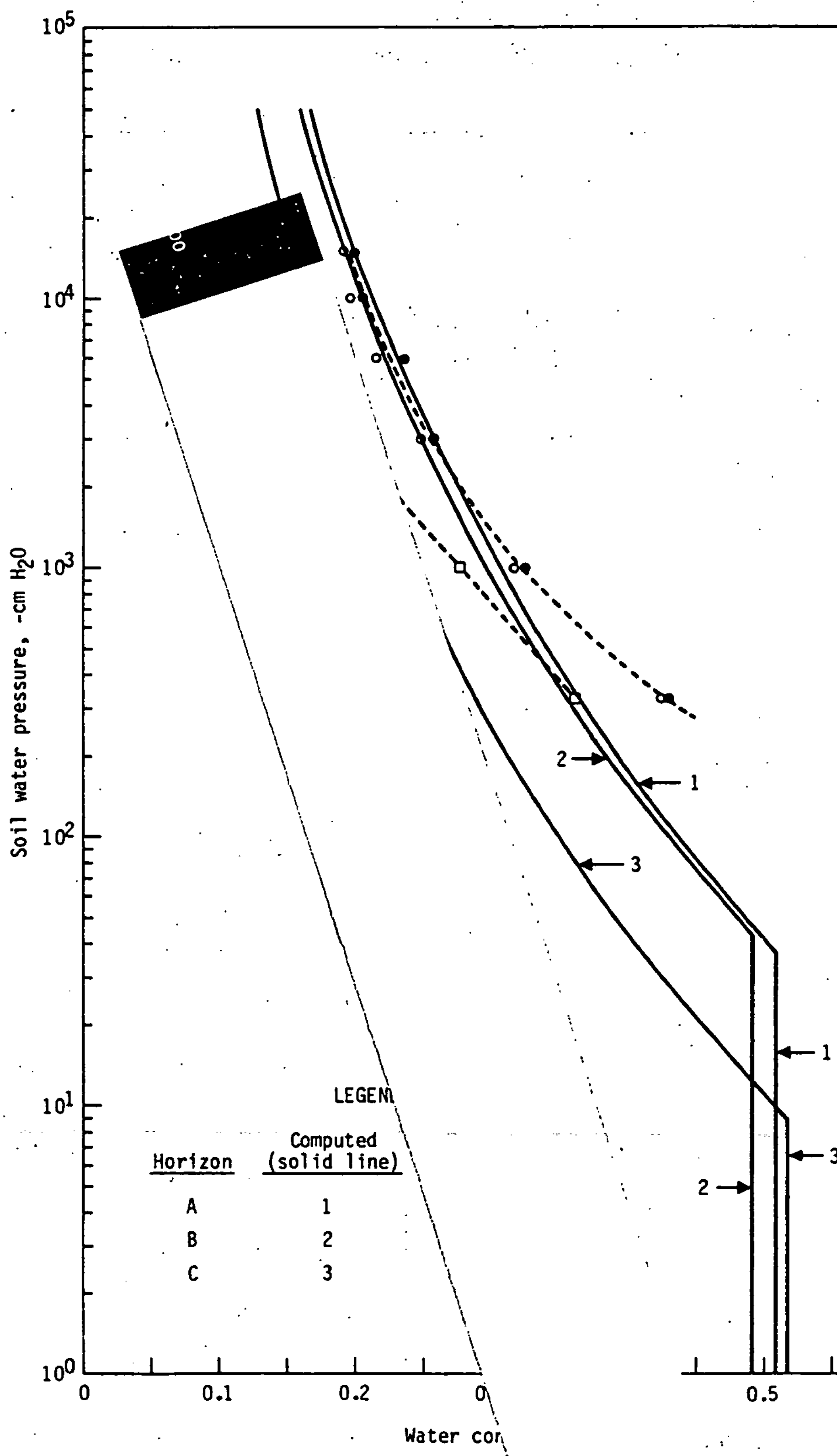


Figure 3-3.- Soil water pressure ver ...ter content relationships for Keith silt loam comput rom the Ghosh model.

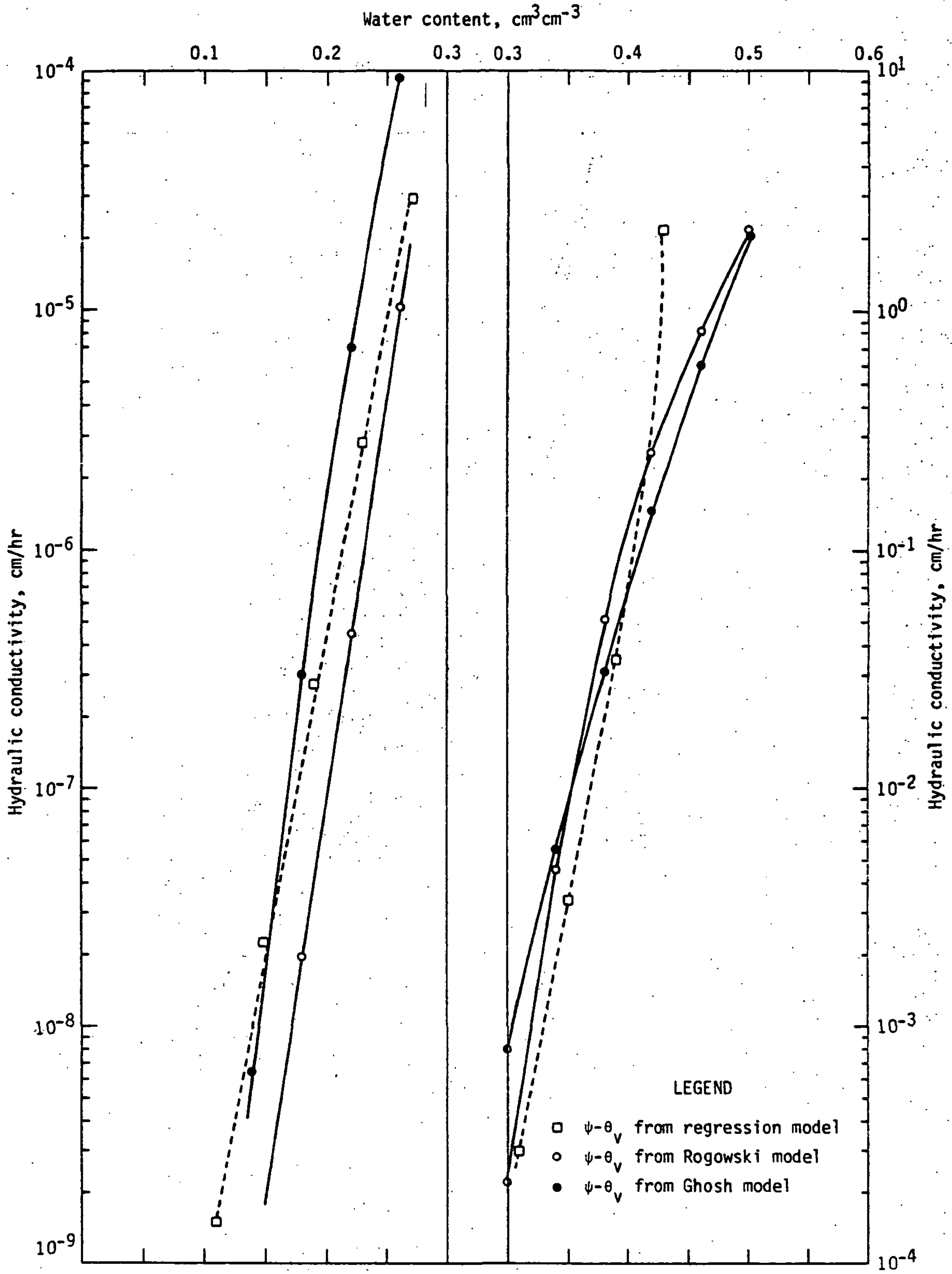


Figure 3-4.- Computed hydraulic conductivity as a function of water content for the A and B horizons in Keith silt loam.

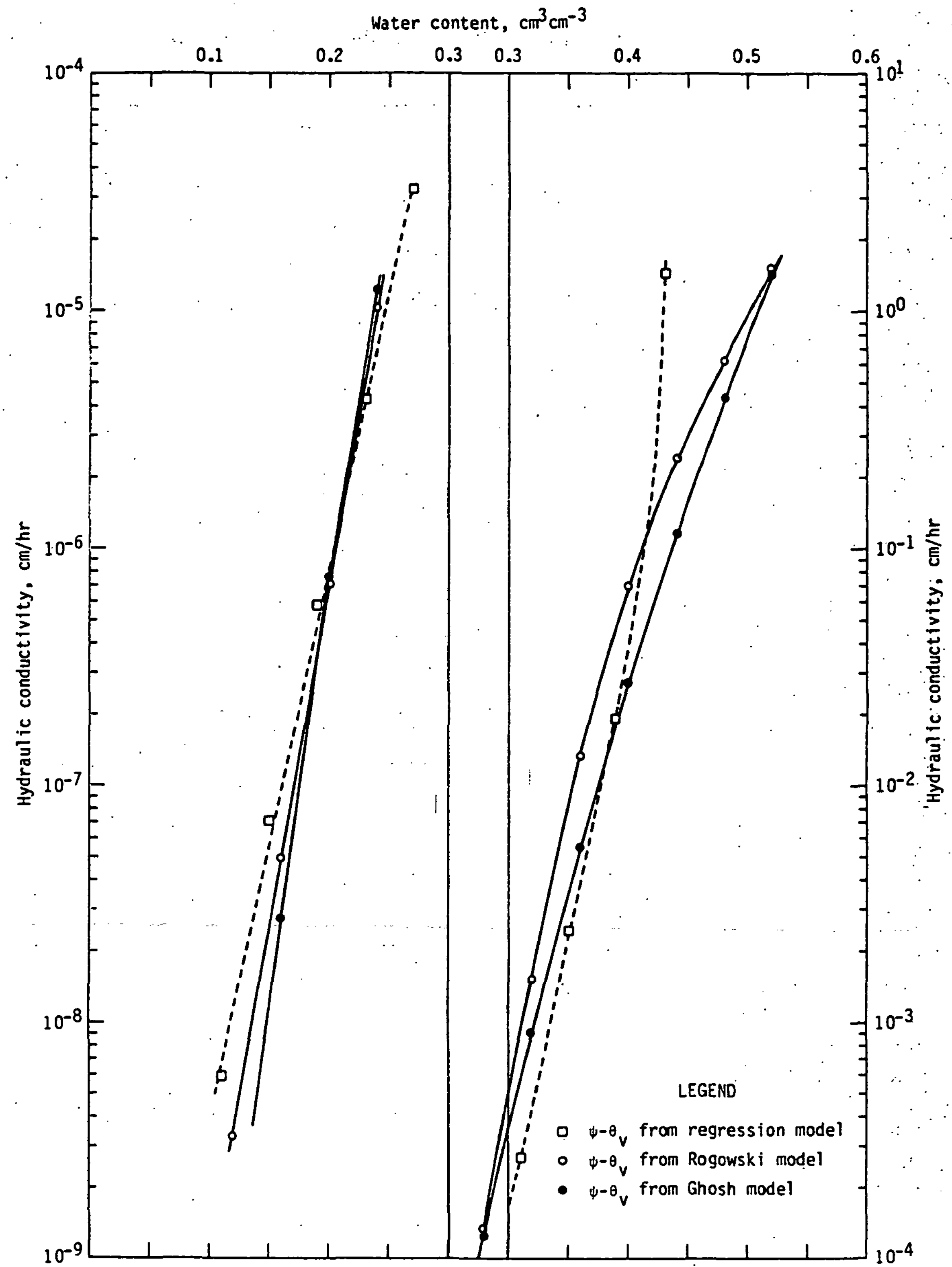


Figure 3-5.- Computed hydraulic conductivity as a function of water content for the C-horizon in Keith silt loam.

4. CONCLUDING REMARKS

For hydraulic conductivity versus soil water content relationships, Marshall's model and its modifications have been shown to represent field conditions adequately. However, because the soil water pressure versus water content relationship and saturated hydraulic conductivity are key inputs to the hydraulic conductivity model, the accuracy of these properties would largely determine the quality of the predicted hydraulic conductivity data.

The regression, Rogowski, and Ghosh models, used to obtain soil water pressure versus soil water content relationships for Keith silt loam at Colby, represent two approaches. In the regression-type approach, no attempt is made to incorporate hydrophysical characteristics of the soil into the model. Hence, predicted results may be useful only to evaluate variations between soils resulting from such factors as texture, bulk density, and organic matter. The Rogowski and Ghosh models, on the other hand, represent the analytical approach and do, in fact, consider some well-recognized hydrophysical quantities, such as water content at one or two specified soil water pressures, soil water content and pressure at the air-entry point, and saturated water content. Thus, the results of the analytical approach may represent a more realistic description of soil hydrologic characteristics than ~~will~~ the regression approach. Colby experimental water contents in the drier range were used as inputs to the Rogowski and Ghosh models; therefore, agreement between experimental and predicted data in that range does not constitute proof of the models' predictive ability. Additional tests over a wide range of water contents need to be carried out. In the wet range, soil water pressure and water content corresponding to the air-entry point and saturation values were based on data in the literature and may not be representative of Keith silt loam soils at Colby. Thus, the reliability of data generated from the Rogowski and Ghosh models should be considered within the limits of the assumptions that experimental water contents in the drier range are valid and that the literature-based air-entry and saturation values are applicable to Keith silt loam.

5. RECOMMENDATIONS

Analyses of physical and hydrologic properties of Keith silt loam indicate similarities between the A and B horizons, which together appear distinctly different from the C-horizon. As far as possible, the two sections of the profile should be treated separately.

Computed hydrologic properties presented in this report appear typical of most loam to silt loam soils and should be adequate for the purpose of comparing different soil moisture models. The results from analytical models should be preferred over those from regression-type models.

Concerning the effects of hydrologic properties on the ability of a soil moisture model to predict the measured soil moisture regime, experimentally determined hydrologic properties would appear more appropriate than those predicted. When detailed information is not available, experimental determination of the soil water pressure versus soil water content relationship near saturation, at the air-entry point, and at a pressure of -15 000 centimeters should be the minimum requirement. In the wet range, field measurements should be preferred over laboratory measurements.

In the application of soil moisture models to the task of predicting soil moisture regime over large areas comprising a variety of soils, it is highly unlikely that experimental data pertinent to different soils would be available. Nor would it be economically feasible to devote experimental efforts. Furthermore, in view of the large variability between soils (even within a series), such efforts would not be justified. Therefore, much of the application of soil moisture models will have to depend on predicted hydrologic properties.

In order to develop reasonable predictive methods, it is recommended that

a. Models for predicting soil hydrologic properties be extracted from the literature

b. For as many soils as possible, a catalog of experimentally determined soil hydrologic properties and such basic properties as are necessary as inputs for the models be developed, maintained, and updated

c. The effects of predicted soil hydrologic properties on predictive performance of soil moisture models be evaluated

d. Efforts be directed toward modification and improvement of existing models

6. REFERENCES

1. Milstead, B. W.: Agricultural Soil Moisture Experiment: 1978 Colby (Kansas) Data Catalog and Documentation. Lockheed technical report LEC-13226 (JSC-16229), NASA/JSC (Houston), Sept. 1979.

2. USDA/SCS Soil Survey of Thomas County, Kansas. Unpublished.

3. Rogowski, A. S.: Estimation of the Soil Moisture Characteristic and Hydraulic Conductivity: Comparison of Models. Soil Sci., vol. 114, 1972, pp. 423-429.

4. Nielsen, D. R.; Biggar, J. W.; and Erh, K. T.: Spatial Variability of Field-Measured Soil-Water Properties. Hilgardia, vol. 42, no. 7, 1973, pp. 215-259.

5. Croney, D.; and Coleman, J. D.: Soil Structure in Relation to Soil Suction (pF). J. Soil Sci., vol. 5, 1954, pp. 75-84.

6. Sharma, M. L.; and Uehara, G.: Influence of Soil Structure on Water Relations in Low Humic Latosols. I, Water Retention. Proc. Soil Sci. Soc. America, vol. 32, 1968, pp. 765-768.

7. Klute, A.: Laboratory Measurement of Hydraulic Conductivity of Saturated Soil. Methods of Soil Analysis, part I, C. A. Black et al. (eds.), American Soc. Agronomy (Madison, Wisc.), 1965, pp. 210-221.

8. Soil Survey of Thomas County, Kansas. USDA/SCS Soil Survey Laboratory (Lincoln, Nebr.), 1958.

9. Hall, D. G. M.; Reeve, M. J.; Thomasson, A. J.; and Wright, V. F.: Water Retention, Porosity, and Density of Field Soils. Tech. Monograph 9, Roltamsted Experimental Station (Harpenden, England), 1977.

10. Baver, L. D.; Gardner, W. H.; and Gardner, W. R.: Soil Physics. Fourth ed. John Wiley and Sons, Inc. (New York), 1972.

11. Rogowski, A. S.: Watershed Physics: Model of the Soil Moisture Characteristic. Water Resources Res., vol. 7, no. 6, 1971, pp. 1575-1582.

12. Ghosh, R. K.: Model of the Soil Moisture Characteristic. J. Indian Soc. Soil Sci., vol. 24, 1976, pp. 353-355.

13. Jackson, R. D.: On the Calculations of Hydraulic Conductivity. Proc. Soil Sci. Soc. America, vol. 36, 1972, pp. 380-382.

14. Marshall, T. J.: A Relation Between Permeability and Size Distribution of Pores. J. Soil Sci., vol. 9, 1958, pp. 1-8.

APPENDIX

FORTRAN PROGRAM FOR THE COMPUTATION OF UNSATURATED HYDRAULIC CONDUCTIVITY

APPENDIX

FORTRAN PROGRAM FOR THE COMPUTATION OF UNSATURATED HYDRAULIC CONDUCTIVITY

FILE: HYCOND   FORTRAN A   CONVERSATIONAL MONITOR SYSTEM

```
C       HYCOND PROGRAM
C       THIS PROGRAM CALCULATES HYDRAULIC CONDUCTIVITY FROM SOILS DATA.
C       EPSILN  IS WATER CONTENT IN VOLUMETRIC FRACTION.
C       SKAY IS MEASURED SATURATED HYDRAULIC CONDUCTIVITY.
C       M IS THE NUMBER OF WATER CONTENT INTERVALS FOR WHICH
C       COMPUTATIONS ARE MADE.
C       H IS THE SOIL WATER PRESSURE AT THE MIDPOINT OF THE WATER
C       CONTENT INTERVALS.
C       TKAY IS THE CALCULATED HYDRAULIC CONDUCTIVITY.
        DIMENSION H(50), EPSILN(50)
        READ(5,25) SKAY,P,M
   25   FORMAT(2X,E11.4,F5.2,I3)
        WRITE(6,25) SKAY,P,M
        DO 5 I=1,M
        READ(5,30) H(I),EPSILN(I)
    5   WRITE(6,30) H(I),EPSILN(I)
   30   FORMAT(1X,E12.4,F4.2)
        SUM2=0
        DO 20 I=1,M
        SUM1=0
        DO 10 J=1,M
        X=I
        Y=J
        VALUE1=(2*Y+1-2*X)/H(J)**2
        IF(I.GT.1)GO TO 7
        VALUE2=(2*Y-1)/H(J)**2
        SUM2=SUM2+VALUE2
    7   SUM1=SUM1+VALUE1
C       WRITE(16,30) VALUE1,VALUE2
   10   CONTINUE
        FACTR=SUM1/SUM2
   12   TKAY=(SKAY)*((EPSILN(I)/EPSILN(1))**P)*FACTR
        WRITE(6,41)SUM1,SUM2,TKAY
        PUNCH41,SUM1,SUM2,TKAY
        WRITE(16,41) SUM1,SUM2,TKAY
   41   FORMAT(1X,3E12.4,/)
   20   CONTINUE
        STOP
        END
```

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SM-LO-00463
JSC-16366

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October 28, 1980

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FT. BELVOIR, VA

WRSC-C/H. McKim

SIOUXFALLS, SD

G. Metz	USDI
A. Watkins	USGS

BROOKINGS, SD

D. Moore
V. Myers

WATERLOO, WI

J. Paster/Radiation Monitoring Div.

TEMPLE, TX

J. Ritchie - USDA/SEA-AR

UNIV. OF ARKANSAS

D. Scott
W. Waite

WATERTOWN, MA

J. Steidley/Radiation Mon. Devices

SILVERSPRING, MD

R. Whitman/ORI

BELTSVILLE, MD

T. Engman	USDA/SEA-AR
T. Jackson	USDA/SEA-AR
R. F. Paetzold	USDA/SCS
J. Ritchie	USDA/SEA-AR

PULLMAN, WA

K. Saxton - USDA/SEA-AR

OREGON STATE UNIV.

M. Schlisinger

UNIV. OF CALIF. AT DAVIS

D. Nielson

10/9/80

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