

Estimating Groundwater Recharge
From Conservation Bench Terraces

by

William H. Neibling

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Approved:



Major Professor

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Estimating Groundwater Recharge
From Conservation Bench Terraces
(William Howard Neibling, M.S. 1976)

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INTRODUCTION

This series of three papers deals with the successive stages necessary in my analysis for determining the potential for groundwater recharge from conservation bench terraces. Due to the small number of recharge events that were likely to occur over the period of my masters program and the difficulty in measuring actual recharge from them, I decided to study the problem by using a continuous water-budget type computer model. The model was calibrated and verified using field data obtained from two conservation bench terraces constructed at the Garden City, Kansas, Branch Agricultural Experiment Station. A typical cross section of a conservation bench terrace system is shown in Figure 4, page 17.

Accurate prediction of water movement between adjacent soil layers in the 213 cm profile required the knowledge of soil water potential-soil water content and unsaturated hydraulic conductivity-soil water content relationships for the Richfield silt loam soil found on the conservation bench terrace area at Garden City. None were available in the literature, so laboratory tests were conducted to determine the relationships. The resulting curves and the procedures used in obtaining them are discussed in Chapter 1, and in more detail in Appendix A.

The water budget model discussed in Chapter 2 utilized these relationships to calculate daily soil water movement across the 183 cm depth boundary. The summation of soil water movement (downward taken as positive) across the 183 cm depth boundary was taken as daily groundwater recharge. Computer runs using 30 years of historical weather records were made to model four combinations of crop rotations and watershed:bench ratios utilized on the conservation bench terraces installed at Garden City. Runs were made using a wheat-fallow rotation on the watershed areas and either wheat-fallow or con-

tinuous grain sorghum rotations on the benches. Watershed:bench area ratios of 2:1 and 4:1 were tested. The results of these runs are discussed in Chapter 3.

Chapter 1: SOIL MOISTURE RELATIONSHIPS FOR A RICHFIELD SOIL

With more sophisticated computer models becoming widely used in modeling various aspects of soil moisture movement within a soil profile, unsaturated hydraulic conductivity-soil moisture content and soil water potential-soil moisture content relationships are required for the soil in question. These two relationships are necessary functions for the model developed in Chapter 2. No relationships for a Richfield silt loam were found in the literature so laboratory tests were performed to determine them.

The Richfield Series

According to the 1972 USDA, SCS Soil Survey of Lane County, Kansas, the Richfield series in the Garden City area consists of deep, nearly level to sloping, well drained soils on the tableland and on knolls and ridges in the rolling upland. These soils formed in deep loess.

In a representative Richfield profile, the surface layer is grayish-brown, noncalcareous heavy silt loam about 13 cm thick. The A horizon ranges from 10 to 25 cm in depth. The subsoil, about 53 cm thick, is a dark grayish-brown, noncalcareous, friable silty clay loam in the uppermost part. The middle portion of the subsoil is a grayish-brown, noncalcareous firm heavy silty clay loam. The lowermost portion is light brownish-bray, strongly calcareous, firm silty clay loam that contains many threads, films and small soft concretions of lime. The depth to lime ranges from 25 to 46 cm. The underlying material, to a depth of about 130 cm, is light gray, strongly calcareous light silty clay loam. Richfield soils have a high available water capacity and moderately slow permeability.

Soil Water Potential-Soil Moisture Curve Procedure

Most methods for determining soil water potential-soil moisture content consist essentially of exposing a soil sample to a desired tension or pressure for a specific amount of time, and either measuring water outflow from the sample during the time period or soil moisture content at the end of the period. The procedure is then repeated for each point used in constructing the soil water potential-soil moisture content curve. Most procedures vary only in the type of equipment used at each pressure step and the time allowed at each step for the sample to come to equilibrium.

The procedure I used is outlined in more detail in Appendix A. Detailed instructions were found in a laboratory exercise written by Dr. W. L. Powers, Dept. of Agronomy, Kansas State University (personal communication).

The tests I ran were conducted at the Kansas State University Evapotranspiration Laboratory, using three different sets of equipment. From zero tension (saturation) to 9.800 kilopascals (kPa) a Buchner funnel apparatus was used. Each undisturbed 7.62 x 7.62 cm cylindrical sample was placed in a funnel and after initial saturation was exposed to the tension created by 5, 10, 25, 50, 75 and 100 cm long columns of water, allowing one day for each equilibration. Outflow from each tension increment was recorded.

From 9.8 kPa to 1.47 megapascals (MPa) air pressure was used to extract soil water. One very basic assumption made was that the soil moisture content would be the same or close to the same under equilibrium tension or pressure conditions. From 9.8 kPa to 196 kPa a set of pressure cells with 196 kPa bubbling pressure ceramic membranes were used. The same samples used in the first set of experiments were again saturated and exposed to 9.8 kPa for 48 hours to re-establish the equilibrium conditions previously obtained on

the Buchner funnels. The samples were then exposed to pressures of 19.6 kPa, 78.4 kPa, 137 kPa and 196 kPa, allowing one day for equilibration at each pressure setting. The outflow from each pressure step was recorded and sample moisture contents determined by the gravimetric method after the 196 kPa outflow was recorded. Soil moisture contents at the end of each pressure step were back-calculated from the known moisture content at 196 kPa and outflow measurements, giving the desired curves over the 0-196 kPa range.

For soil water potentials in the 490 kPa to 1.47 MPa range, a set of three pressure membrane plates was used. The dried, undisturbed samples from the 196 kPa pressure cells were crushed, poured into 3.8 cm diameter rubber rings resting on the cellulose membranes and allowed to come to saturation. Pressures of 490 kPa, 980 kPa, and 1.47 MPa were applied to the three plates for six days. Samples were assumed to be at equilibrium, or close enough to it for practical purposes, at the end of six days. Measurement of outflow from each plate confirmed this assumption. The samples from the three plates were oven-dried and weighed. From these data, the curve points from 490 kPa to 1.47 MPa for each sample were determined. The soil water potential-soil moisture content curves for our Richfield silt loam are shown in Figure 1.

Unsaturated Hydraulic Conductivity-Soil Moisture Content Curves

Several factors were considered in determining which of the methods available to determine unsaturated hydraulic conductivity should be used. First, the method had to be compatible with the equipment, or minor modifications in the equipment available at the Evapotranspiration Laboratory. Second, time requirements, both from periods of equipment availability and man-hours necessary to run the tests should be minimized. And finally, realizing

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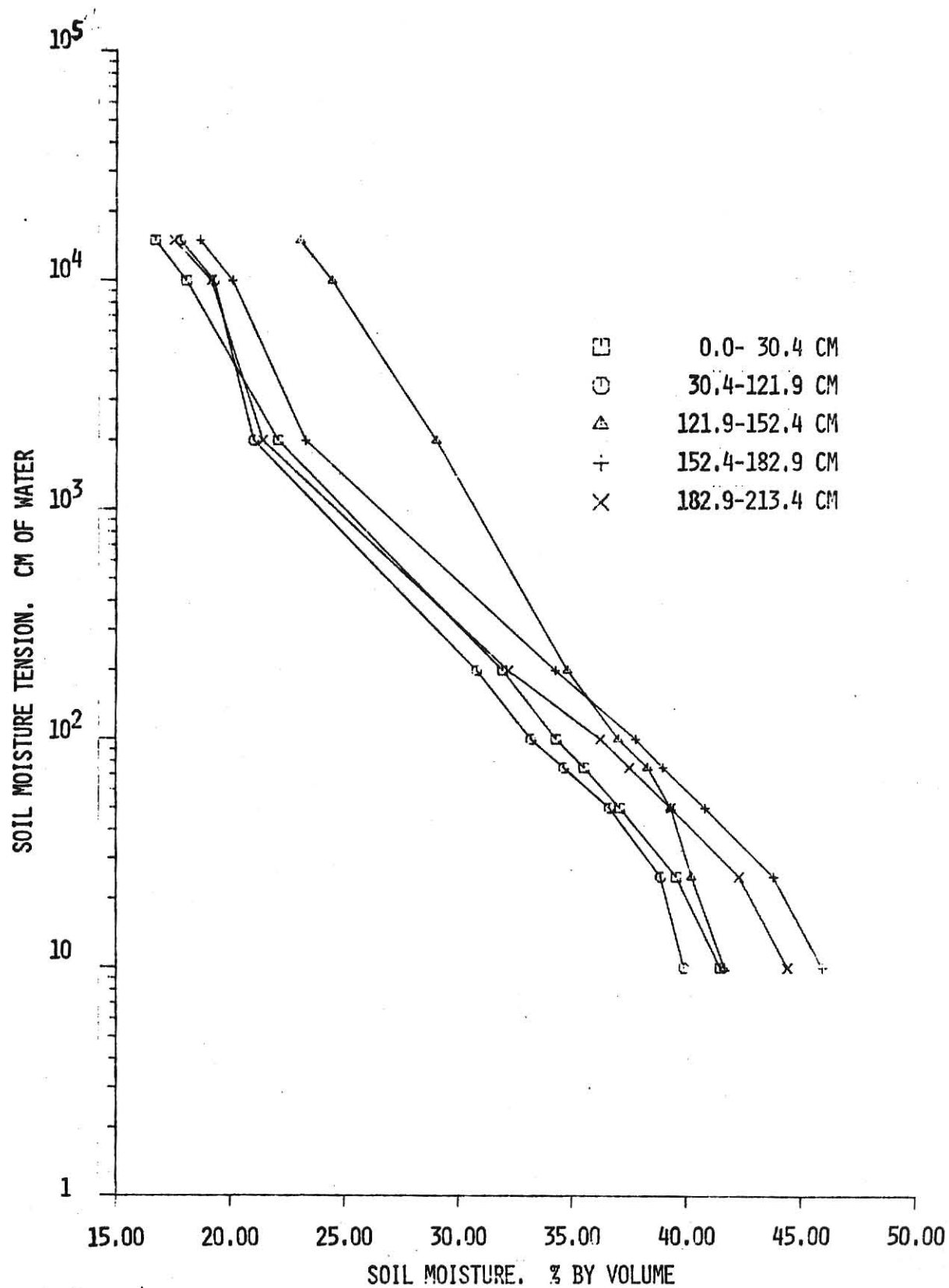


Figure 1. Soil Moisture Retention Curves for Richfield Silt Loam.

the great variability in soil properties with location in a plot for the same soil, some accuracy could be sacrificed for the sake of simplicity and reduced time requirements.

Kirkham and Powers (1972) give an excellent discussion of various methods of determining unsaturated conductivity (or the related unsaturated diffusivity) and the general approach taken by each as reported through 1971. Several additional methods reported since 1971 were also considered (Bouma and Denning, 1972; Gupta et al, 1974; Hillel, et al, 1972; Klute, 1972; Smiles and Harvey, 1973; Stroosnijder and Bolt, 1974).

The One-Step Method as reported by Doering (1965) was selected as a compromise between simplicity, shortened time requirements, general compatibility with existing equipment and accuracy. The accuracy of this procedure, especially at soil moistures near saturation has been questioned (Gupta, et al, 1974), but was deemed sufficiently accurate for use in the model developed in Chapter 2.

In Doering's method, diffusivity is calculated by Equation 1 developed by Gardner (1962):

$$D = \frac{4L^2}{\pi^2 (W - W_f)} \frac{dW}{dt} \quad (1)$$

where D = soil diffusivity in cm^2/hour

L = sample length, cm

dw/dt = change in water content with time (e.g. outflow per time divided by sample volume, here 347.5 cm^3)

W = sample water content, percent by volume, when the rate dW/dt is determined

W_f = final equilibrium sample water content, percent by volume

Equation 2 converts calculated diffusivity to unsaturated hydraulic conductivity (Doering, 1965):

$$K = -D \frac{dW}{ds} \quad (2)$$

K is unsaturated hydraulic conductivity in cm/hour and dW/ds is the slope of the soil water potential vs. soil water content curve at the soil water content represented by D.

Undisturbed samples identical to those for the soil water potential-soil moisture tests were collected and prepared as described in Appendix A. Equipment arrangement was identical to that required for the 9.8-196 kPa pressure cell determination of soil water potential-soil moisture content tests with two exceptions. First, a plastic pipe tee fitting and a 15-cm long vertical plastic standpipe was attached to the outflow line on each set of equipment. Second, outflow was collected in 10 ml graduated cylinders instead of in sealed 150 ml beakers. This allowed rapid observation and recording of outflow data. A small one-hole rubber stopper was fitted over each of the outflow pipe tips and into the mouth of a graduated cylinder to prevent evaporation losses. A small vent notch was cut in each stopper to prevent pressure increase in the cylinders. On a preliminary run, air accumulated in the curved area of the outflow tips and blocked water passage into the cylinders. This greatly interfered with the outflow vs. time measurements necessary in this procedure. The standpipes were added to eliminate the problem and in most cases worked well.

Experimental Procedure

The samples were soaked for 48 hours to achieve saturated conditions. Air pressure equal to 196 kPa was applied, with outflow measurements from each core beginning immediately. The initial outflow rates were quite large and required the use of 25 ml graduated cylinders for ease of reading and ability to "keep up" with the equipment. Time increments were selected so that the outflow for all cores was usually between 0.5 and 1.5 ml for each period. This gave between 100 and 150 data points, producing good definition of the accumulated outflow vs. time curve, Figure 2. The pressure was applied

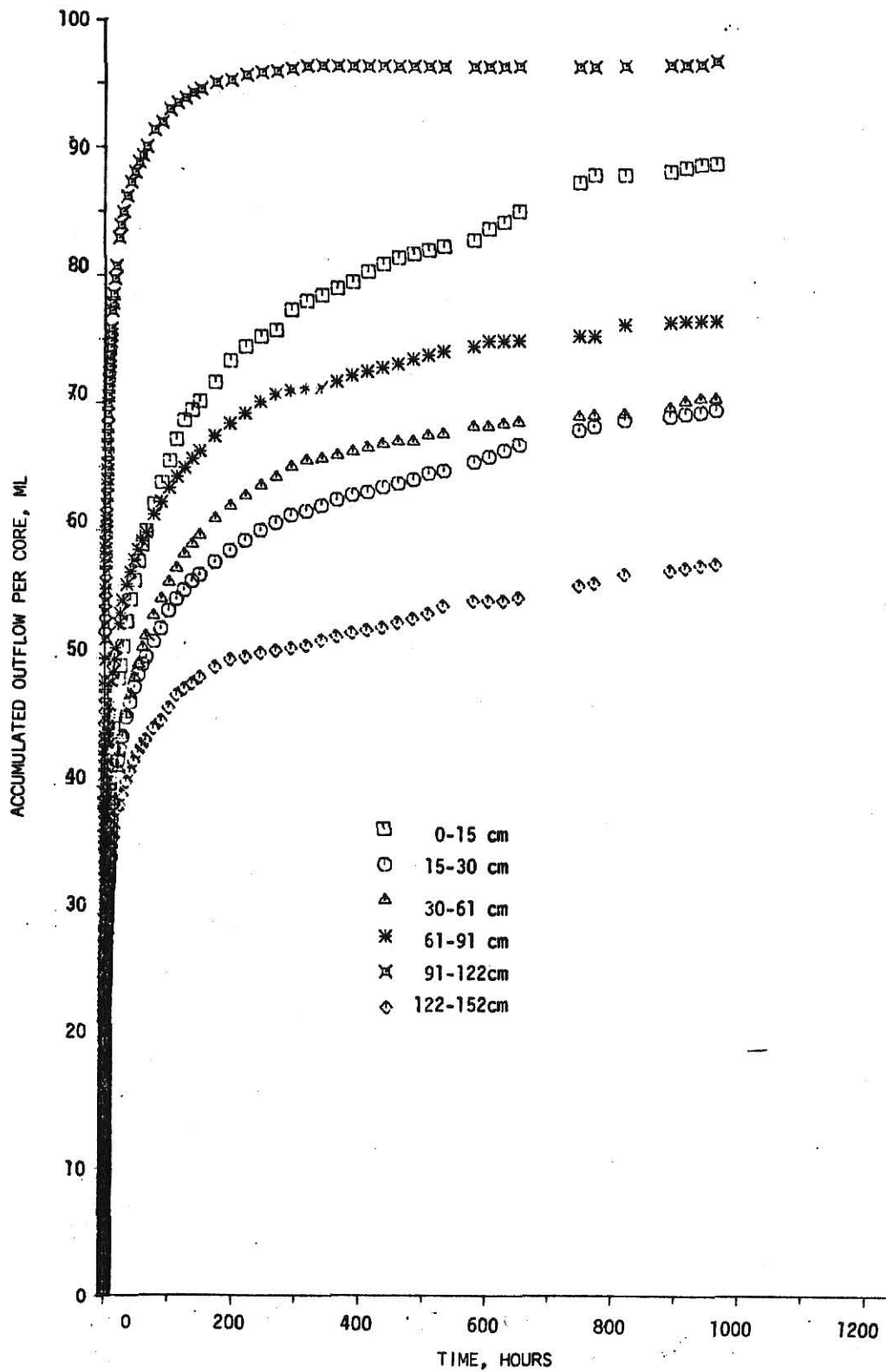


Figure 2. Accumulated Outflow Over Time from 3.62 x 3.62 cm Cylinders of Richfield Silt Loam with 196 kPa Applied Pressure.

and outflow recorded for 40 days. At that time none of the cores had reached equilibrium, but all were sufficiently close to justify ending the experiment.

Doering (1965) made plots of accumulated outflow vs. time and graphically determined the slope (d accumulated outflow/ d time) at various times and divided this instantaneous outflow rate by the sample volume (347.5 cm^3 in this case) to obtain the dW/dt values used in Equation 1. Repeating this procedure for each data point would give the curves shown in Figure 3.

Two methods of calculating unsaturated hydraulic conductivity were used in obtaining the curves shown in Figure 3. Both were modifications of Doering's (1965) One-Step Method. In Method 1 the slope of the accumulated outflow vs. time curve was obtained by taking the first derivative of a continuous function fitted to the data. Doering determined this slope graphically from the actual data. All other parts of the Method 1 procedure were the same as Doering's procedure.

Method 2 again used continuous functions to describe the accumulated outflow vs. time curves shown in Figure 2. It also used the curve fitting equations of soil water potential vs. soil moisture content in determination of unsaturated hydraulic conductivity values. From these developed relationships and Equations 1 and 2, direct relationship between unsaturated hydraulic conductivity and soil moisture content was developed.

Method 1

The model developed in Chapter 2 required a continuous function with unsaturated hydraulic conductivity as the dependent variable and soil moisture content as the independent variable. A statistical analysis showed that for the soil depths considered, accumulated outflow vs. time could be described by a general equation of the form:

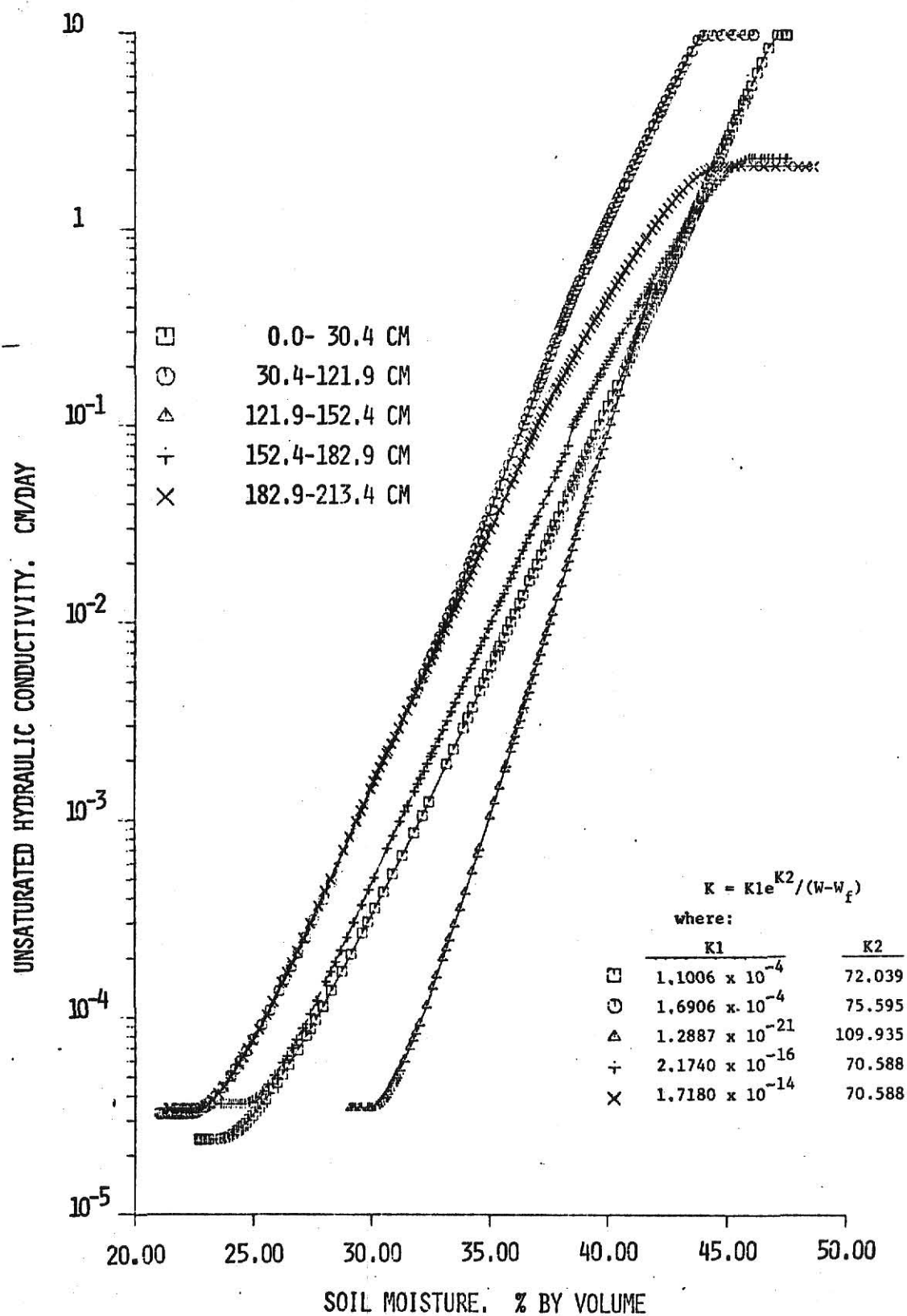


Figure 3. Unsaturated Hydraulic Conductivity- Soil Moisture Relationships for Richfield Silt Loam.

$$Y = a + b \ln x \quad (R^2 \text{ from } 0.974 \text{ to } 0.995) \quad (3)$$

where Y is accumulated outflow in cm, x is time in hours, and a and b are constants evaluated for each depth. Similarly, soil water potential (H) vs. soil moisture (W) in the 980 Pa-1.47 MPa range could be described by

$$H = c - d \ln W \quad (R^2 \text{ from } 0.981 \text{ to } 0.995) \quad (4)$$

where c and d are constants evaluated for each depth.

By differentiating Equation 3 with respect to time, an equation for the instantaneous outflow rate was produced. Using values from this equation and dividing them by the sample volume of 347.5 cm^3 , the values of dW/dt for use in Equation 1 were calculated. Values for a specific soil moisture content were then substituted into Equation 1 and the corresponding unsaturated diffusivity calculated. Use of Equation 4 provided the unsaturated conductivity-soil moisture content points necessary to develop the curves in Figure 3.

Method 2

By manipulating Equations 1, 2, 3, and 4 Equation 5 was obtained:

(A complete derivation is available in Appendix A.)

$$K = \frac{1.625 \, bd}{-N(W-W_f) \frac{dW}{dH}} \quad (5)$$

where

$$N = \frac{347.5 \, W_i}{e \, b} = \frac{a}{b} - \frac{c}{d} \quad (6)$$

Equations 5 and 6 allowed direct calculation of an unsaturated hydraulic conductivity value for a given soil moisture content.

N = a constant

K = unsaturated hydraulic conductivity, cm/day

a, b, c, d , are coefficients for Equations (3) and (4) at the desired depth (see Appendix A for actual values)

W = water content, percent by volume, at which a value of K is desired

W_f = final sample equilibrium water content at 196 kPa

V = sample volume, here 347.5 cm³

W_1 = water content when the 196 kPa pressure was first applied (assumed to be saturation water content)

Results and Conclusions

Values of apparent specific gravity, field capacity and permanent wilting point obtained from the soil water potential-soil moisture content tests are summarized in Table 1. Data from Method 1 of the unsaturated hydraulic conductivity-soil moisture content procedure are plotted as shown in Figure 3. Conductivities for water contents ranging from that at final equilibrium water content at 196 kPa (22-25 percent by volume) to 38 percent by volume were calculated. Comparisons between conductivities calculated by Methods 1 and 2 were made. Method 1 was judged to provide a better fit. Differences in Method 2 with respect to Method 1 for each sample ranged from 5 to 60 percent in the W_f to 38 percent by volume soil moisture range. In most samples W_f was approximately twenty-three percent by volume. The curves calculated by Method 2 were corrected with a series of linear factors to give values within 5 percent of those calculated by Method 1 in the W_f to 38 percent by volume soil moisture range. Gupta et al (1974) reported that for soil moisture contents approaching saturation, the One-Step Method overpredicted unsaturated hydraulic conductivity. Because of this, calculated conductivities above 10 cm/day were set equal to 10 cm/day. Conductivities at soil moisture contents below that for the minimum conductivity calculated for each sample were set equal to the minimum conductivity calculated. Due to equipment limitation, the maximum allowable pressure was 196 kPa. (A more complete explanation of problems encountered with Method 2 and reasons for the above corrections are given in Appendix A.)

Table 1. Soil Moisture Related Properties of Richfield Silt Loam.

Depth, cm	Apparent Specific Gravity	Percent Pore Space	Field Capacity ^a	Permanent Wilting Point ^b
0-15	1.46	44.90 ^c	31.96	16.03
15-31	1.43	46.42	31.93	17.37
31-61	1.55	41.51	31.19	17.71
61-91	1.56	41.13	30.48	17.01
91-122	1.47	44.53	30.71	18.65
122-152	1.48	44.15	34.80	23.03
152-183	1.39	47.55	34.25	18.64
183-213	1.36	48.68	32.19	17.52
213-244	1.34	49.43	33.71	17.54
244-274	1.32	50.19	35.87	15.67

^a19.6 kPa., Soil moisture content in percent by volume.

^b1.47 MPa., Soil moisture content in percent by volume.

^cin percent by volume

$$\text{Pore Space} = \frac{\rho_b}{1 - \rho_b} \times 100 \quad \text{where } \rho_b = 2.65 \text{ and } \rho_p = \text{apparent}$$

specific gravity.

The wide variation in hydraulic conductivities obtained from different samples of the same soil type, the errors introduced by equipment limitations, and those inherent in the One-Step Method may not accurately reflect actual field conductivities. However, the uncorrected results of Equations 5 and 6 probably predict unsaturated conductivity as well as can be expected by laboratory procedures. Method 1, or some of the other methods mentioned earlier may provide more accurate estimates of conductivity, but they may in fact be implying more precision than is actually possible in sample collection and experimental procedures. The model in Chapter 2 required unsaturated conductivity as an input in a Darcy equation calculation of moisture flow between two adjacent soil layers. In that model, errors of up to 100 percent in unsaturated hydraulic conductivity will produce negligible differences in the quantity of water flowing between layers in the soil moisture content range occurring naturally. Therefore, Equations 5 and 6 may be used directly in the model with very little error.

Summary

Soil water potential-soil moisture and unsaturated hydraulic conductivity-soil moisture relationships for a Richfield silt loam soil at the Garden City, Kansas, Branch Agricultural Experiment Station were developed for use in a computer simulation model of soil moisture movement.

The soil water potential-soil moisture relationships from 0-1.47 MPa were developed using rather standard Buchner funnel-outflow, pressure cell-outflow and pressure plate-equilibrium soil moisture content procedures. Curves were developed for soil layers in the zero to 213 cm profile over the saturation to permanent wilting point range (e.g. 0-1.47 MPa).

Unsaturated hydraulic conductivity-soil moisture curves for the same soil profile were computed by Doering's One-Step Method (1965). The effective range of the curves was from about 23 to 38 percent by volume with values of unsaturated hydraulic conductivity for soil moisture contents above or below this range set equal to those at 38 or 23 percent respectively. A continuous function was developed to compute unsaturated hydraulic conductivity over the above range for any given soil moisture content. Although other investigators (Gupta et al. 1974) have shown possible errors in conductivity calculations by the One-Step Method over certain moisture ranges, the accuracy of the curves produced was considered sufficient for use in soil moisture movement models.

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Chapter 2: A CONTINUOUS WATER BUDGET MODEL FOR WESTERN KANSAS

With computer simulation the long-term effects of changes in specific parameters in a study may be investigated in a period of days, instead of the years required for collection and study of field data. In this way only the most promising combinations of parameters involved in the study need be field tested.

The ability to accurately model evapotranspiration and the changes over time in soil moisture contents at desired depths in the soil profile allows model calculations of the kinds of information necessary for the various water-use, and fallow efficiency problems peculiar to the western Kansas climate. The model as presently written is set up to model hydrologic variables on both the sloping contributing watershed area and the leveled bench area of a conservation bench terrace. A typical cross section of a conservation bench terrace system is shown in Figure 4.

Models similar to mine have been reported by Saxton et al. (1974), Anderson (1975), and Kanemasu (1975). Some were developed and calibrated for a different climate and crops than we desired while others provided very good models of only some of the processes we wished to model. This model was to be developed to study hydrologic variables in western Kansas but was to be written with enough flexibility to be readily modified for use elsewhere.

The Model

This model is a continuous watershed model with interflow assumed to be negligible and streamflow not calculated. The main objective of the present model is to estimate soil moisture movement so that groundwater recharge rates may be estimated as various input parameters are changed.

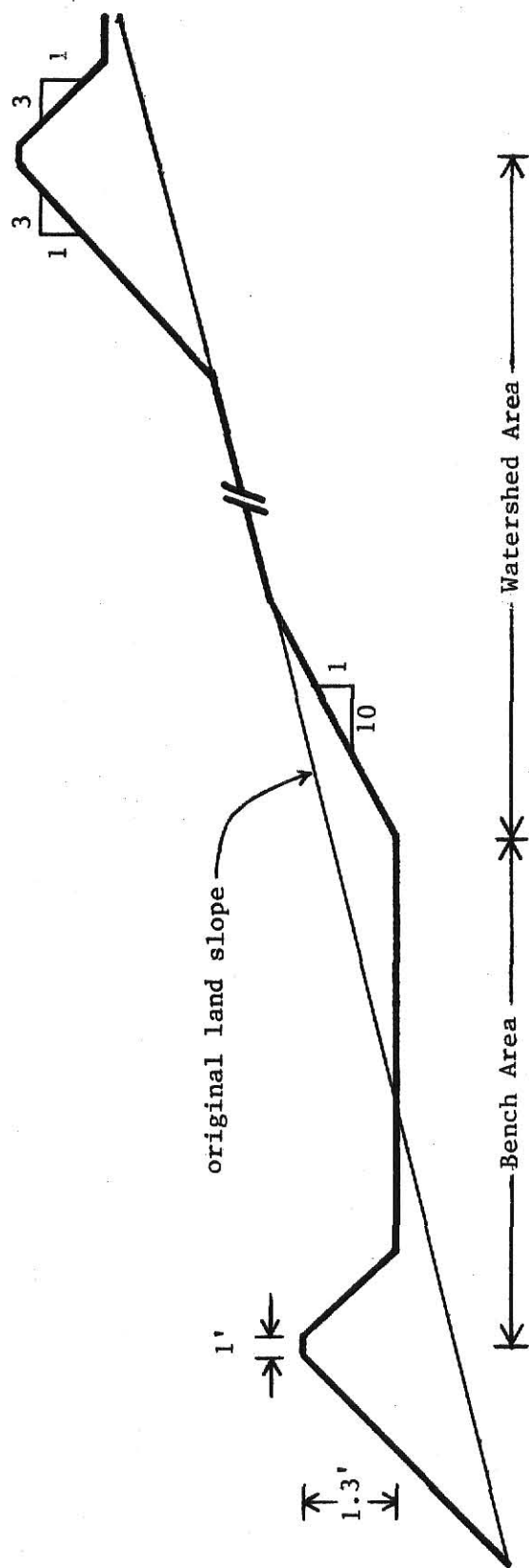


Figure 4. Cross Section of Conservation Bench Terrace System.

The approach used to model soil moisture movement in this work is similar in many respects to that of Saxton et al. (1974) and Anderson (1975).

General inputs required for the model are the crop rotations desired on the watershed and bench areas, the watershed:bench ratio desired, and the soil type (irrigation design group from the Kansas Irrigation Guide and Planners Handbook, 1975). These variables are input as constants in the model. (For actual values see Tables 14, 15, and 16, Appendix B.)

Other input data required are:

- Daily maximum and minimum air temperature
- Daily precipitation
- Mean monthly relative humidity
- Mean monthly percent sunshine
- Mean monthly wind speed
- Mid monthly extraterrestrial solar radiation

The daily weather inputs are read from a tape containing records for Garden City, Kansas, from 1912-1974. This data was obtained from the Kansas Agricultural Experiment Station Weather Data Library.

Daily values of potential evapotranspiration (PET), actual evapotranspiration (AET), interception-storage, runoff, surface evaporation and soil moisture movement to or from assumed groundwater storage are calculated. Moisture withdrawal from the 0-15 cm, 15-30 cm, 30-61 cm, 61-91 cm, 91-122 cm, 122-152 cm, 152-183 cm, and 183-213 cm layers, and corresponding changes in soil moisture in each layer are calculated. Daily model outputs are precipitation, runoff water added to the benches, interception-storage, runoff, movement to or from groundwater storage, actual evapotranspiration, and change in soil moisture storage for the 0-183 cm profile. Accounting for these outputs is updated daily and a yearly summary is printed as shown in Table 2. The general model algorithm is shown in Figure 5.

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Table 2. Annual Summary of Computer Model Results

WATER BALANCE (IN CM) IN THE WATERSHED AREA - 1948						
INPUTS			OUTPUTS			CHANGE IN SW
MONTH	PRECIPITATION	INTERCEPTION	SURFACE RUNOFF	PERCOLATION	ACT	
JAN.	3.15	0.13	0.0	-0.06	0.77	-0.65
FEB.	2.57	0.94	0.0	-0.05	1.09	1.24
MAR.	2.59	1.52	0.1	-0.05	1.55	-0.47
APR.	0.0	0.0	0.0	-0.04	0.78	-0.74
MAY	3.02	1.04	0.0	-0.04	1.01	0.12
JUNE	13.41	1.83	1.13	-0.04	3.44	7.36
JULY	4.52	1.73	0.0	-0.04	2.30	-0.75
AUG.	11.56	2.04	0.04	-0.04	6.45	3.11
SEPT.	1.42	0.51	0.0	-0.03	2.36	-1.52
OCT.	2.16	0.85	0.0	-0.03	5.32	-3.03
NOV.	0.43	0.0	0.0	-0.03	2.09	-1.55
DEC.	0.13	0.13	0.0	-0.03	0.76	-0.74
TOT.	42.42	10.43	1.17	-0.47	29.75	1.41

WATER BALANCE (IN CM) IN THE RENCH AREA - 1948						
INPUTS			OUTPUTS			CHANGE IN SW
MONTH	PRECIPITATION	RUNOFF APPLIED	INTERCEPTION	PERCOLATION	ACT	
JAN.	3.15	0.0	0.13	-0.05	1.05	-0.93
FEB.	2.57	0.0	0.94	-0.05	0.53	1.32
MAR.	2.59	0.0	1.52	-0.05	1.97	-0.83
APR.	0.0	0.0	0.0	-0.04	1.04	-1.03
MAY	3.02	0.0	1.04	-0.04	0.71	1.30
JUNE	13.41	4.52	1.83	-0.04	3.56	12.44
JULY	4.52	0.0	1.73	-0.03	3.33	-0.80
AUG.	11.56	0.15	2.04	-0.03	6.45	3.29
SEPT.	1.42	0.0	0.51	-0.01	2.36	-1.54
OCT.	2.16	0.0	0.85	-0.01	5.61	-4.21
NOV.	0.43	0.0	0.0	-0.01	2.09	-2.14
DEC.	0.13	0.0	0.13	0.00	1.03	-1.02
TOT.	42.42	4.67	10.43	-0.34	30.63	6.25

ICRDP= 1	PACK ON DECEMBER 31 = 0.0	CHANGE IN SNOW STORAGE =-0.10	WATERSHED:RENCN AREA RATIO=4:1
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ICRDP CODE :	1 = WHEAT PLANTING YEAR
	2 = WHEAT HARVEST YEAR
	3 = SORGHUM FALL W YEAR
	4 = SORGHUM CR73 YEAR
	5 = CONTINUOUS GRAIN SORGHUM
	6 = CONTINUOUS WHEAT

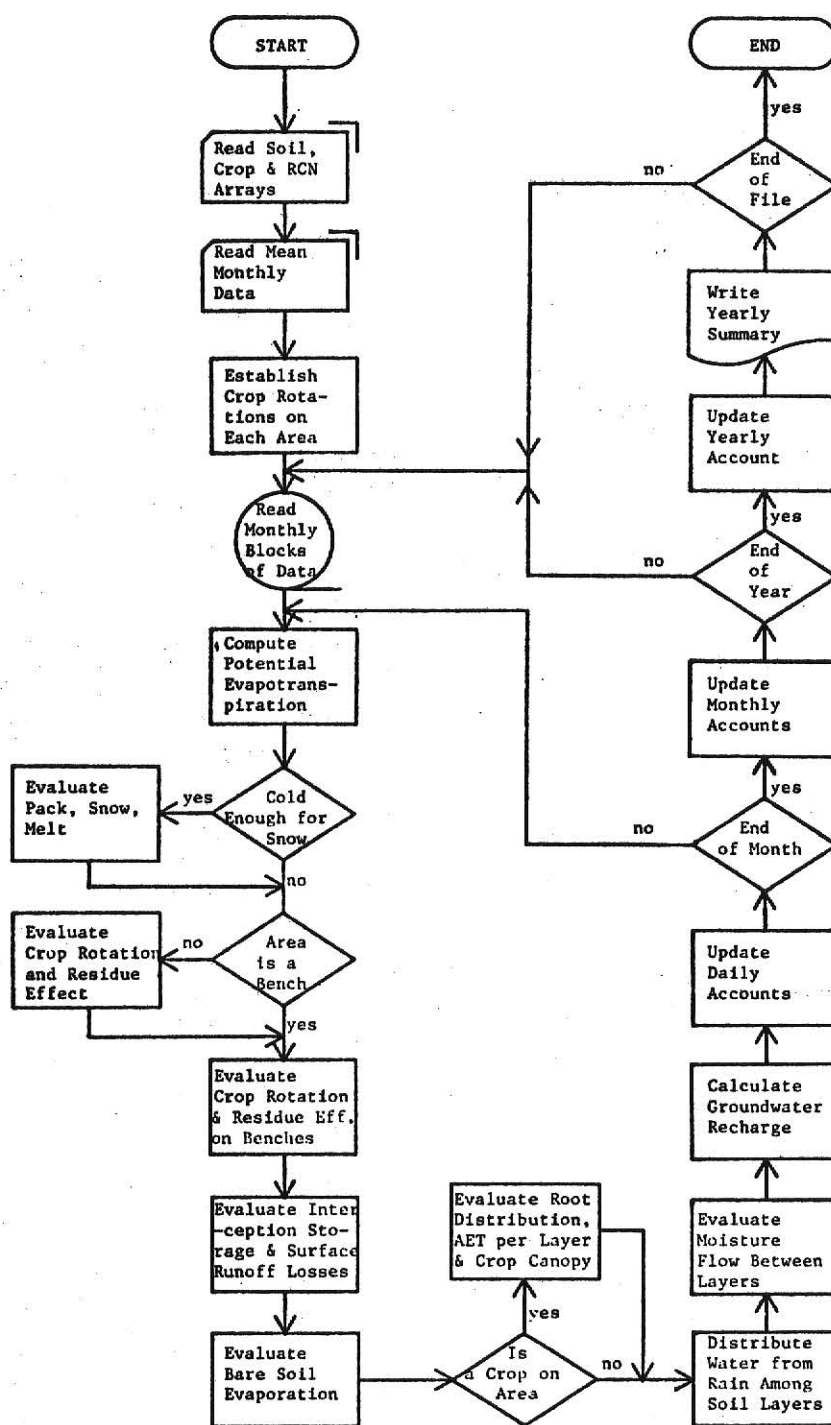


Figure 5. Algorithm for Water Budget Model.

**THIS BOOK
CONTAINS
NUMEROUS PAGES
WITH MULTIPLE
PENCIL AND/OR
PEN MARKS
THROUGHOUT THE
TEXT.**

**THIS IS THE BEST
IMAGE AVAILABLE.**

Potential Evapotranspiration

Daily potential evapotranspiration is calculated using the Penman combination equation as modified by Zovne and Nawaz (1975). Anschutz et al. (1976) found good agreement between potential evapotranspiration (PET) calculated using monthly averages of percent sunshine, relative humidity and wind speed as opposed to PET calculated using actual daily values of these same variables when comparing PET over 5-day periods. Calculation of PET using daily values requires data available only at first-order weather stations, greatly reducing model applicability for many areas. However, by using estimates of monthly averages for all inputs except maximum and minimum temperatures and precipitation, data available from all local temperature and rainfall recording stations may be used in the model. This gives the model more flexibility and widespread application.

Evaluating Runoff and Interception-Storage Losses

The form of precipitation is not designated on input data. A snow-melt routine (Bean, 1976) establishes the form of the precipitation as rain or snow, depending on the average daily temperature. Sublimation and the amount of snow accumulated or melted each day are evaluated as approached by Bean (1976). This function produces the daily value of precipitation, composed of rain, snowmelt or both, that is evaluated for runoff.

Runoff

Runoff is calculated according to the SCS equation (USDA, SCS National Engineering Handbook, 1964.) Since daily values of soil

moisture in the surface 15 cm are known, I have modified the growing season criteria for establishing antecedent soil moisture conditions as follows:

- Condition I: soil moisture is less than 0.4 of soil moisture at field capacity
- Condition II: soil moisture is between 0.4 and 0.8 of field capacity
- Condition III: soil moisture is greater than 0.8 of field capacity

Runoff curve numbers for Condition II antecedent moisture (RCN_2) are input to the model according to soil and crop type. RCN_2 's used in the model may be found in the USDA, SCS National Engineering Handbook (or Table 18, Appendix B). (Soil and crop codes are listed in Tables 16 and 17, Appendix B.) The USDA, SCS Kansas Irrigation Guide and Planners Handbook, 1975 classified Richfield silt loam as an Irrigation Design Class 3 soil. For this particular version of the model additional soil properties, especially unsaturated hydraulic conductivity and soil moisture tension-soil moisture content relationships are necessary. My estimates of these relationships may be applied with reasonable confidence only to the deep soils composed of silt loam, loam or clay loam surface and subsoil layers displaying moderate to moderately slow permeability characteristic of Design Class 3-5 soils. As a result, the present model is limited in application to Design Group 3-5 soils. When necessary, the RCN_2 is modified by

$$RCN_1 = RCN_2 \times 0.39 e^{0.009 \times RCN_2} \quad (7)$$

$$RCN_3 = RCN_2 \times 1.95 e^{-0.00663 \times RCN_2} \quad (8)$$

giving the runoff curve number for Condition I (RCN_1) or III (RCN_3) that is used in the model. I developed Equations 7 and 8 from tables contained in USDA, SCS National Engineering Handbook. These equations allow simple computer evaluation of RCN 's for conditions ranging from sandy pasture or

range soils in good condition ($RCN_2 = 39$) to fallow, moderately heavy clay soils ($RCN_2 = 91$). This eliminates the need for table storage and an interpolation routine.

Interception-Storage

Interception-storage losses are defined here as the amount of precipitation that is evaporated back to the atmosphere from the surface of plant leaves and/or surface storage.

An effective approach for computer simulation of these losses involves fixing an interception-storage capacity (Saxton et al. 1974, Ward, 1975), which must be satisfied before water from precipitation or snowmelt is available for infiltration or runoff.

Interception-storage losses are evaluated and assumed to be lost by evaporation at the potential rate. If no precipitation occurs the previous day, or if all previous interception losses have been evaporated, these losses are assumed to be 2.5 mm for rainfall amounts exceeding 2.5 mm and equal to precipitation for lesser amounts (Anderson, 1975, Saxton et al, 1974). If precipitation occurs the previous day, or if any water is present in the interception-storage account, available interception-storage is first reduced by this amount before being deducted from precipitation.

Interception-storage losses should average between 10 and 20 percent of the total annual precipitation (Ward, 1975). Model calculations of interception-storage for Garden City, Kansas, for the 1945-1974 period accounted for 25 percent of the total precipitation. Observation of climatological data indicate that Garden City experiences almost as many precipitation events as areas of higher precipitation, but most events at Garden City are smaller. Since interception-storage losses as evaluated

here are based on the number of events as well as their size, a larger fraction of total yearly precipitation allocated to interception-storage losses is justified.

Evaporation Losses from a Bare Soil Surface

According to Ritchie (1972) and Kanemasu (1975), evaporation from a bare soil surface may be considered to take place in two stages; a constant, and a falling rate stage. Stage I, or the constant rate stage occurs as long as the soil is sufficiently moist to transport water to the surface at the evaporative rate. Stage I evaporation (E_1) takes place at the PET rate (e.g. $E_1 = PET$) until the moisture in the surface layer drops below a given threshold (U), at which time Stage I evaporation ceases and Stage II evaporation (E_2) is initiated.

Reduction in Stage I evaporation resulting from the effect of crop residues present on the soil surface is calculated from curves presented by Bond and Willis (1970). A linear decrease in crop residues remaining on the surface from harvest to the next planting season is assumed in all cases. Wheat residue rates on the wheat-fallow rotation were assumed to be 3262 kg/ha at harvest and decrease linearly to 560 kg/ha by the following planting season. For continuous wheat the corresponding values were 2242 kg/ha and 560 kg/ha respectively. Grain sorghum residues were assumed to be only one-half as effective as wheat straw in reducing Stage I evaporation. Values of 1681 kg/ha effective residues (3362 kg/ha actual residue) at harvest and 112 kg/ha at seeding time were assumed for the grain sorghum-fallow rotation. For continuous grain sorghum effective residue rates of 1121 kg/ha for harvest and 112 kg/ha for planting seasons were used.

In Stage II evaporation the hydraulic properties of the soil begin to limit the rate of water transfer to the surface, causing a decrease from

the constant rate stage. Ritchie (1972) and Kanemasu (1975) calculate Stage II evaporation by

$$E_2 = 25.4 (ct^{\frac{1}{2}} - c(t - 1)^{\frac{1}{2}}) \quad \{9\}$$

where

E_2 = Stage II evaporation from a bare soil surface, mm
 c = soil dependent coefficient, mm/day $^{\frac{1}{2}}$
 t = time since the beginning of Stage II evaporation, days

The value of the Stage II threshold (U) and of c were obtained from Ritchie (1972) and field experiments at Manhattan, Kansas, by Kanemasu (1975).

Reduction of Stage I and II evaporation by a developing canopy is calculated by the use of Equation 10

$$E_c = E_i \left(\frac{t}{\alpha} \right) \quad \{10\}$$

where

E_c = soil evaporation corrected for canopy effects
 E_i = original uncorrected soil evaporation for $i = 1$ (Stage I) and $i = 2$ (Stage II)
 t = a constant, indicating canopy effect
 α = a calibration constant

and

$$t = e^{-0.398 \text{ LAI}} \quad \{11\}$$

where

LAI = leaf area index

(Ritchie, 1972; Kanemasu, 1975). Kanemasu calculated PET based on radiation and temperature conditions only and included the effect of the advective

component of PET by multiplying this calculated PET by α , calibrated for Manhattan, Kansas, as 1.69. The E_1 value used in Equation 10 includes the effect of Kanemasu's estimated advective component (e.g. $E_1 = PET \times \alpha$). To eliminate the advective effects, Kanemasu divides E_1 by α as shown in Equation 10. This results in calculation of surface evaporation using only the solar radiation component of Kanemasu's PET determination. This is a reasonable approach when crops are present. However, on fallow areas and in areas with higher mean windspeed, the advective component of PET is more important and its effects should possibly be included. In this model, PET is calculated by the combination method which directly calculates an advective component. So, use of α is unnecessary. Another calibration constant, α_1 , includes only the correction factor necessary to reduce calculated evaporation from a free-water surface to the actual first stage evaporation rate. Bond and Willis (1970) estimate this reduction in the first stage evaporation rate to be 11 percent for a bare soil surface. First stage evaporation in the model is calculated by using Equation 10 and replacing α with α_1 . For Stage II evaporation Equation 10 is used with $\alpha = 1.0$. Total daily soil evaporation is then the sum of Stage I and II evaporation, the sum of which can never exceed the day's PET minus any unevaporated water from the interception-storage account.

Transpiration

That portion of the potential evapotranspiration remaining after water held in interception-storage is evaporated and after bare soil evaporation has been satisfied is allocated to potential transpiration. Potential transpiration is first reduced by a factor indicating the crop's seasonal ability to transpire. Blaney-Criddle monthly crop coefficients (USDA, SCS TR 21, 1967) adjusted to give a maximum value of 1.0 are used as an indicator of this factor. These original monthly crop coefficients were not developed for

this purpose. They are, in fact, a ratio of measured consumptive use to potential ET evaluated on a monthly basis (Schwab, et al, 1966; Taylor and Ashcroft, 1972). However, due to the widespread testing that went into the development of these coefficients and their availability for several crops, it is felt that by scaling the coefficients for various crops down by dividing by the maximum value when greater than 1.0, to give a maximum value of 1.0, these adjusted coefficients should provide a reasonable estimate of a crop's seasonal ability to transpire. Relationships used for grain sorghum and wheat are shown in Figures 6 and 7.

Potential transpiration is next reduced by a soil moisture factor, K_s . Ritchie (1973) reported that transpiration from sorghum or corn was not affected by soil moisture deficit until the available water in the root zone is less than 0.3 of the maximum available water content (θ_{max}). Tanner and Ritchie (1975) found that $0.3 \theta_{max}$ represented the critical moisture level for nearly all data. When the available soil moisture content (θ_a) was above $0.3 \theta_{max}$, no correction was necessary (e.g. $K_s = 1.0$). For moisture contents below $0.3 \theta_{max}$ potential ET was multiplied by K_s where $K_s = \theta_a / 0.3 \theta_{max}$ (Kanemasu, 1975.) We use this approach. Actual transpiration is divided among the soil layers according to the root extraction patterns listed in Tables 3 and 4 (Dr. H. L. Manges, Agricultural Engineering Dept., personal communication; Russell and Ellis, 1968; Weaver, 1926).

If the available soil moisture in a layer is unable to satisfy its fraction of the day's actual transpiration demand, and the next deeper soil layer also contains roots, any unsatisfied demand is shifted to this lower layer. This assumes that if the plant root system is present and physiologically developed to a given depth on this day it would be capable of expanding to satisfy the increased demand transferred from above soil layers. If roots are not present in the lower layer, only the portion of

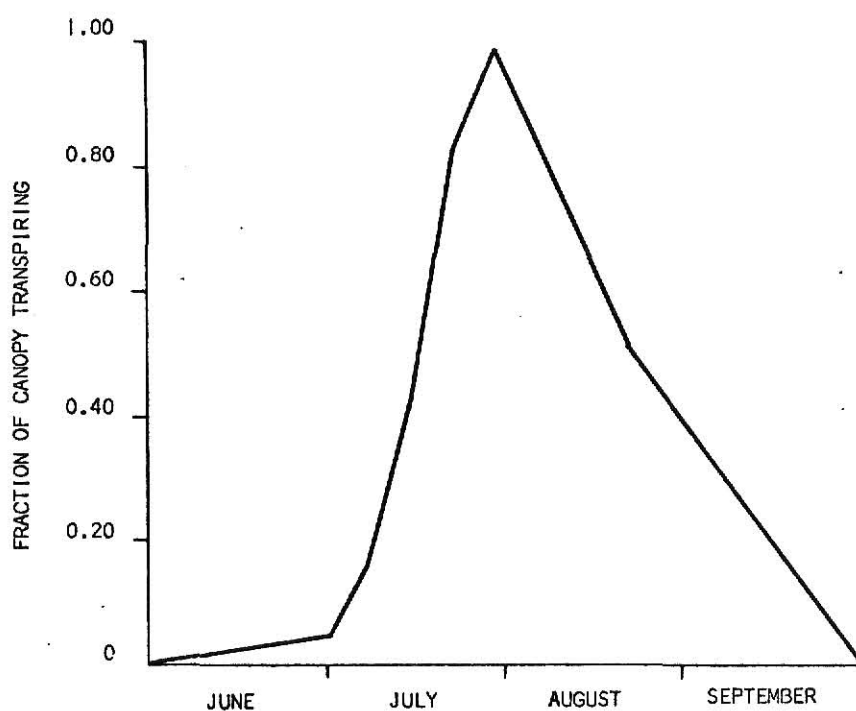


FIGURE 6. ADJUSTED BLANEY-CRIDDLE CROP COEFFICIENTS FOR GRAIN SORGHUM.

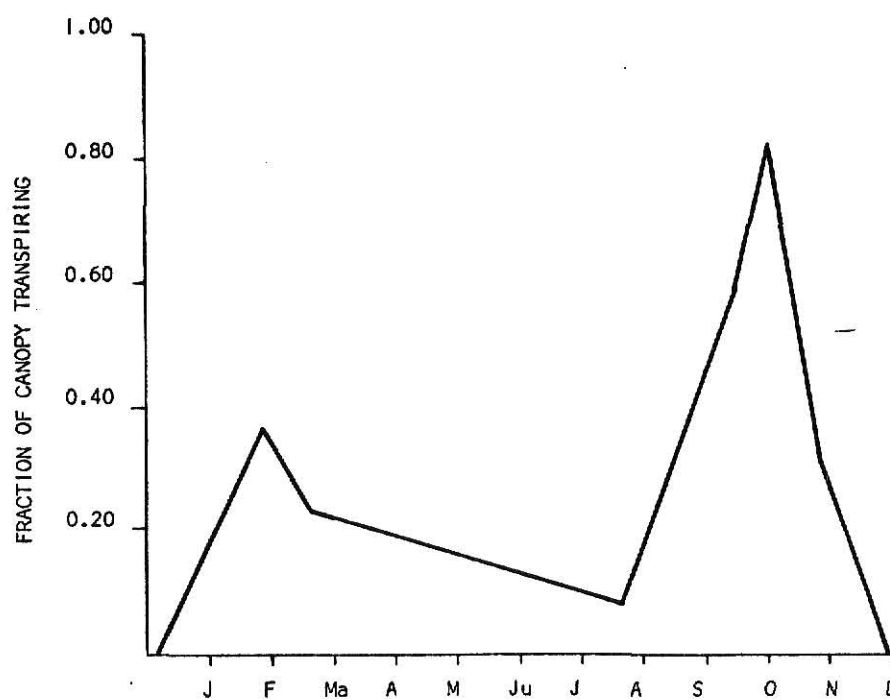


FIGURE 7. BLANEY-CRIDDLE CROP COEFFICIENTS FOR WHEAT.

Table 3. Seasonal Variation for Grain Sorghum in the Percentage of Total Daily Water Consumption Removed from Each Soil Zone.

Zone Depth, cm	Days since Planting							
	61	63	73	76	104	106	119	130
0-15	56	55	51	50	40	39	33	29
15-30	23	22	16	16	13	13	12	12
30-61	21	21	19	19	19	19	19	19
61-91			13	13	13	13	13	13
91-122					10	10	10	10
122-152					5	5	10	10
152-183								5

Table 4. Seasonal Variation for Wheat in the Percentage of Total Daily Water Consumption Removed by Roots from Each Soil Zone.

Zone Depth, cm	Days since Planting							
	55	189	197	210	218	231	238	247
0-15	72	58	57	56	55	54	53	52
15-30	20	13	13	13	12	12	11	11
30-61	8	14	14	14	14	14	14	14
61-91		9	9	9	9	9	9	9
91-122		4	8	8	8	8	8	8
122-152					3	3	3	3

the actual transpiration that may be satisfied in the active root zone is considered as actual transpiration. Total daily AET is then reduced accordingly.

Moisture Redistribution

Any rainfall or snowmelt not lost by runoff or interception-storage is assumed to enter the soil profile, filling the top 15 cm to field capacity. Any remaining moisture moves downward, filling each succeeding layer to field capacity until all the moisture available for increasing soil moisture is depleted. Any moisture passing from the 152-183 cm layer to the 183-213 cm layer is assumed to be ultimately used for groundwater recharge, similar to the approach used by Saxton (1974).

Soil moisture movement between adjacent soil layers is calculated by the one dimensional form of the Darcy equation (Equation 11, Appendix A). On days when no water enters the soil surface, soil hydraulic properties are evaluated at the beginning of the day and Δt in the Darcy equation is taken as one day. When water does enter the soil surface, Δt is taken as 1/6 day. Flow is calculated, soil moisture re-evaluated, and hydraulic properties re-calculated at the end of each four-hour period.

The soil water potential-soil moisture relationships used in the Darcy equation were obtained experimentally from undisturbed soil samples taken from the conservation bench terrace area at the Garden City, Kansas, Branch Agricultural Experiment Station. These curves were obtained using undisturbed 7.62 cm diameter samples 7.62 cm in length in the 0 to 196 kPa range and disturbed samples from 490 kPa to 1.47 MPa soil moisture tension range as outlined in Chapter 1. Similar curves were combined, giving the curves shown in Figure 8.

The soil moisture-unsaturated hydraulic conductivity relationships used were obtained using Doering's (1965) One-Step Method as discussed in

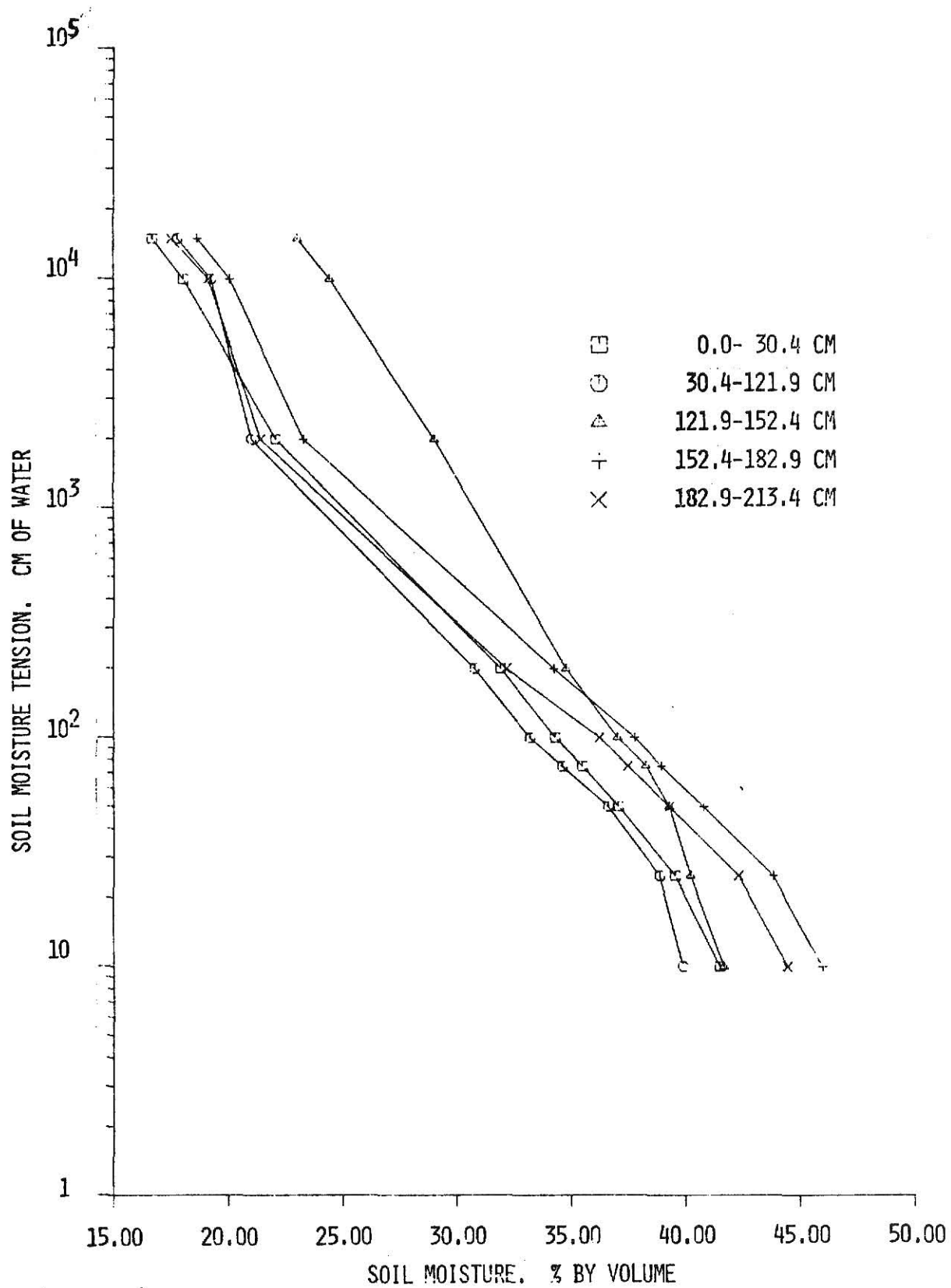


Figure 8. Soil Moisture Retention Curves for Richfield Silt Loam.

Chapter 1. Due to equipment limitations, these curves are limited in application to soil moistures above equilibrium moisture content at 196 kPa. Conductivities at moisture contents below this were assumed to be the same as the 196 kPa values. Conductivities above 10 cm/day were limited to 10 cm/day to compensate for errors in model calculations above that point. Conductivities of this magnitude compare favorably with saturated hydraulic conductivities for soils similar to Richfield silt loam as listed in Taylor and Ashcroft (1972). Relationships used in the model are shown in Figure 9.

Groundwater recharge is calculated as the sum of recharge due to water entering the 183-213 cm zone from heavy rainfall and the movement of water across the 183 cm depth, downward taken as positive, as calculated by the Darcy equation. The 183-213 cm zone is allowed to seek its own moisture level. This gives a realistic set of conditions for moisture flow across the 183 cm boundary. The negative deep percolation values shown in the yearly summary from the model, Table 2, page 16 indicate soil moisture movement upward across the boundary from a moist 183-213 cm zone to a drier 152-183 cm zone.

Model Calibration and Results

The model was calibrated with one year of data obtained from a conservation bench terrace system constructed at the Garden City, Kansas, Branch Agricultural Experiment Station. Koelliker et al. (1976) furnish a complete description of plot layout and method of data collection.

Two sets of computer runs were made for the calibration period. Both sets used daily maximum and minimum temperature readings and mid monthly extraterrestrial solar radiation as inputs for PET calculation. In addition, one set used daily observed values for wind speed, percent sunshine and relative humidity while the other set used monthly averages of these in-

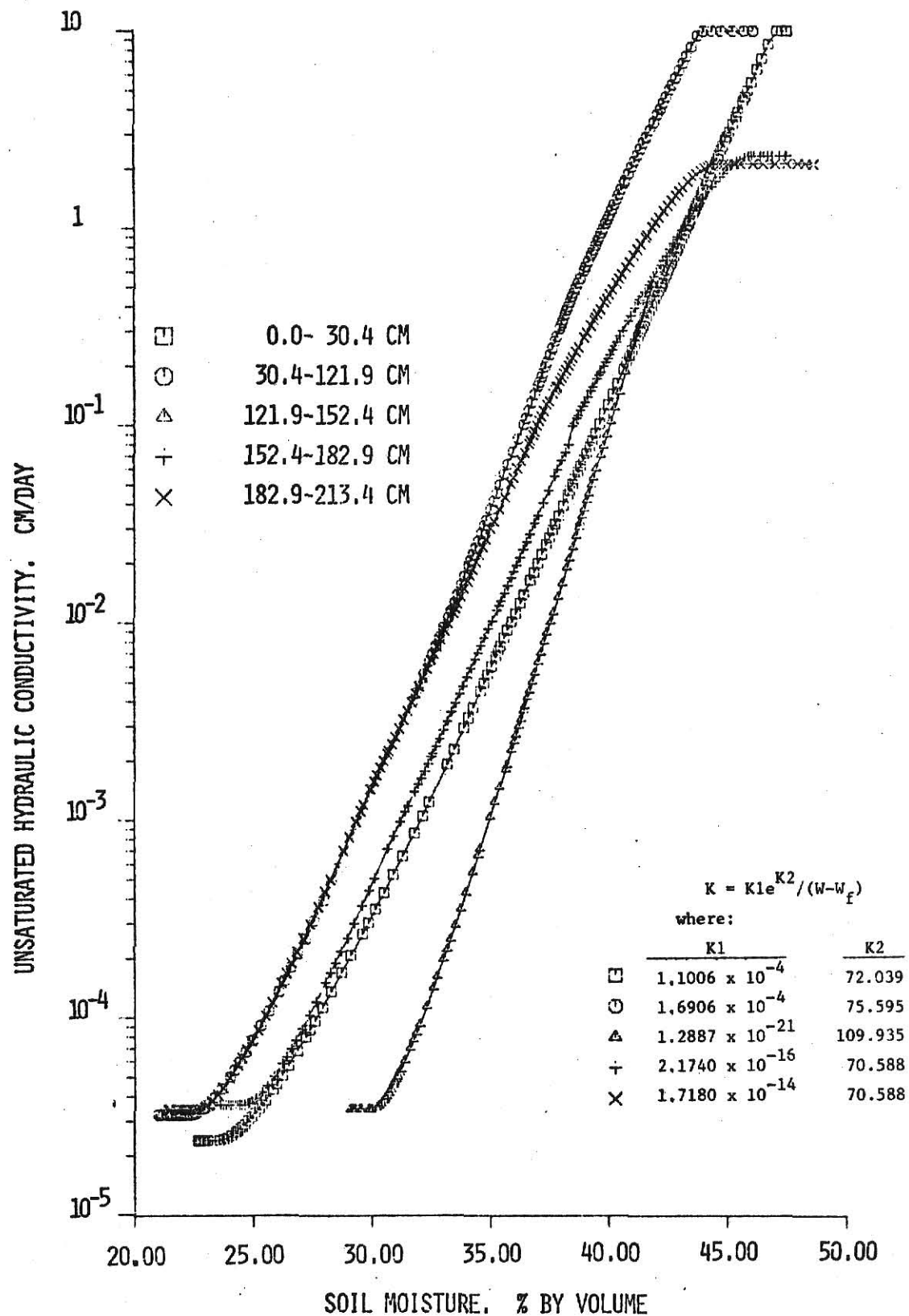


Figure 9. Unsaturated Hydraulic Conductivity - Soil Moisture Relationships for Richfield Silt Loam.

puts as well. Measured relative humidity readings from 12 a.m., 6 a.m., 12 p.m., and 6 p.m. were averaged to give the daily relative humidity values used for the calibration run. Soil moisture data from 0-213 cm was available from June 11, 1975 through June 3, 1976. The model was run using data for the June 1, 1975 to May 31, 1976 period. Soil moisture contents at each depth considered were re-initialized to the June 11 value on that day.

Due to an extremely dry summer and the temporary changes in soil properties resulting from leveling and establishing the experimental layout, the sorghum crop on the benches experienced an almost complete crop failure, so we were unable to obtain any meaningful moisture use data for sorghum. As a result, all calibration was done using fallow bench and fallow watershed areas.

Actual soil moisture contents and predicted moisture contents using both methods are shown in Table 5. At depths below 31 cm predictions from each method generally agreed to within 5%. In the top 31 cm of soil, predicted moisture contents using daily data generally appeared to be a better predictor of soil moisture content than did soil moistures calculated from monthly averages.

For model verification, soil moisture contents calculated from daily climatological information should be considered, as this represents the most sensitive form of the model. Actual moisture contents and predicted moisture contents based on daily climatological data are shown in Figure 10 for each of the eight soil layers studied. Rainfall events produced the rapid increases in soil moisture contents visible in the 0-15 and 15-30 cm layers. Stage I evaporation may be seen as the rapid decline in soil moisture contents in the 0-15 cm layer following rainfall. This rapid decline then tapers into a more gradual, Stage II decay curve. With the exception of the June 5 observation, predicted soil moistures are within

Table 5.

Actual and Predicted Soil Moisture Contents
from Model Calibration Runs ^a

Date

	6/5/75	6/11/75	7/7/75	7/23/75	8/8/75	9/2/75	10/1/75	1/4/76	4/19/76	5/31/76
<u>0-15 cm depth</u>										
actual	27.00			19.83	21.33	15.00	20.00			23.33
predicted ^b (monthly)	22.34			17.18	20.00	15.76	16.55			28.13
predicted ^c (daily)	19.13			16.58	19.10	16.82	19.86			23.70
<u>15-31 cm</u>										
actual	25.67			25.50	23.33	23.67	22.00			23.67
predicted (M)	27.12			25.62	27.75	24.11	22.16			25.41
predicted (D)	27.00			24.12	26.69	23.52	21.30			23.48
<u>31-61 cm</u>										
actual		19.00	20.17		20.67	20.58	20.42	21.25	21.50	23.58
predicted (M)		22.04	27.48		26.49	26.06	25.28	26.52	23.94	25.79
predicted (D)		21.31	25.97		25.38	25.10	24.29	24.49	23.37	24.09
<u>61-91 cm</u>										
actual		21.00	20.92		21.58	21.16	21.75	21.58	21.67	22.83
predicted (M)		21.16	22.74		23.65	23.97	24.14	24.83	24.69	24.77
predicted (D)		21.18	21.90		22.51	22.80	23.01	23.26	23.37	23.41

a June 1, 1975-May 31, 1976. Each actual soil moisture content is the average of six watershed plot measurements on the conservation bench terrace area at the Garden City, Kansas Branch Agricultural Experiment Station. Soil moistures in percent by volume.

b Predicted soil moisture contents using monthly averages for values of solar radiation, wind speed, relative humidity and percent sunshine.

c Predicted soil moisture contents using observed daily values for all climatological variables listed above.

Table 5. continued.

		Date									
Soil Moisture Content		6/5/75	6/11/75	7/7/75	7/23/75	8/8/75	9/2/75	10/1/75	1/4/76	4/19/76	5/31/76
% by volume											
<u>91-122 cm</u>											
actual		20.58	25.17			25.00	25.58	25.42	25.58	25.75	26.17
predicted (M)		24.95	24.19			23.84	23.71	23.63	23.66	23.88	23.95
predicted (D)		24.51	23.77			23.38	23.21	23.10	23.02	23.11	23.15
<u>122-212 cm</u>											
actual		26.19	26.50			26.64	26.20	26.08	26.42	26.42	26.58
predicted (M)		26.33	26.36			26.59	26.64	26.67	26.77	26.77	26.79
predicted (D)		26.30	26.45			26.54	26.58	26.60	26.65	26.65	26.65

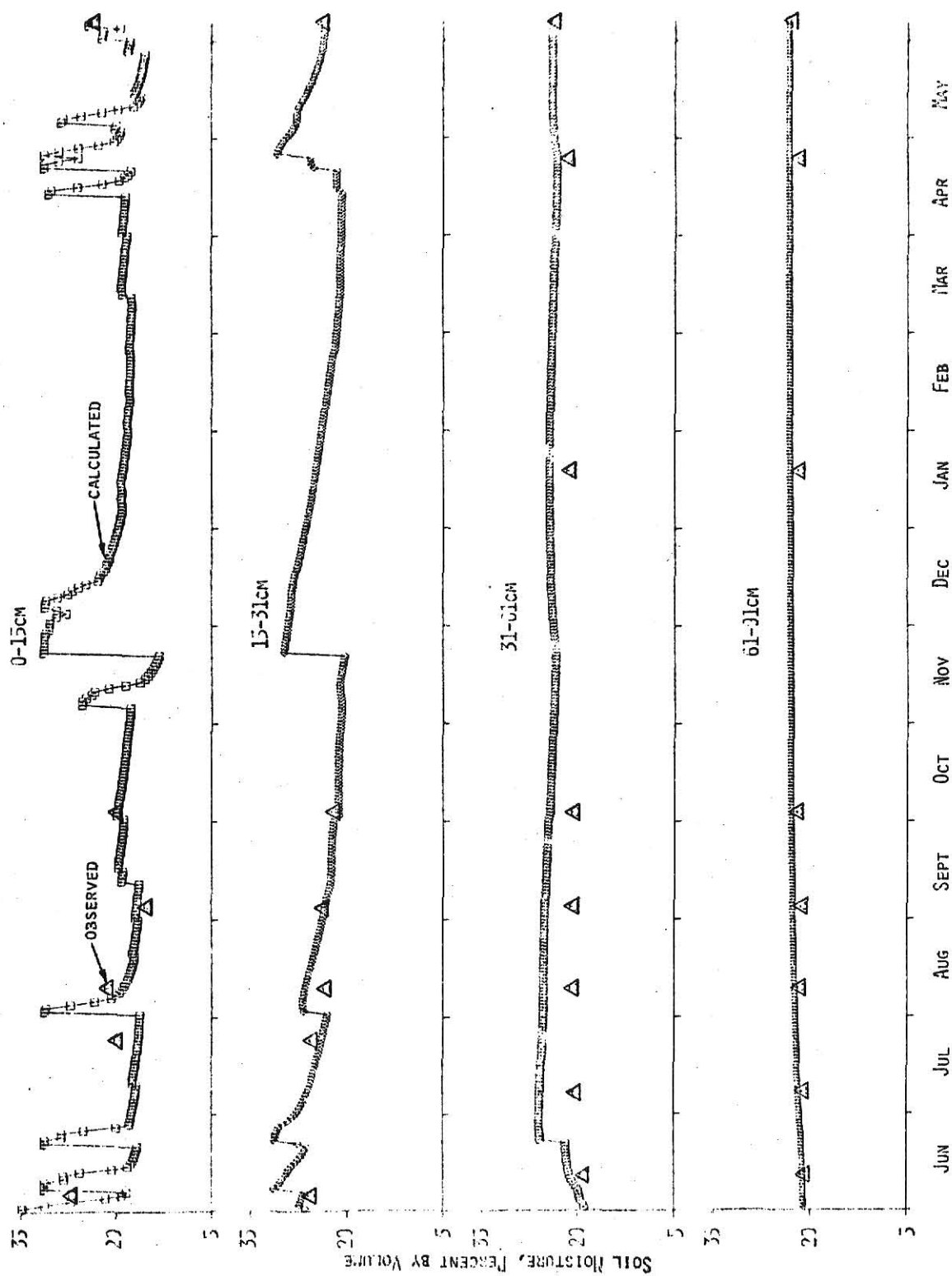


FIGURE 13. CALCULATED AND OBSERVED SOIL MOISTURES FOR FALLOW BENCH AREAS, JUNE 1, 1975 TO MAY 31, 1976.

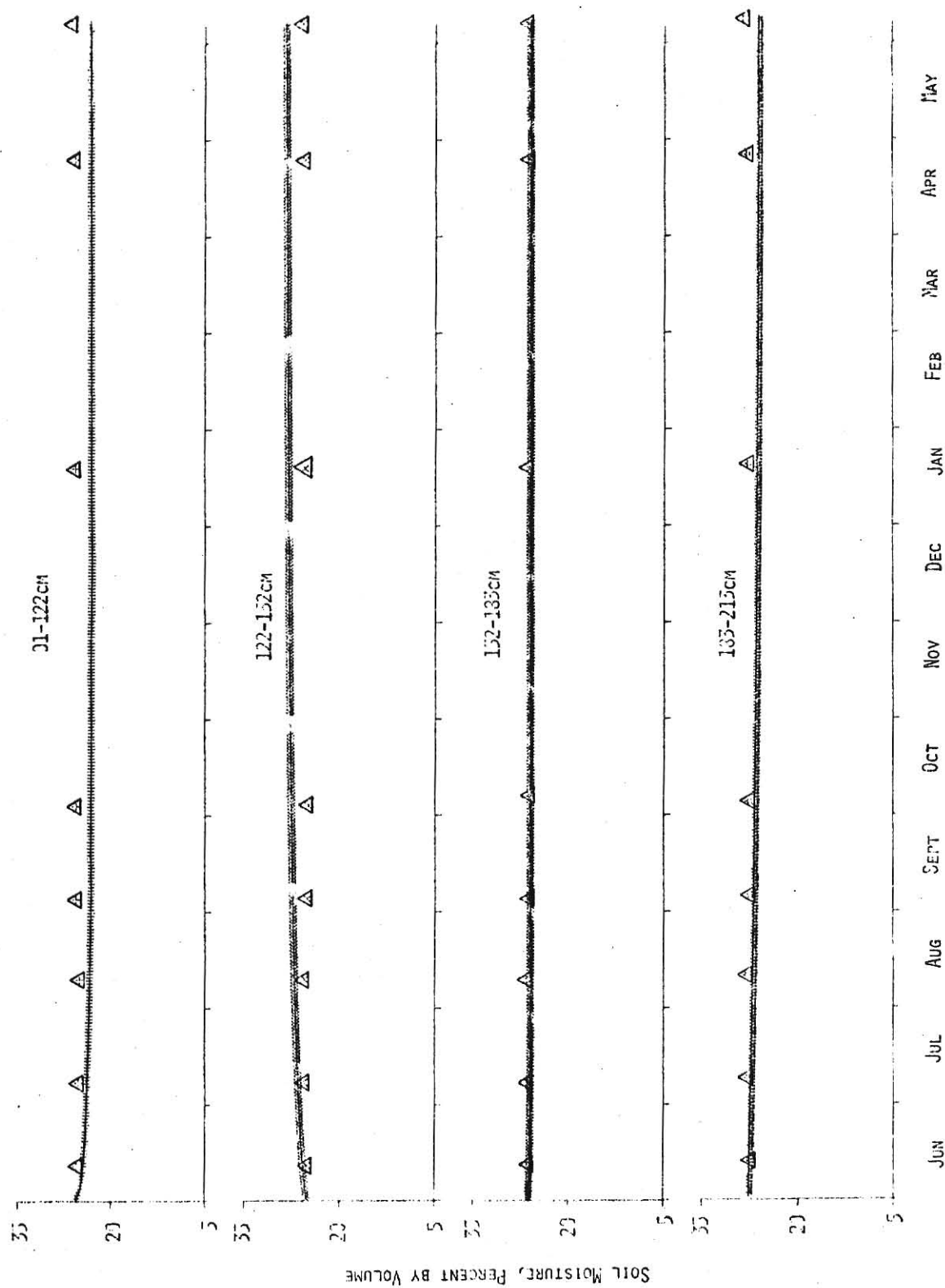


FIGURE 13. CONTINUED

3.3 percent by volume of actual observed soil moistures in the 0-15 cm range, 3.4 percent by volume in the 15-31 cm layer, 5.8 percent by volume in the 31-61 cm zone and within 3.9 percent by volume for all depths between 61 and 213 cm.

In considering only the surface 31 cm, the predicted soil moisture contents were in error by an average of 5.3 percent over the one year calibration and test period. A maximum error of 12.3 percent was observed after five days of the test run. A minimum error of 0.4 percent was observed at the end of the 366 day run. The average error for the four days when the entire 213 cm soil profile was sampled was 2.4 percent and ranged from 1.2 to 3.4 percent. The improved model predictions when considering the entire 213 cm profile were due to the inclusion of the deeper soil layers where little water movement occurred. As a result, smaller differences between actual and predicted moisture contents were obtained.

The 30-year model runs were made using PET calculations based on monthly averages of all but temperature data. Comparing daily and monthly based predicted values to the observed soil moisture conditions shown in Table 5 gives an indication of the relative magnitude of the model sensitivity that is sacrificed when using the monthly average approach.

Model calibration over a longer period of time could result in improved model prediction, especially in the surface 31 cm. However, the present errors in model prediction are within the range of errors produced by present soil moisture sampling and measurement techniques.

By using modified Blaney-Criddle coefficients (USDA, SCS TR 21, 1967) and root soil moisture extraction patterns developed for the Concordia, Kansas, area (Dr. H. L. Manges, Agricultural Engineering Dept., Kansas State University, personal communication) and for England (Russell and Ellis, 1968) and making decisions about coefficient changes necessary for transfer to the Garden City area, realistic model results should be obtained.

The model as now written contains two simultaneous soil moisture accounting procedures, one for watershed conditions and one for the leveled bench area where runoff is concentrated and applied as supplementary water. Watershed results may be considered as results typical of unmodified field areas in the Garden City area. With slight model modifications, results for unmodified field conditions alone may be obtained.

The addition of unsaturated hydraulic conductivity-soil moisture and soil water potential-soil moisture relationships for several other soil groups would allow this model to be used for a variety of simulation studies in semi-arid regions. The use of the soil water potential-soil moisture and the difficult-to-obtain unsaturated hydraulic conductivity-soil moisture content relationships somewhat limit the widespread use of this model. But in areas where appropriate relationships are available, it should more closely approximate actual field conditions and provide a larger amount of supplementary information than some of the less complex models now available.

Summary

A continuous water budget type of computer model was developed and calibrated for use in western Kansas. Daily potential evapotranspiration (PET), actual ET and soil moisture changes in a 213 cm soil profile were calculated from inputs of crop and soil moisture characteristics and daily meteorological observations. Interception-storage evaporation, evaporation from the soil surface and plant transpiration were computed and combined to give the actual ET estimate for the day. Soil moisture was redistributed by tension and conductivity-soil moisture relationships. The model was calibrated with one year's data from fallow watershed. Model calculated soil moisture contents averaged within 5.3% of the measured moisture content in the 0-31 cm soil layer. Predicted total moisture content in the 213 cm profile averaged within 2.4 percent and ranged from 1.2 to 3.4 percent over the one-year test period.

Although this model is somewhat limited by the required soil water potential-soil moisture content and unsaturated hydraulic conductivity-soil moisture content curves it should more closely approximate actual field conditions and provide a larger amount of supplementary information than some of the less complex, lower input data requirement models available.

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Chapter 3:

ESTIMATING GROUNDWATER RECHARGE
FROM CONSERVATION BENCH TERRACES

In 1965, 27 counties in the western one-third of Kansas were pumping water at rates higher than the natural recharge rate. In a study made of the present and future water resources of the state, recoverable groundwater was estimated to be two-thirds of that in storage in 1965 (USDI, Bureau of Reclamation 1974). Using this criteria, two of the 27 counties would deplete their recoverable groundwater by 1980, three more by 1990, eight more by 2000, five more by 2010 and nine more by 2020 (Kansas Water Resources Board 1967, USDI, Bureau of Reclamation 1974). For the state as a whole, a water shortage of roughly 6.4 million m³ per year was projected if the predicted water use occurs (USDI, Bureau of Reclamation 1974).

Direct measurements of recharge to groundwater storage are difficult to obtain and limited in number. It is believed that most recharge in the western one-third of Kansas comes from precipitation on the land surface and averages from 0.6 to 1.3 cm per year. (Kansas Water Resources Board 1958 and 1962, USDI, Bureau of Reclamation 1974)

Several factors inherent in the climate of the area are responsible for these low recharge rates. First, the climate is dry with an average annual rainfall of 45 to 48 cm per year. Second, when rainfall does occur, a large percentage of it occurs as local downpours, with water running off rapidly, leaving little opportunity for the water to enter the soil surface. Much of the remaining rainfall occurs as light showers and is lost to evaporation from the soil surface in one to two days. And third, the largest percentage of the yearly rainfall occurs during the months of May through August, when evapotranspiration demands are largest. This greatly reduces the amount of water available to infiltrate below the root zone (Kansas Water Resources Board 1958).

With water usage exceeding the natural recharge rate by an increasingly large factor, some means of augmenting natural recharge is necessary if large-scale irrigation and other water usage increases are to be successfully met. Ideally recharge structures could be designed to be compatible with, and hopefully produce an economic incentive for use in production agriculture systems.

Recharge basins (Schiff 1948, Bouwer et al. 1974), pits (Schiff 1954, Bauman 1965) and wells (Johnson 1948, Bauman 1965) have been used with varying degrees of success in recharging clear or low turbidity water to aquifers. Runoff water from agricultural lands has a much higher turbidity than any water used in previously mentioned work. Recharge of higher turbidity water in basins formed by removing the slowly permeable Pullman clay loam surface soil were conducted with runoff water collected in playas at the USDA Southwestern Great Plains Research Center, Bushland, Texas (Goss et al. 1971, Jones et al. 1974). The average recharge rate for eleven tests over a five-year period on a 0.04 hectare basin was 43.28 cm per day. To maintain this rate however, sediments were removed by sweeping or air blasting after each test, a practice economically unfeasible for large-scale production agriculture.

Conservation bench terrace systems have been tested at several locations across the High Plains (Black 1968, Cox 1968, Haas and Willis 1968, Hauser 1968, Mickelson 1968, Wittmuss 1968). Significant increases in soil moisture storage and crop production were noted in each case. Conservation bench terraces act as water-harvesting and spreading devices during periods of excess, runoff producing rainfall. As a result, they may be an effective method of increasing the potential for groundwater recharge while maintaining, if not increasing total crop production on suitable sites in the western one-third of Kansas.

Two conservation bench terraces 152 m in length were constructed at the

Garden City, Kansas Branch Agricultural Experiment Station. Bench widths were 18.3 m. Watersheds with contributing watershed area:bench area ratios of 0:1, 2:1 and 4:1 were constructed. Koelliker et al. (1976) give a more detailed description of experiment objectives and plot layout.

PROCEDURE

Since direct measurements of groundwater recharge are difficult to obtain and usually represent less than five events per year, computer modeling was chosen as the most effective approach to examine the effects of land modification and cropping practice changes on groundwater recharge rates over extended periods of time. A continuous water-budget model was developed and field calibrated for fallow conditions using one year's data. A crop failure on the sorghum plots during the summer of 1975 rendered them useless for calibration.

The general algorithm for the computer model used to estimate groundwater recharge is shown in Figure 11. Precipitation and maximum and minimum temperatures are first input to the model on a daily basis. Daily actual ET, interception-storage, runoff, change in soil moisture in the 183 cm profile, and deep percolation to groundwater recharge are then calculated. Soil moisture is redistributed daily during periods of no rainfall and six times per day on days when precipitation exceeds the interception-storage capacity for that day. Maximum interception-storage is taken as 2.5 mm. The Darcy equation and the soil water potential-soil moisture and unsaturated hydraulic conductivity-soil moisture content relationships developed in Chapter 1 are used to redistribute soil moisture. Water applied to the soil either by precipitation or runoff added is considered to first fill the uppermost soil layer to field capacity. Any water remaining after the top 183 cm profile is filled to field capacity is allocated to groundwater recharge. Total recharge over a given period is then the sum of this recharge and the summation of water movement across the 183 cm depth boundary during the period, downward taken as positive, as calculated by the Darcy equation.

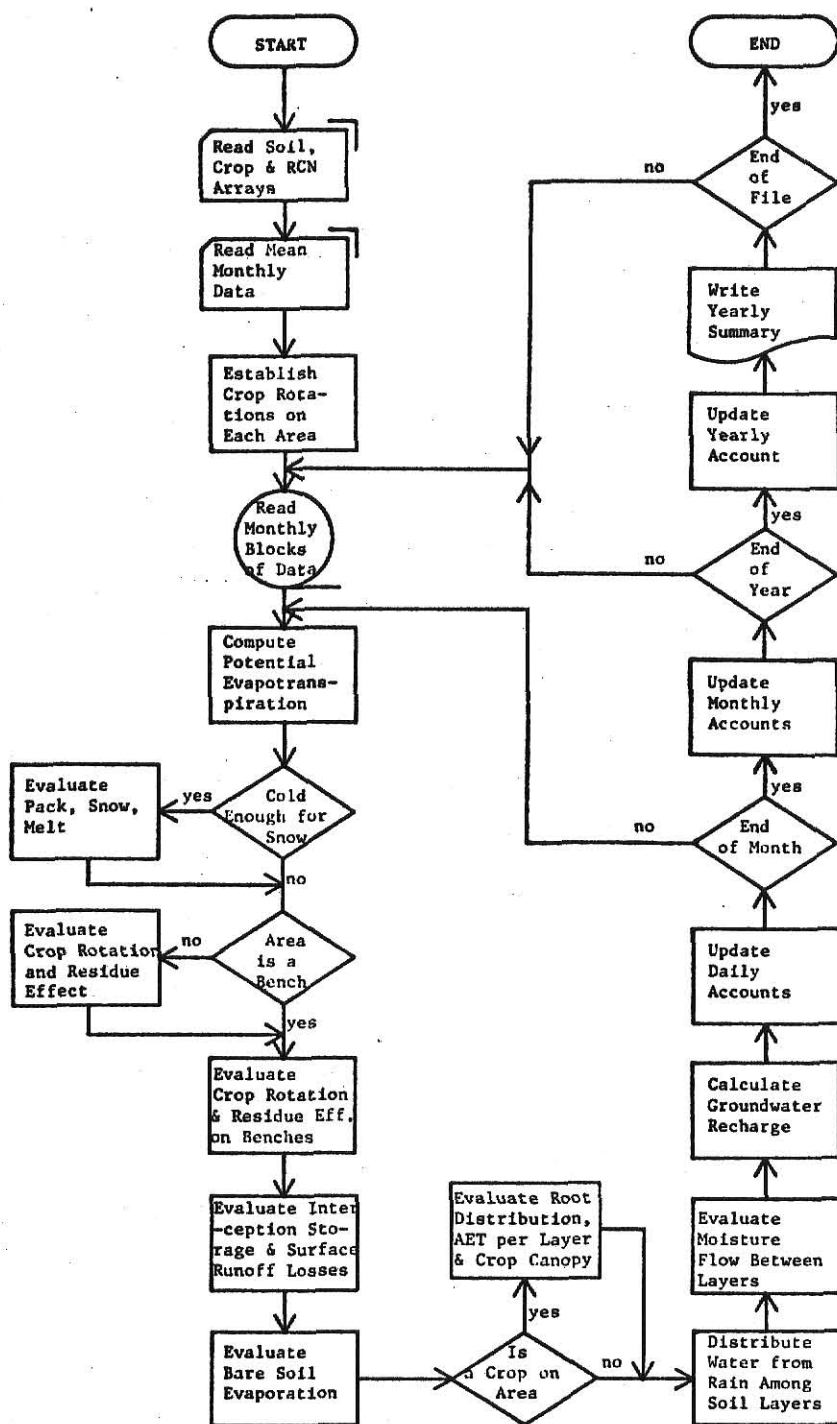


Figure 11. General Algorithm for Computer Model Used to Estimate Groundwater Recharge.

RESULTS AND DISCUSSION

The model was run for a 30-year period, 1945-74 for watershed:bench area ratios of 2:1 and 4:1. A wheat-fallow rotation was used on the watershed areas for all runs. Wheat-fallow, continuous grain sorghum and continuous wheat rotations were used for each of the two watershed:bench area ratios. (Yearly summaries for three of the years studied are shown in Tables 20, 21, and 22, Appendix C.)

Results of a 4:1 watershed:bench area ratio, using a wheat-fallow crop rotation on the bench areas are shown in Table 6. Computer runs for 2:1 and 4:1 watershed:bench area ratios using continuous wheat, continuous grain sorghum and wheat-fallow rotations for each ratio are summarized in Table 7. (Yearly values for each variable considered are listed in Table 19, Appendix B.)

From Table 7, average annual recharge estimates for the 1945-1974 periods ranged from 0.48 cm per year for a 2:1 watershed:bench area ratio and a continuous wheat cropping rotation to 5.11 cm per year for a 4:1 wheat-fallow rotation. Groundwater recharge on the sloping watershed areas was estimated as 0.33 cm per year from model runs. Recharge estimates considering the watershed area to be fallow in even years were averaged with estimates considering **them as fallow in odd numbered years to obtain my estimate of 0.33 cm per year.** This value was taken as my estimate of the natural recharge rate for the Garden City, Kansas area. Bureau of Reclamation (1974) estimates of groundwater recharge in the western one-third of Kansas range from 0.6 cm per year at the Kansas-Colorado border to 1.3 cm per year at the eastern edge of the region. These estimates, however, give recharge values for entire watersheds and still larger areas. My recharge estimates are for a Richfield silt loam soil and may be extended with some care to the similar Ulysses and Harney silt loam soils. All three soils show moderately slow

Table 6. Summary of Model Results for a Conservation Bench Terrace System at Garden City, Kansas, 1945-1974^a

	Watershed Area					Bench Area				
	Inter-ception Storage	Runoff	Deep Perco-lation	Actual Evapo-transpi-ration	Change in soil Moisture	Runoff Applied	Inter-ception Storage	Deep Perco-lation	Actual Evapo-transpi-ration	Change in soil Moisture
Year	Precip-itation									
1945	43.08	0.49	-0.43	36.09	-5.55	1.95	12.07	-0.54	38.37	-3.40
1946	62.94	4.51	1.98	34.05	9.56	18.05	12.95	16.81	38.88	14.10
1947	46.00	1.13	-0.38	45.30	4.53	4.53	12.28	-0.38	52.36	-13.94
1948	42.42	1.17	-0.47	29.75	1.41	4.67	10.83	-0.56	32.64	2.59
1949	57.91	3.27	-0.40	43.47	-1.36	13.09	12.85	0.08	54.72	-0.38
1950	52.20	3.01	-0.34	34.07	3.41	12.02	12.04	9.95	42.01	5.84
1951	75.21	4.54	-0.18	50.96	4.45	18.17	15.29	17.12	60.19	0.95
1952	21.08	0	-0.11	17.16	-5.58	0.02	9.45	-0.52	22.56	-10.42
1953	38.53	2.09	-0.14	26.65	-0.49	8.35	10.44	-0.58	27.23	5.70
1954	27.64	0.62	-0.23	23.32	-4.28	2.48	7.93	-0.36	32.91	-7.22
1955	52.73	3.67	-0.24	42.39	-1.63	14.68	8.98	-0.40	59.14	-0.38
1956	14.43	0	-0.27	9.49	-1.16	0.00	6.27	-0.38	11.67	-2.02
1957	54.25	2.00	-0.30	35.35	3.22	7.99	13.94	-0.41	47.21	1.00
1958	72.06	2.91	-0.07	45.33	8.07	11.65	15.47	-0.25	59.78	6.93
1959	45.90	0.28	0.17	37.79	-5.70	1.12	13.39	-0.06	42.43	-6.85
1960	42.62	0.05	-0.00	29.63	-0.83	0.20	13.50	-0.26	30.97	-0.78
1961	49.25	0.76	-0.11	33.31	3.14	3.02	12.04	-0.36	34.84	4.49
1962	47.35	0.34	-0.16	35.89	-1.89	1.34	13.04	-0.27	40.31	-3.35
1963	40.34	1.60	-0.12	32.12	-3.17	6.42	8.92	-0.18	34.64	0.58
1964	31.70	0.63	-0.16	24.28	-0.92	2.51	9.88	-0.06	30.49	-1.68

^aWatershed crop rotation is wheat-fallow. Bench crop rotation is continuous wheat. Watershed: Bench ratio is 4:1. Location: Conservation Bench Terrace Area, Garden City, Kansas Branch Agricultural Experiment Station.

Table 6. continued.

Year	Watershed Area					Bench Area					
	Percip- itation	Inter- ception Storage	Runoff	Deep Perco- lation	Actual Evapo- transpi- ration	Change in soil Moisture	Runoff Applied	Inter- ception Storage	Deep Perco- lation	Actual Evapo- transpi- ration	Change in soil Moisture
1965	70.36	12.94	2.55	-0.14	44.09	10.66	10.19	12.94	-0.15	57.46	7.92
1966	30.68	8.55	0.21	0.04	26.54	-6.64	0.85	8.55	0.06	32.11	-8.84
1967	58.37	12.19	5.35	0.04	42.05	2.94	21.41	12.19	15.66	43.09	13.67
1968	38.99	10.82	0.53	0.04	30.75	-2.42	2.12	10.82	-0.44	40.18	-8.74
1969	65.76	14.34	3.00	-0.00	42.67	5.78	12.02	14.34	5.78	46.01	11.83
1970	38.02	10.13	1.72	0.03	31.46	-5.43	6.87	10.13	-0.36	42.28	-9.86
1971	45.36	12.09	0.63	00.00	34.42	-1.97	2.52	12.09	-0.53	37.36	0.57
1972	68.12	13.37	4.18	0.32	39.31	10.37	16.74	13.37	3.50	56.25	9.29
1973	42.95	13.59	0.33	0.38	41.21	-12.89	1.31	13.59	-0.40	46.57	-13.77
1974	30.12	9.82	0.01	0.07	22.01	-0.82	0.04	8.82	-0.66	23.66	-1.48
Total	1406.27	343.40	51.58	-1.39	1020.81	5.32	206.33	348.40	60.85	1218.23	-7.75
Average	46.88	11.61	1.72	-0.05	34.03	0.13	6.88	11.61	2.02	40.61	-0.26

Table 7.

Computer Model Estimates of Average Annual Hydrologic Variables
from Conservation Bench Terraces at Garden City, Kansas.^a

	Bench Area									
	Watershed Area ^b					Watershed Area:Bench Area Ratio				
	2:1					4:1				
	wheat-fallow (even ^c year)	wheat-fallow (average)	continuous wheat ^d	continuous grain sorghum	wheat-fallow	continuous wheat	continuous grain sorghum	wheat-fallow	continuous wheat ^d	wheat-fallow
Groundwater Recharge	-0.05	0.33	0.48	1.41	2.59	2.02	3.80	5.11	5.11	5.11
Precipitation	46.88	46.88	46.88	46.88	46.88	46.88	46.88	46.88	46.88	46.88
Interception-Storage	11.61	11.61	11.61	11.61	11.61	11.61	11.61	11.61	11.61	11.61
Surface Runoff	1.72	1.68	3.28	3.44	3.44	6.88	6.88	6.88	6.88	6.88
Actual Evapotranspiration	34.03	33.64	38.67	37.66	36.66	40.61	38.67	37.59	37.59	37.59
30-Year accumulated change in soil moisture storage	5.32	-1.62	-7.75	-4.73	-10.83	-7.75	-4.28	-10.91	-10.91	-10.91

^a Richfield silt loam soil, all values in cm.

^b Representative of unmodified field conditions found in the vicinity of Garden City, Kansas, average of even-year fallow and odd-year fallow runs.

^c Crop rotation on the watershed area, area is fallow in even years

^d Crop rotation on the level bench area.

^e Surface runoff on watershed areas, runoff water added on bench areas.

permeabilities and as such may have a lower recharge rate than that for a composite of the soils found in the area. Because of this, I believe my estimates do accurately reflect recharge rates present on these soils.

Estimates of average annual recharge for the watershed and bench areas of conservation bench terraces at Garden City, Kansas are summarized in Table 7a. The effect of conservation bench terraces on increasing the percolation rates on the entire watershed-bench area are also listed. In all cases an improvement was noted. Under a 4:1 area ratio using a wheat-fallow rotation, recharge was increased by a factor of 15.

From Table 7, increasing the watershed:bench area ratio from 2:1 to 4:1 increased groundwater recharge ratios by 4.2, 2.7 and 2.0 times for continuous wheat, continuous grain sorghum and wheat-fallow rotations respectively.

Two factors are responsible for the crop rotation dependent change in benefits in recharge rates shown in Table 7 for a 4:1 watershed:bench area ratio as opposed to a 2:1 ratio. First, although yearly AET estimates for continuous wheat and continuous grain sorghum are very close to the same, continuous wheat derives more of a benefit in increased recharge rate than does continuous grain sorghum when the watershed:bench area ratio is increased from 2:1 to 4:1 because it is lying fallow during the period of the summer when the heaviest rainfall occurs. Second, the wheat-fallow rotation shows the least increase in recharge rates for increasing watershed:bench area ratios because at the 2:1 ratio recharge is already much closer to a potential recharge rate than is the case for the other two rotations studied. When the ratio is increased to 4:1, an additional 1.85 cm per year is available for use on the bench area. Actual ET uses only 0.12 cm of the additional water with the other 1.73 cm going to groundwater recharge.

Table 7a. Computer Model Estimates of Average Annual Recharge from Conservation Bench Terraces at Garden City, Kansas.^a

Average Annual Recharge, cm

<u>Watershed</u>		<u>Watershed: Bench Area Ratio</u>			
		<u>Percolation^b</u>			
<u>wheat-fallow</u>	<u>Rotation</u>	<u>2:1</u>	<u>4:1</u>	<u>2:1</u>	<u>4:1</u>
0.33	wheat-fallow	2.59	5.11	1.08	1.29
	continuous wheat	0.48	2.02	0.38	0.67
	continuous grain sorghum	1.41	3.80	0.69	1.02

^a Richfield Silt Loam Soil

For 2:1 : percolation for entire area =

$$\frac{2(\text{Watershed Perc.}) + \text{Bench Perc.}}{3}$$

For 4:1 : percolation for entire area =

$$\frac{4(\text{Watershed Perc.}) + \text{Bench Perc.}}{5}$$

Table 6 indicates that AET values on the bench areas are generally larger than those on the watershed areas when the same crop rotation is used on both. In years of above average rainfall or runoff, such as 1953, 1957, 1958 or 1969, more runoff water is ponded on the bench areas. This produces larger increases in soil moisture storage on the bench areas than on the corresponding watershed areas. As a result, more soil moisture is available on the bench areas for use in crop production in following years of below average precipitation. This moisture storage ability of the bench areas is shown in the larger bench area AET values and estimated negative changes in soil moisture storage occurring in 1954, 1959, 1960 and 1970 for the bench areas as opposed to those for the corresponding watershed areas. In these cases more water was present in storage on the bench areas so more was available to be lost through AET. This caused a larger decrease in soil moisture on the benches than was possible on the watershed areas.

In 1951 more rainfall was recorded than for any other year in the 30-year test period. As shown in Table 5, 75.21 cm of precipitation and 18.17 cm of runoff water were added to the bench plots in 1951. An additional 4.54 cm in surface runoff losses not available to the watersheds was added to the bench plots by preventing runoff from the benches. This much larger than normal inflow was used to produce 17.77 cm of groundwater recharge.

Yearly groundwater recharge exceeded 15 cm in only six years: 1946, 1951, 1958, 1967 and 1972. Total recharge in these years was 127.65 cm. When recharge from these years was eliminated recharge estimates dropped from 153.17 cm for the 30-year period to 25.09 cm for the remaining 24-year period. Average yearly recharge for the 30-year period was 5.11 cm. For the remaining 24-year period it was only 1.04 cm per year. This indicates that most recharge takes place only during periods much wetter than normal.

Due to the extra water available for increasing soil moisture contents on the bench areas during years when runoff occurs, higher fallow efficiencies

were observed on the bench areas than on the watersheds. Watershed fallow efficiencies averaged about 18 percent while bench fallow efficiencies averaged about 23 percent. Due to this increased fallow efficiency, more water is available for crop growth the following year. Comparisons of rainfall, change in soil moisture, and AET columns in Table 6 for 1946, a fallow year and 1947, a crop year illustrate this quite well.

Some care must be taken when comparing watershed and bench values in Table 7 because of the different crop rotations used on the watershed and bench areas. Another factor that must be taken into consideration, especially when comparing values from two different years is that due to the crop rotation used, a large water input may be used for AET during a crop year while most water added would go to increasing soil moisture and deep percolation in a fallow year. This may be seen by comparing rainfall, recharge and change in soil moisture values in Table 6 for 1950, a fallow year and 1949, a crop year. Comparison of years as opposed to results assuming fallow in odd-numbered years also illustrates this point.

Also, time of occurrence of rainfall with respect to crop development will greatly affect the disposition of water inputs. For example, in Table 6, 1950 was a wheat planting year on the watershed and bench areas, meaning that all areas were fallow until planted in the fall. The soil profile was relatively full from 6.94 cm of water added to it in 1949. As a result, the 37.49 cm of rain that fell on the fallow areas in May and June went to runoff, bare soil evaporation and interception-storage losses, but mostly to groundwater recharge. Wheat was planted in mid-September. For the rest of the year AET demands exceeded the precipitation available for crop use after runoff and interception-storage losses for each storm were evaluated. The result was a net change in soil moisture of -6.20 cm for a year with rainfall of 52.20 cm.

The years 1951 and 1967 are examples of years when conservation bench terraces are most effective. These are years where precipitation produced large runoff volumes, giving the bench areas the benefit of an additional 22.70 and 26.76 cm of water not available to the watershed areas. These figures assume runoff values of 4.54 and 5.35 cm, a watershed:bench area ratio of 4:1 and zero runoff from the bench areas. In 1951 and 1967 recharge on the benches exceeded recharge on the watersheds by 17.95 and 20.17 cm respectively.

SUMMARY

A continuous watershed model developed and tested for the Garden City, Kansas area was used to evaluate the potential for groundwater recharge from conservation bench terraces. Computer runs were made using historical weather records for the period 1945 to 1974. Watershed:bench area ratios of 2:1 and 4:1 were used. A wheat-fallow rotation was used on the watershed areas. Continuous wheat, continuous grain sorghum or wheat-fallow rotations were used on the bench areas for both 2:1 and 4:1 watershed:bench area ratios.

Daily values of runoff, interception-storage, groundwater recharge, actual ET, and change in soil moisture content in the 183 cm depth profile were calculated. A large portion of total deep percolation to groundwater recharge occurred any time water was applied to an area when the 183 cm profile was at field capacity. The remaining fraction of deep percolation was calculated as the summation of water movement, downward taken as positive, between adjacent 30.4 cm soil layers across the 183 cm boundary, using the Darcy equation.

Groundwater recharge on the watersheds under wheat-fallow rotation was estimated as 0.33 cm per year for the period 1945 to 1974. Recharge rates for the rotations used, in order of increasing amount were continuous wheat,

continuous grain sorghum and wheat-fallow. This was true for both 2:1 and 4:1 watershed:bench ratios. Continuous wheat gave the largest response to an increase in watershed:bench ratios from 2:1 to 4:1. Continuous grain sorghum was next, and the wheat-fallow rotation gave the smallest increase in recharge rate. All bench areas, regardless of watershed:bench ratios or crop rotations used showed a larger recharge rate than was calculated for the sloping watershed conditions. Utilizing runoff from the sloping watershed areas on the bench areas of a conservation bench terrace increased fallow efficiencies from about 18 percent on the watersheds to 23 percent on the leveled bench areas. From this it would appear that conservation bench terraces do have the potential for groundwater recharge when used on Richfield silt loam or other soils with similar permeabilities, with the effectiveness as a recharge structure dependent upon the choice of crop rotations and watershed:bench area ratio used.

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Appendix A. Procedures Used and Data Collected

In computing moisture flow between adjacent soil layers a one dimensional form of Darcy's law was used:

$$q = K \Delta t \frac{\partial (h + z)}{\partial z} \quad \text{or} \quad q = K \Delta t \frac{\Delta h + \Delta z}{\Delta z} \quad (11)$$

where q = flow per unit in the vertical direction, cm

K = unsaturated hydraulic conductivity, average of the two adjacent layers, cm/day

Δh = difference in soil water potential between centers of adjacent soil layers, cm of water

Δz = change in elevation between centers of adjacent soil layers, cm

Δt = time increment over which the process is allowed to run before the above variables are re-evaluated, days

Equation 11 requires soil water potential and unsaturated hydraulic conductivity for each soil layer on a continuous basis. The only model variable that is continuous over time is soil moisture content. Therefore, soil water potential-soil moisture content and unsaturated hydraulic conductivity-soil moisture content relationships were needed. Because of the time and equipment requirements necessary to obtain these relationships, especially the unsaturated hydraulic conductivity-soil moisture content curves, only limited data was available in the literature. None was available for a Richfield silt loam so laboratory experiments were conducted at the Evapotranspiration Laboratory, Kansas State University, to develop soil water potential-soil moisture content and unsaturated hydraulic conductivity-soil moisture content relationships for this soil.

Moisture Retention Curve (Soil Water Potential-Soil Moisture) Procedure

Three different sets of equipment were necessary to obtain retention curves over the 0 to 1.47 MPa pressure range. Detailed instructions for the three methods were found in a laboratory exercise written by Dr. W.L. Powers.

Agronomy Dept., Kansas State University (personal communication).

Stage 1

From zero tension (saturation) to 9.8 kPa, the Buchner funnel apparatus shown in Figure 12 was used. Undisturbed 7.62 cm diameter samples were placed in a 7.62 cm length of 7 cm nominal diameter thinwall plastic tubing in the field and sealed in plastic bags to retain soil moisture. In the laboratory, both ends of each core were planed down to the tubing ends, giving a 7.62 x 7.62 cm cylindrical sample with both ends sufficiently uniform to make proper contact with the ceramic plate in the Buchner funnel.

The bottom portion of the funnel was filled with water, taking care to remove all air bubbles. The rubber stopper - flexible tubing - stopcock apparatus was then filled with water and attached to the funnel, closing the stopcock before filling. Cores from six different depths were placed in the funnels. Water was added to the area between the soil cores and the outside wall of the funnels, filling to within 1.3 cm of the top of the cores. Care was taken not to pour water directly on the cores, especially sandy ones. Plastic bags were placed over the top of the funnels to prevent evaporation. The entire apparatus for each sample was placed in the rack as shown in Figure 12 and the cores were allowed to soak for 24 hours.

After 24 hours, the 250 ml flasks and stopcock tubes were lowered until the tips of the stopcock tubes were 5 cm below the center of the cores. The stopcocks were opened and the water allowed to drain into the flasks for 24 hours. The stopcocks were then closed and the collected water discarded. The tube tips were lowered to 10 cm below the center of the cores, the stopcocks opened and the soil allowed to drain for 24 hours.

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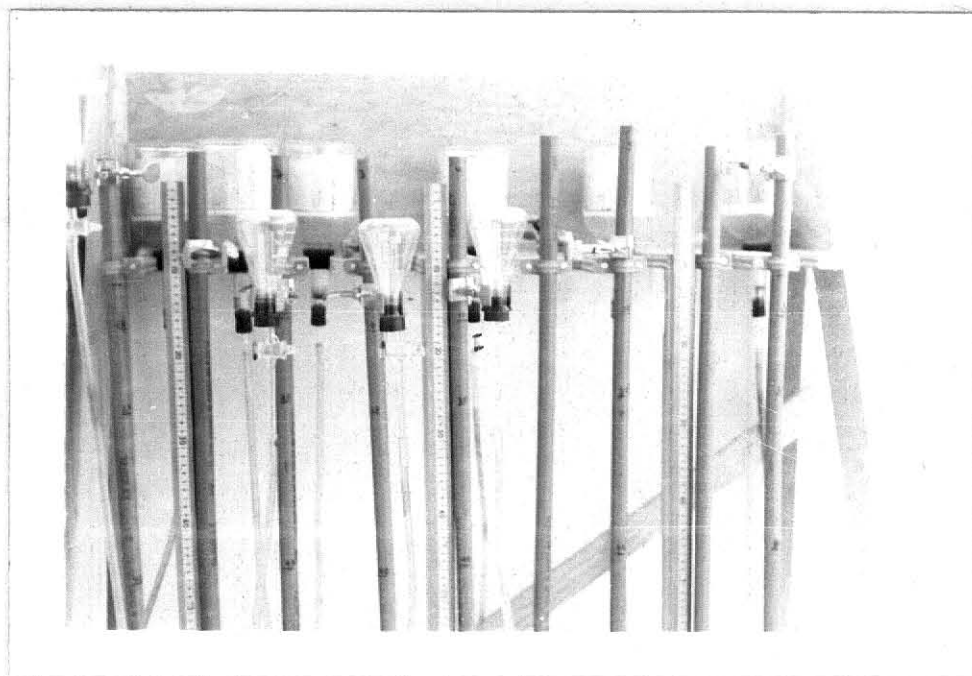


Figure 12. Buchner Funnel Apparatus for Stage 1, Soil Moisture Retention Curve Procedure. 0-9.8 kPa Tension Range.

This procedure was repeated for 25, 50, 75 and 100 cm differences in elevation, with the volume of water released at each step from 10 to 100 cm recorded as shown in Table 8.

Stage 2

For the 9.8-196kPa pressure range, a set of six 196 kPa pressure cells with ceramic plate bottoms was used. Above 196 kPa the plates allowed excessive air to pass.) The cores were carefully removed from the Buchner funnels and the more uniform end placed on the ceramic plates. Water was added to within 1.3 cm of the top of the cores. They were allowed to soak for 48 hours, adding more water if necessary. The excess water was then siphoned from the cells. The retaining bars were removed and replaced with the cell covers. The covers were each attached with four bolts, hand-tightening the wing nuts. The pressure was set at 9.8 kPa to bring the soil back to the equilibrium moisture content achieved at 9.8 kPa on the Buchner funnel apparatus. After draining for 48 hours, the water in the beakers was discarded and the pipettes and the beakers were sealed as units, as shown in Figure 14. The pressure was then set at 19.6kPa and the outflow collected for 24 hours. The outflow was measured and recorded in Table 8. The beakers were re-sealed, the pressure set at 78.4 kPa and the outflow collected for the following 24 hour period. The outflow was measured and recorded and the procedure repeated for 137 and 196 kPa.

When the outflow from the 196 kPa run had been recorded, the cores were removed from the cells. The soil from each sample was pushed from its plastic cylinder back into its original storage carton. The samples were oven dried for 48 hours. Apparent specific gravity and soil moisture content by weight were determined. Values for five different plot locations are listed in Table 9.

Table 8. Volume of Water Released (ml) for Stages 1 and 2 of Moisture Retention Curve Procedure.^a

Sample No. ^b	Tension (or Pressure Applied), cm of water								
	10	25	50	75	100	200	800	1400	2000
I ₁	1.9	5.0	7.5	6.9	6.8	9.7	10.7	4.9	3.7
I ₂	2.1	5.5	9.5	4.7	4.7	4.9	9.4	4.6	2.4
I ₃	2.2	5.0	7.1	4.5	3.5	5.1	10.5	4.2	2.1
I ₄	0.8	6.0	9.7	7.4	5.2	11.0	12.4	3.8	2.2
I ₅	0.6	5.5	9.0	9.0	7.0	15.2	15.7	4.0	2.5
I ₆	1.5		3.2	3.5	4.4	7.8	8.8	3.8	2.7
I ₇	1.5	7.4	10.5	6.4	4.1	12.3	12.9	5.4	4.0
I ₈	1.2	7.4	10.4	6.3	4.4	14.1	13.1	5.0	3.5
I ₉	2.3	8.6	9.8	5.7	3.8	10.1	12.0	4.7	2.8
I ₁₀	2.5	7.9	8.8	5.4	3.6	11.6	21.0	6.0	3.8
II ₁	3.7	9.3	10.9	5.5	3.8	11.2	9.0	4.6	3.4
II ₂	4.4	16.0	14.5	6.2	4.4	11.4	8.2	4.3	3.2
II ₃	0.4	4.6	7.0	5.4	3.5	9.5	7.6	3.3	2.3
II ₄	0.6	1.1	5.1	5.2	3.1	8.8	8.9	3.0	2.1
II ₅	0.5	2.0	6.4	6.4	5.0	13.4	11.3	2.2	1.4
II ₆	0.8		6.7	8.6	8.9	25.0	9.3	3.3	2.3
II ₇	0.8	1.1	8.2	5.3	3.2	6.8	7.0	3.3	2.4
II ₈	0.4	0.9	6.0	5.2	4.2	9.0	6.1	3.5	2.5
II ₉	0.7	3.3	8.7	7.8	5.4	3.5	12.2	3.3	2.2
II ₁₀	0.4	4.0	8.8	12.3	6.4	3.4	11.7	2.5	2.0
III ₁	1.5	7.0	7.1	4.7	3.0	1.0	9.2	2.1	2.1
III ₂	0.3	9.4	0.0	4.6	0.5	2.4	12.7	3.5	2.7
III ₃	1.0	8.7	8.5	5.0	4.0	2.4	12.7	2.8	2.2
III ₄	0.5	2.2	9.1	7.8	5.6	3.2	14.1	4.3	3.0
III ₅	3.9	3.4	12.1	9.9	7.5	11.0	11.3	4.6	3.3
III ₆	1.3	4.8	6.3	4.1	3.3	4.6	6.3	2.6	1.7
III ₇	0.6	2.6	6.0	4.5	4.0	4.7	7.0	2.8	1.4
III ₈	0.3	1.3	5.8	5.9	5.9	11.6	12.7	3.0	1.8
III ₉	0.5	0.0	2.3	5.3	3.6	9.5	9.0	3.2	2.4
III ₁₀	0.4	5.7	10.7	7.6	5.5	7.9	9.1	3.6	2.8

^a Richfield silt loam soil, Garden City, Kansas, Branch Agricultural Experiment Station

^b I₁-I₁₀ = 5WB 0-8' II₆-II₁₀ = 8WB 0-4' III₆-III₁₀ = 8EB
 II₁-II₅ = 8WWS 0-4' III₁-III₅ = 2EWS 0-4'

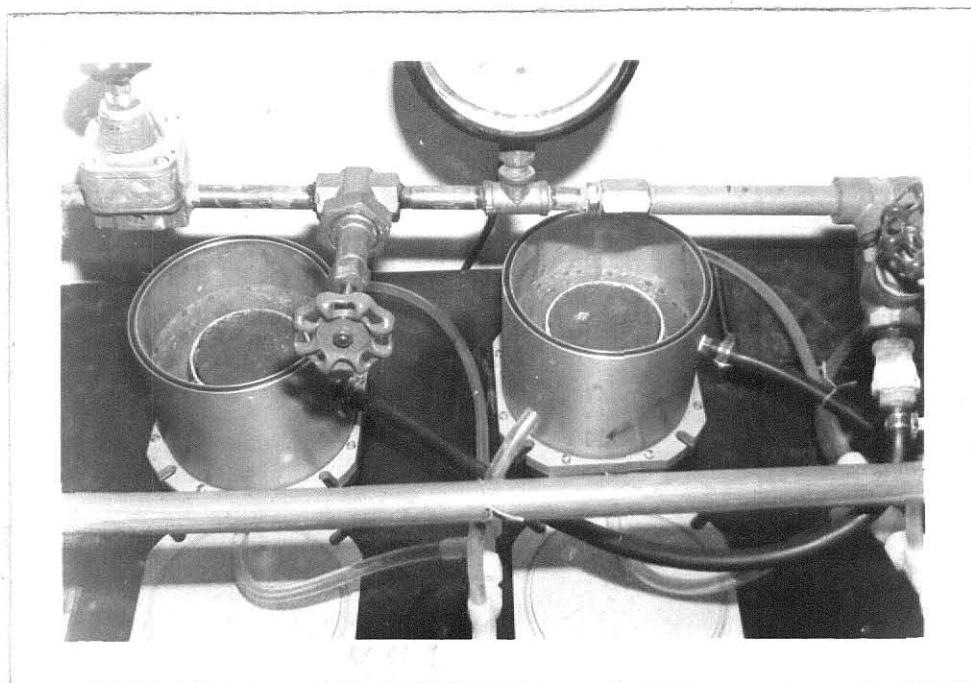


Figure 13. Equipment Arrangement, Preliminary Stage 2 Moisture Retention Curve Procedure.

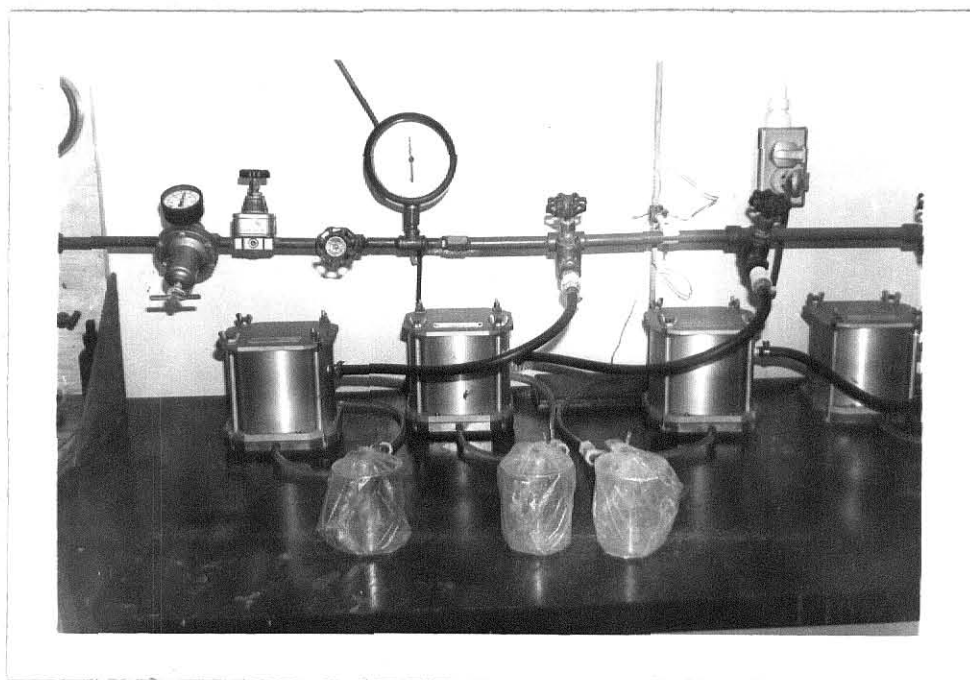


Figure 14. Final Equipment Arrangement, Stage 2 Moisture Retention Curve Procedure. 9.8 kPa-196 kPa Pressure Range.

Table 9. Apparent Specific Gravity, Soil Moisture Content, Percent by Volume and Weight, for Stages 2 and 3 of Soil Moisture Retention Curve Procedure.

Sample No.	Core No.	2atm			5atm		10atm		15atm	
		Pw	As	Pv	Pw	Pv	Pw	Pv	Pw	Pv
I ^c	1	17.70	1.45	25.60	11.99	17.39	9.80	14.21	9.17	13.30
I ¹	2	19.47	1.41	27.47	15.68	22.11	12.98	18.30	12.12	17.09
I ²	3	17.08	1.51	25.87	14.62	22.08	12.13	18.32	11.23	16.96
I ³	4	15.08	1.52	22.95	13.20	20.06	11.08	16.84	10.17	15.46
I ⁴	5	15.24	1.48	22.50	14.64	21.67	12.37	18.31	11.84	17.52
I ⁵	6	20.60	1.48	30.40	19.88	29.42	16.51	24.43	15.56	23.03
I ⁶	7	20.09	1.39	27.84			14.42	20.04	13.41	18.64
I ⁷	8	19.09	1.36	25.97			14.06	19.12	12.88	17.52
I ⁸	9	20.95	1.34	28.10			15.19	20.35	13.67	18.32
I ⁹	10	20.43	1.32	27.01			13.29	17.54	11.87	15.67
II ¹⁰	11	18.75	1.43	26.73			10.92	15.62	10.16	14.53
II ¹	12	18.65	1.34	25.01			11.14	14.93	10.30	13.80
II ²	13	18.20	1.48	27.00	23.19		12.15	17.98	11.35	16.80
II ³	14	15.24	1.68	25.67	20.58		10.88	18.28	9.98	16.77
II ⁴	15	14.04	1.65	23.14	18.23		10.11	16.68	9.34	15.41
III ⁵	16	18.18	1.45	26.42	19.92		10.65	15.44	9.33	13.53
III ¹	17									
III ²	18	18.55	1.61	29.81	25.20		13.57	21.85	12.48	20.09
III ³	19	16.24	1.60	26.00	13.57	21.57	11.76	18.82	10.51	16.82
III ⁴	20	17.23	1.50	25.93	15.21	22.82	13.55	20.33	12.51	18.76
IV ⁵	21	18.93	1.51	28.53	15.18	22.92	13.01	19.64	12.12	18.30
IV ¹	22	16.41	1.52	24.87	13.64	20.73	11.63	17.68	10.39	15.79
IV ²	23	14.01	1.62	22.68	11.57	18.75	9.90	16.04	9.29	15.05
IV ³	24	20.20	1.42	28.77	17.88	25.39	15.24	21.64	14.43	20.49
IV ⁴	25	20.96	1.31	27.49	19.52	25.57	17.10	22.40	15.68	20.54
V ⁵	26	20.87	1.48	20.89	16.77	24.82	14.71	21.77	13.86	21.51
V ¹	27	22.97	1.44	33.08	18.76	27.01	16.67	24.00	15.83	22.80
V ²	28	18.56	1.53	28.35	15.62	23.90	13.66	20.90	12.85	19.66
V ³	29	15.57	1.56	24.28	12.49	19.48	10.91	17.02	9.94	15.51
V ⁴	30	20.88	1.40	29.17	18.30	25.62	16.52	23.13	15.02	21.03

^aRichfield Soil, Garden City, Kansas, Branch Agricultural Experiment Station

^bCore Number Plot Location Code:

1-10 = Plot 5, West bench 16-20 = Plot 8, West bench
11-15 = Plot 8, West Watershed 21-25 = Plot 2, East Watershed
26-30 = Plot 8, East Bench

^cSample Number Depth Code: 1 = 0-15 cm 6 = 122-152 cm
2 = 15-30 cm 7 = 152-183 cm
3 = 30-61 cm 8 = 183-213 cm
4 = 61-91 cm 9 = 213-244 cm
5 = 91-122 cm 10 = 244-274 cm

Stage 3

For tensions of 490 kPa to 1.47 MPa a set of three pressure membrane plates were used as shown in Figures 15 and 16. The dried soil cores from Stage 2 tests were crushed until roughly 100 gm of each sample would pass a 2 mm sieve (the soil should not be crushed to a fine powder if it can be avoided). Presoaked 1.47 MPa bubbling pressure cellulose casing were then placed on the base plates. All air between the membrane and base plates was removed before the spacing cylinders were attached to the base plates. Water was added to keep the membranes moist at all times. For each sample to be tested, a 3.2 cm diameter by 1.0 cm length of rubber tubing was placed on each membrane and filled with soil. The plate covers were bolted in place, tightening opposite bolts in a rotating pattern to 16 N · m of torque. Preliminary and final Stage 3 equipment arrangement is shown in Figures 15 and 16. The samples were allowed to soak for 24 hours. Pressure of 1.47 MPa, 980 kPa and 490 kPa were then applied to the first, second, and third plates respectively. (The valves should be opened slowly or the air flow will disturb any samples in the immediate area of the plate cylinder air inlet.)

Outflow was measured in partially sealed 10 ml graduated cylinders to determine when the samples in each plate had reached equilibrium. When no change was observed in the outflow cylinder level for 2 days, the samples in that plate were assumed to be at equilibrium conditions. The pressure on that plate was released and the samples were oven dried for 24 hours. Moisture content for each sample was determined and the data recorded in Table 10. Most runs required five to ten days to reach equilibrium.

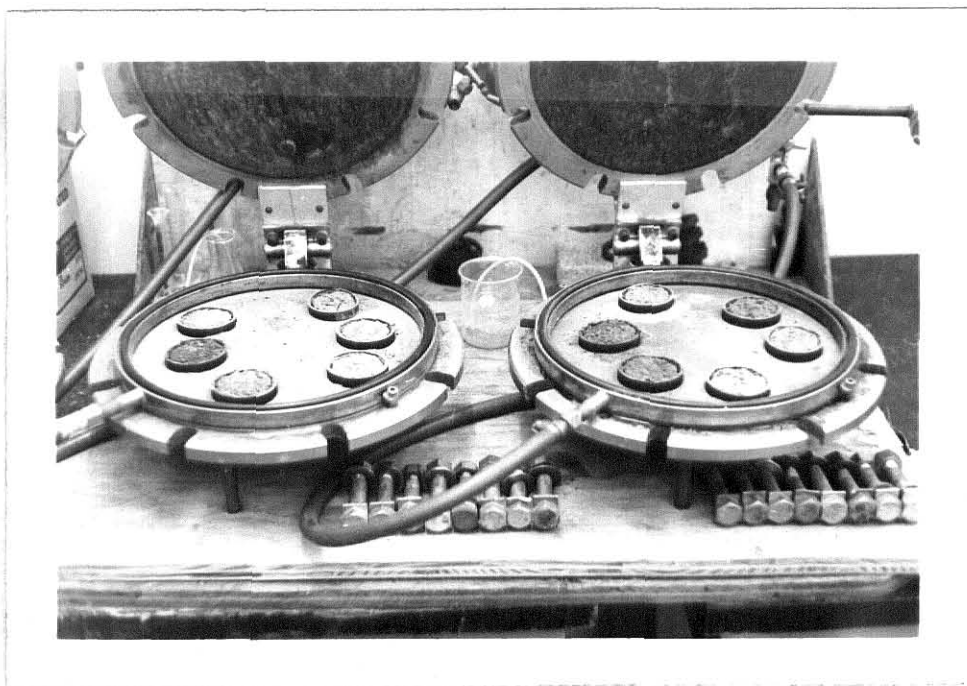


Figure 15. Preliminary Equipment and Sample Arrangement, Stage 3, Soil Moisture Retention Curve Procedure.

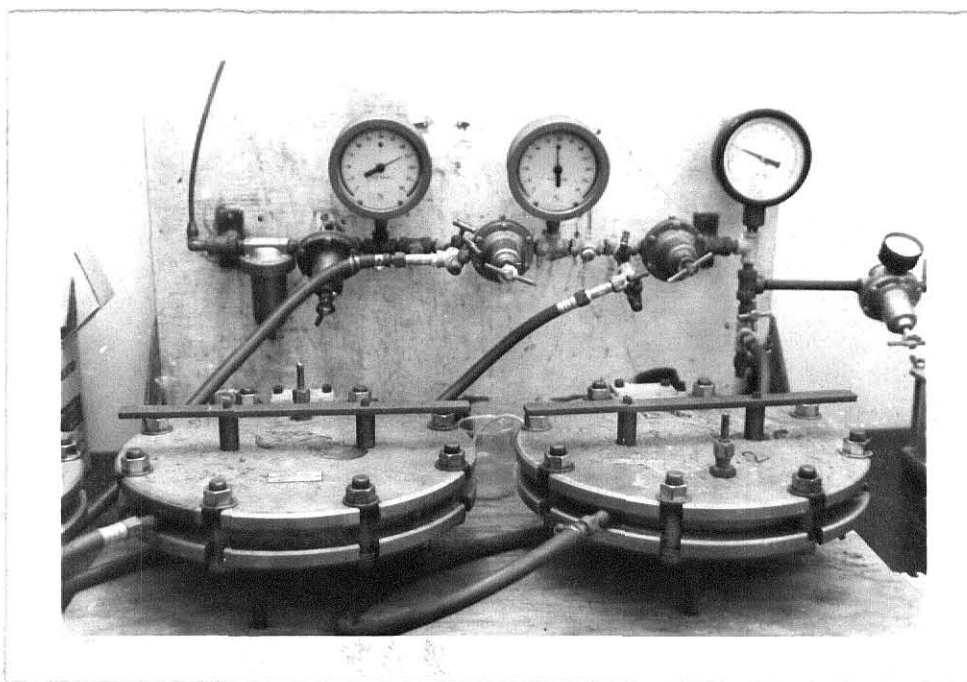


Figure 16. Final Equipment Arrangement, Stage 3, Soil Moisture Retention Curve Procedure. 490 kPa-1.47 MPa Pressure Range.

Table 10
Wet, Dry and Can Weights for Stages 2 and 3
Soil Moisture Retention Curve Procedure ^a

Sample #	Wet ^b wt	Dry	Can	Wet	Dry	Can	Wet	Dry	Can	Wet	Dry	Can
1	617.92	529.00	26.51	50.95	47.68	20.41	45.70	43.41	20.03	48.89	46.51	20.55
2	611.66	516.25	26.26	49.40	45.48	20.48	45.12	42.25	20.13	48.25	45.25	20.49
3	642.19	557.33	26.17	54.72	50.31	20.15	53.03	49.50	20.39	58.32	54.49	20.37
4	634.90	555.20	26.76	53.97	50.06	20.45	53.40	50.12	20.51	57.36	53.92	20.08
5	617.42	539.26	26.47	54.81	50.39	20.20	48.07	45.02	20.37	55.28	51.54	19.96
6	644.64	539.05	26.47	54.48	48.98	20.47	46.75	42.93	20.15	51.49	47.27	20.14
7	603.00	506.31	25.11	59.66	48.88	20.41	51.30	47.26	20.03	50.82	47.24	20.55
8	587.79	497.57	24.90	56.94	47.97	20.48	54.78	50.51	20.13	51.70	48.14	20.49
9	588.77	491.18	25.28	58.80	49.54	20.15	52.99	46.69	20.39	53.06	49.13	20.37
10	578.16	484.34	25.20	57.06	47.76	20.45	52.65	48.80	20.51	51.84	48.47	20.08
11	612.96	520.10	24.82	59.68	49.86	20.20	53.08	49.86	20.37	52.92	49.88	19.96
12	577.42	490.54	24.71	60.00	50.22	20.47	51.67	48.51	20.15	53.66	50.53	20.14
13	635.05	541.26	26.05	55.53	48.92	20.41	47.72	44.72	20.03	50.46	47.41	20.55
14	700.36	611.20	26.17	50.10	52.51	20.48	53.02	46.93	20.13	49.79	47.13	20.49
15	678.92	598.55	26.27	54.98	49.61	20.15	53.50	50.46	20.39	50.11	47.57	20.37
16	622.83	531.06	26.18	55.06	49.31	20.45	52.00	48.97	20.51	50.54	47.94	20.08
17	638.99	510.32	26.22	53.57	45.08	20.20	47.92	43.06	20.37	50.57	45.54	19.96
18	687.62	584.09	25.86	55.89	48.76	20.47	50.37	46.76	20.15	53.95	50.20	20.14
19	672.71	582.41	26.23	52.93	49.07	20.63	53.59	50.06	20.03	52.53	49.49	20.55
20	638.99	548.63	26.05	51.34	47.28	20.59	49.55	46.04	20.13	50.88	47.50	20.49
21	648.29	549.21	25.87	48.28	44.55	19.98	48.32	45.90	20.39	48.50	45.46	20.37
22	639.36	522.96	26.41	51.70	47.96	20.54	48.83	45.80	20.51	34.95	33.55	20.08
23	667.01	538.25	25.93	53.51	50.04	20.05	53.56	50.57	20.37	52.20	49.46	19.96
24	620.63	520.70	25.94	50.56	45.92	19.97	50.78	46.73	20.15	50.99	47.10	20.14
25	577.07	481.59	26.07	48.94	44.28	20.41	48.31	44.18	20.03	49.17	45.29	20.55
26	647.50	540.21	26.18	49.66	45.47	20.48	48.21	44.61	20.13	51.06	47.34	20.49
27	641.04	526.15	25.92	49.73	45.10	20.15	48.53	44.51	20.39	47.52	43.81	20.37
28	655.45	556.97	26.28	51.17	47.02	20.45	52.63	48.77	20.51	49.67	46.30	20.08
29	652.29	567.94	26.04	52.26	48.70	20.20	52.28	49.14	20.37	52.70	49.74	19.96
30	613.01	511.69	26.42	51.31	46.54	20.47	49.84	45.63	20.15	53.99	49.57	20.14

^aGarden City, Kansas, Branch Agricultural Experiment Station, Richfield Silt Loam

^bAll weights in gm

By initially filling the cylinders to a given level and placing the plate outlet tube ends below the water surface, the size of any membrane leaks was quickly determined. (If more than one air bubble every 2-3 seconds appears the membrane and samples should be removed. Otherwise, samples will be "air dry" after a one week run). Before replacing a leaky membrane, the base plate should be checked for small rust scales which occasionally fall from the plate covers and may puncture the membrane. Also, once every two or three runs, the base plate should be removed and have high pressure water passed backwards through it to remove any small rust particles that may be partially blocking the base plate outlet.)

A completely sealed graduated cylinder will experience a gradual pressure increase over time due to the small amount of air passing through the membranes. If this air is not allowed to escape, it will accumulate between the membrane and base plate, producing a large air pocket that separates the base plate and membrane. This interferes with flow through the membrane and gives samples with higher equilibrium moisture contents at a given pressure than actually exist. This was the case in some preliminary runs.

When all the data was in the form of Tables 9-11 it was reduced to the coordinates of the moisture retention curve by the following procedure:

1) The moisture contents, percent by volume, were calculated for the 196, 490, 980 kPa and 1.47 MPa samples using the appropriate wet, dry and can weights and apparent specific gravity values. These values were entered in Table 9.

2) The soil moisture, as percent by volume, that was lost from each sample for each pressure increment between zero and 196 kPa was calculated by dividing the ml of water removed during each increment by the sample volume (347.5 cm^3) and multiplying by 100. These values were entered in Table 11.

Table 11. Water Released in Percent by Volume for Each Pressure Increment Applied During Stages 1 and 2 of Soil Moisture Retention Curve Procedure.^a

Sample	Cm Water Tension								
	10	25	50	75	100	200	800	1400	2000
1 ^b	.55	1.44	2.16	1.98	1.96	2.79	3.08	1.41	1.06
2	.60	1.58	2.73	1.35	1.35	1.41	2.70	1.32	.69
3	.63	1.44	2.04	1.29	1.01	1.47	3.02	1.21	.60
4	.23	1.73	2.79	2.13	1.50	3.17	3.57	1.09	.63
5	.17	1.58	2.59	2.59	2.01	4.37	4.51	1.15	.72
6	.43		.92	1.01	1.27	2.24	2.53	1.09	.78
7	.43	2.13	3.02	1.84	1.18	3.54	3.71	1.55	1.15
8	.34	2.13	2.99	1.81	1.27	4.06	3.77	1.44	1.01
9	.66	2.47	2.82	1.64	1.09	2.91	3.45	1.35	.81
10	.72	2.27	2.53	1.55	1.04	3.34	6.04	1.73	1.09
11		2.68	3.14	1.58	1.09	3.22	2.59	1.32	.98
12		4.60	4.17	1.78	1.27	3.28	2.36	1.24	.92
13	.12	1.32	2.01	1.55	1.01	2.73	2.19	.95	.66
14	.17	.32	1.47	1.50	.89	2.53	2.56	.86	.60
15	.14	.58	1.84	1.84	1.44	3.87	3.25	.63	.40
16	.23		1.93	2.47	2.56	7.19	2.68	.95	.66
17	.23	.32	2.36	1.52	.92	1.96	2.01	.95	.69
18	.12	.26	1.73	1.50	1.21	2.59	1.76	1.01	.72
19	.20	.95	2.50	2.24	1.55	1.01	3.51	.95	.63
20	.12	1.15	2.53	3.54	1.84	.98	3.37	.72	.58
21	.43	2.01	2.04	1.35	.86	.29	2.65	.60	.60
22	.09	2.71	0	1.32	.14	.69	3.65	1.01	.78
23	.29	2.50	2.45	1.44	1.15	.69	3.65	.81	.63
24	.14	.63	2.62	2.24	1.61	.92	4.06	1.24	.86
25		.98	3.51	2.85	2.16	3.17	3.25	1.32	.95
26	.37	1.38	1.81	1.18	.95	1.32	1.81	.75	.49
27	.17	.75	1.73	1.29	1.15	1.35	2.01	.81	.40
28	.09	.37	1.67	1.70	1.70	3.34	3.65	.86	.52
29	.14	0	.66	1.52	1.04	2.73	2.59	.92	.69
30	.12	1.64	3.08	2.19	1.58	2.27	2.62	1.04	.81

^aRichfield silt loam, Bench terrace area, Garden City, Kansas Branch Agricultural Experiment Station.

^bCore Number Plot Location Code:

1-10 = Plot 5, West bench

11-15 = Plot 8, West Watershed

26-30 = Plot 8, East Bench

16-20 = Plot 8, West bench

21-25 = Plot 2, East Watershed

Sample Number Depth Code:

(Samples 11-30 were sampled at the same depth increments

as 1-10 but were sampled only to a depth of 122 cm.)

1 = 0-15 cm

2 = 15-30 cm

3 = 30-61 cm

4 = 61-91 cm

5 = 91-122 cm

6 = 122-152 cm

7 = 152-183 cm

8 = 183-213 cm

9 = 213-244 cm

10 = 244-274 cm

3) Beginning with the known moisture content at 196 kPa, soil moisture at 137 kPa was back-calculated by subtracting the percent by volume of water removed at 196 kPa from the water content at 196 kPa. This procedure was repeated for each pressure step back to 490 Pa. All values for the same depth were averaged, giving the values shown in Table 12.

4) For moisture content at saturation, Equation 12 was used (moisture content at saturation was assumed to be equal to the pore space).

$$\text{saturated moisture content} = \text{percent pore space} = \left(1 - \frac{\rho_b}{\rho_p}\right) \times 100 \quad (12)$$

where ρ_b is the apparent specific gravity of the soil sample and ρ_p is the density of the soil particles, assumed to be 2.65 g/cm^3 .

Moisture content at saturation may very well be less than that at 490 Pa for several reasons: 1) apparent specific gravity may be in error; 2) particle density may not be 2.65 g/cm^3 ; 3) not all water drained from the soil that should have drained at the 490 Pa setting. (Moisture content at 490 Pa is back-calculated from the equilibrium moisture content at the 980 Pa setting and the outflow measured at 980 Pa. The measured outflow at 980 Pa will be too large if insufficient time was allowed for slow draining soils to come to equilibrium at the 490 Pa pressure setting. When the resulting extra-large outflow at 980 Pa is added to the equilibrium soil moisture content at 980 Pa, too large a 490 Pa equilibrium soil moisture content will be obtained.)

Curves for 0-15 and 15-30 cm were similar enough to be combined as one curve in the model, as were the 30-61, 61-91 and 91-122 cm curves. Figure 8, Chapter 2, shows the relationships actually used in the model.

Table 12. Final coordinates for Soil Moisture Retention Curves for Richfield Silt Loam.^a

Soil Moisture Tension cm	Depth, cm									
	0-15	15-30	30-61	61-91	91- 122	122- 152	152- 183	183- 213	213- 244	244- 274
0 ^b	44.90	46.42	41.51	41.13	44.53	44.15	47.55	48.68	49.43	50.19
5	42.61	41.05	39.47	38.72	42.09	42.10	46.39	44.79	45.30	47.32
10	42.21	40.78	39.22	38.54	41.95	41.67	45.96	44.45	44.64	46.60
25	40.33	38.79	38.05	37.81	40.76	40.24	43.83	42.32	42.17	44.33
50	38.11	36.09	36.05	35.80	38.05	39.32	40.81	39.33	39.35	41.80
75	36.4	34.64	34.57	33.87	35.45	38.31	38.97	37.52	37.71	40.25
100	34.92	33.67	33.35	32.55	33.64	37.04	37.79	36.25	36.62	39.21
200	31.96	31.93	31.19	30.48	30.71	34.80	34.25	32.19	33.71	35.87
800	29.4	29.38	28.34	27.22	27.31	32.27	30.54	28.42	20.26	29.83
1400	28.39	28.31	27.37	26.21	26.34	31.18	28.99	26.98	28.91	28.1
2000	27.63	27.61	26.74	25.53	25.65	30.40	27.84	25.97	28.10	27.01
5000	23.50	23.28	21.58	21.66	23.92	29.42	25.49	22.98	24.16	19.63
10,000	17.34	18.73	19.02	18.52	20.17	24.43	20.04	19.12	20.35	17.54
15,000	16.03	17.37	17.71	17.01	18.65	23.03	18.64	17.52	17.54	15.67

^aBench Terrace Area, Garden City, Kansas Branch Agricultural Experiment Station

$$^b \rho_v \text{ at saturation} = \frac{\rho_b}{(1 - \rho_p)} \times 100, \rho_p = 2.65$$

Unsaturated Hydraulic Conductivity-Moisture Content Curves

Several factors were considered in determining which of several methods available to determine unsaturated hydraulic conductivity should be used. First, the method had to be compatible with the equipment, or minor modifications in the equipment available at the Kansas State University Evapotranspiration Laboratory. Second, time requirements, both from time periods of equipment availability and man hours necessary to run the tests should be a minimum. And finally, realizing the great variability in soil properties with location for the same soil, some accuracy could be sacrificed for the sake of simplicity and reduced time requirements.

Kirkham and Powers (1972) discuss the advantages and disadvantages of various methods of obtaining soil diffusivity. From their discussion and additional searching, Doering's One Step Method (1965) was chosen as the method that best fit the above considerations.

In this method, diffusivity is calculated by Equation 13 developed by Gardner:

$$D = \frac{4L^2}{-\pi^2(W-W_f)} \frac{dW}{dt} \quad (13)$$

where D = soil diffusivity, cm/hr

L = sample length, cm

W = sample water content, percent by volume, when the instantaneous outflow rate dW/dt is determined

W_f = final equilibrium water content, percent by volume, at the pressure used in the experiment

To obtain unsaturated hydraulic conductivity from these calculated diffusivity values, Equation 14 was used (Doering 1965).

$$K = - D \, dW/ds \quad (14)$$

where K is unsaturated hydraulic conductivity in cm/hr and dW/ds is the slope of the soil water potential vs. soil water content curve at the water content represented by D .

Experiment Description

Undisturbed samples were taken in the 0-15 and 15-30 cm layers and at 46, 76, 107, and 138 cm with a 7.62 cm Giddings probe. Samples about 10 cm in length were placed in 7 cm nominal diameter plastic sleeves and sealed in plastic bags in the field to prevent excessive drying.

In the laboratory, the samples were prepared using the same procedure as outlined for the moisture retention curve samples, giving uniform-faced cylindrical samples with a volume of 347.5 cm^3 .

The equipment was set up as shown in Figure 17. Equipment arrangement was identical to that for Stage 2 of the moisture retention curve procedure with two small exceptions. First, a plastic pipe tee fitting and a 15 cm plastic pipe standpipe were added. And second, outflow was collected in 10 ml graduated cylinders in this experiment. A small one-hole rubber stopper with a narrow groove cut parallel to the hole on the outer surface was fit over each of the outflow tips and into the mouth of a graduated cylinder. This provided a seal to prevent evaporation and a small vent to prevent a pressure increase in each cylinder. The standpipe, containing about 1.3 cm of water was necessary to remove any air that collected in the apparatus before the air had a chance to reach the tip of the graduated tubing. On a preliminary run, air accumulated in the curved area of these tips and blocked water passage into the cylinder. This greatly interfered with the outflow vs. time measurement

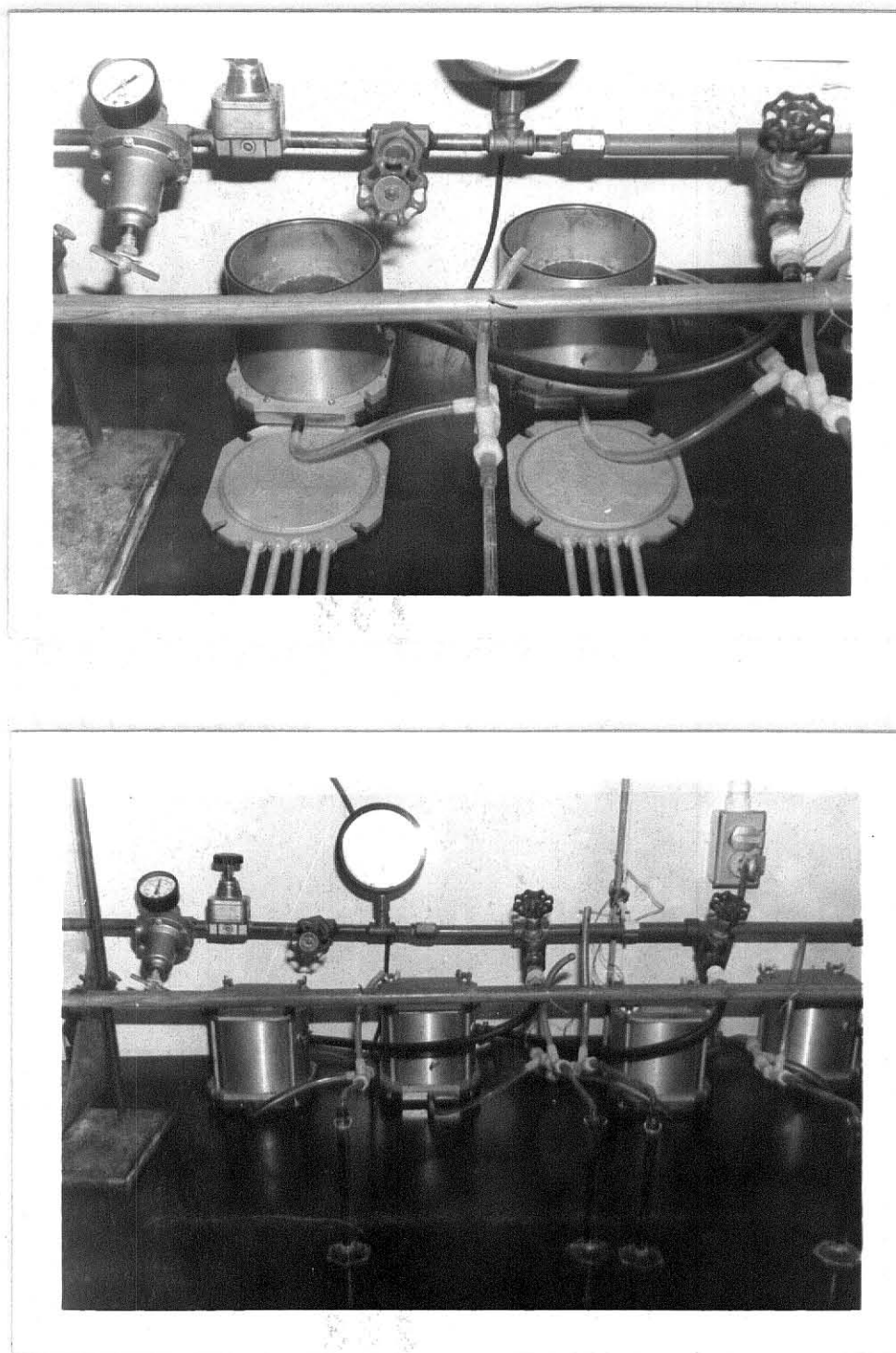


Figure 17. Preliminary (Top) and Final (Bottom) Equipment Arrangement for "One-Step" Method of Determining Unsaturated Hydraulic Conductivity-Soil Moisture Relationships.

necessary in this procedure. The standpipes were added to eliminate this problem and in most cases worked well. Large bubbles 2 cm in length or longer did have a tendency to pass the standpipe entrance intact and created problems if they were not removed from the systems before reaching the tips. By removing the tip from the cylinder, maintaining it at a constant level over another container and adding water to the standpipe, the bubbles and extra water could be flushed from the system with no problems created. By observing the apparatus at least once a day and flushing when necessary, reliable data were obtained.

Samples were placed on the ceramic plate of the 196 kPa pressure cells, soaked for 48 hours and the water remaining between the cores and cylinder walls siphoned off as in Stage 2 of the moisture retention curve procedure. Covers were bolted in place and 196 kPa was applied. Outflow measurements from each core began immediately and were recorded vs. time as shown in Table 13. The initial outflow rates were very large and required the use of 25 ml graduated cylinders for ease of reading and ability to "keep up" with the experiment. Time increments for recording outflow were determined as the experiment progressed. They were selected so that the outflow for all the cores was usually between 0.5 and 1.5 ml at the end of each time period. This gave between 100 and 150 data points for each curve and good definition to the accumulated outflow vs. time curves, Figure 2, Chapter 1. The experiment was run for 40 days. As seen from comparing total outflow on the last two days of the run, none of the cores had truly reached equilibrium conditions but all were approaching equilibrium.

Doering (1965) took plots of accumulated outflow vs. time and graphically determined the slope at various points to get values for $347.5 \times dW/dt$. I chose instead to attempt to find a continuous function to describe these curves and then take the first derivative of the

Table 13. Accumulated Outflow vs. Time for Unsaturated Hydraulic Conductivity-
Soil Moisture Curves^a

Time hrs. 5.55 x 10 ⁻³ 8.33 x 10 ⁻³	Sample No. ^b						Time hrs.	Sample No. ^b					
	1	2	3	4	5	6		1	2	3	4	5	6
0.011	1.3		1.6				0.129	25.9	21.7	21.3	28.6	31.0	24.4
0.014	2.5		2.6		1.1	3.3	0.133	26.2	22.0	21.4	28.8	32.0	24.7
0.010	3.9		3.8	3.9			0.138	26.4	22.2	21.6	29.5	32.6	25.0
0.019	5.3	1.5	4.9	5.4	5.0	5.0	0.142	26.7	22.5	21.8	30.0	33.2	25.2
0.022	6.6	1.9	6.0	6.5	5.5	6.0	0.146	26.9	22.7	21.9	30.6	34.2	25.2
0.025	8.0	3.4	6.9	8.1	5.7	8.0	0.150	27.2	23.1	22.0	31.2	35.0	25.7
0.028	9.7	4.8	8.6	9.8	7.2	9.0	0.154	27.4	23.3	22.2	31.7	35.9	25.9
0.031							0.158	27.6	23.4	22.4	32.3	36.8	26.2
0.033							0.163	27.9	23.9	22.5			
0.0375	12.2	6.9	10.3				0.167	28.1	24.0	22.7	33.1	38.0	26.5
0.0417	13.6	8.6	11.5	13.0	10.6	10.5	0.171	28.3	24.1	22.8	33.7	39.0	26.7
0.0458	14.6	9.6	12.2	14.8	11.4	11.5	0.175	28.5	24.3	23.0	34.1	39.8	26.9
0.05	15.4	10.6	12.9	15.7	12.4	12.2	0.179	28.7	24.4	23.1	34.5	40.4	27.1
0.0542				16.7	13.4	13.5	0.183	28.9	24.6	23.3	34.8	41.2	27.3
0.0583	17.1	11.6	14.5	17.3	14.3	14.4	0.188	29.3	25.0	23.4	35.4	42.2	27.6
0.0625	17.8	13.5	15.0	17.9	15.0	14.9	0.192	29.6	25.1	23.6	35.8	43.0	27.7
0.067	18.7	14.5	15.5	18.4	16.0	15.7	0.196	29.8	25.2	23.7	36.1	43.5	27.8
0.071	19.4	15.2	15.8	19.3	17.0	17.4	0.200	30.1	25.4	23.8	36.3	44.3	28.0
0.075	20.2	16.1	16.4		18.0		0.208	30.5	25.6	24.1	36.8	46.0	28.2
0.079	20.8	16.6	16.7	20.1	19.0	18.8	0.217	30.8	26.0	24.3	37.4	47.0	28.6
0.083	21.0	17.2	17.2				0.225	31.1	26.3	24.4	37.8	48.4	28.8
0.0875	21.2	17.6	17.5	21.3	20.0	19.8	0.233	31.5	26.5	24.7	38.6	49.8	29.0
0.0917	22.0	18.2	17.8	21.8	21.0	20.5	0.241	31.6	26.7	24.9	39.0	50.8	29.2
0.0958	22.3	18.5	17.9	22.5	22.4	20.8	0.250	32.0	27.0	25.1	39.5	51.8	29.4
0.10	22.8	19.0	18.3	23.3	23.0	21.3	0.258	32.3	27.3	25.4	39.8	52.8	29.6
0.104	23.3	19.5	18.9	23.8	24.0	21.8	0.267	32.5	27.5	25.5	40.1	53.9	29.8
0.108	23.6	19.8	19.4	24.3	25.0	22.2	0.275	32.8	27.7	25.7	40.5	54.6	30.1
0.1125	23.8	20.0	19.6	24.9	25.8	22.5	0.283	33.0	27.9	25.9	40.8	55.2	30.3
0.117	24.3	20.3	19.9	25.5	26.6	22.8	0.292	33.3	28.1	26.0	41.1	56.0	30.6
0.121	24.6	20.6	20.2	26.1	27.4	23.2	0.300	33.5	28.4	26.2	41.4	57.0	30.8
0.125				26.8	28.4	23.6	0.308	34.0	28.5	26.4	41.8	57.6	31.0
	25.1		20.7	27.3	29.0	23.8	0.317	34.1	28.7	26.6	41.9	58.0	31.1
	25.4	21.4	21.1	27.8	30.0	24.0	0.325	34.2	28.9	26.7	42.1	58.4	31.3
							0.333	34.5	29.1	26.8	42.4	59.0	31.7

^a Plot 8WB, Garden City Experiment Station, Richfield Silt Loam

^b 1 = 0.15 cm 2 = 15-31 cm 3 = 31-61 cm 4 = 61-91 cm 5 = 91-122 cm 6 = 122-153 cm

Table 13 continued.

Time (hrs)	Core #						Core #						Core #					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
0.350	34.7	29.4	27.1	43.0	60.4	32.1	2.83	51.4	44.4	41.4	60.0	87.1	46.9	51.4	44.4	41.4	60.0	87.1
0.367	35.1	29.6	27.3	43.3	61.0	32.4	3.00	51.8	44.9	41.9	60.4	87.6	47.5	51.8	44.9	41.9	60.4	87.6
0.383	35.5	30.0	27.6	43.8	61.9	32.6	3.25	52.5	45.5	42.5	61.0	88.4	48.2	52.5	45.5	42.5	61.0	88.4
0.400	35.8	30.4	27.9	44.2	63.3	33.0	3.50	53.1	46.1	43.1	61.6	89.1	48.6	53.1	46.1	43.1	61.6	89.1
0.417	36.2	30.7	28.5	44.5	64.0	33.3	3.75	53.8	46.6	43.6	62.2	89.8	49.1	53.8	46.6	43.6	62.2	89.8
0.433	36.5	31.1	28.7	44.8	64.7	33.6	4.00	54.3	47.1	44.2	62.7	90.5	49.5	54.3	47.1	44.2	62.7	90.5
0.450	36.8	31.3	29.0	45.2	65.3	33.8	4.33	55.3	48.0	44.5	63.3	91.5	50.0	55.3	48.0	44.5	63.3	91.5
0.467	37.1	31.4	29.2	45.4	65.9	34.0	4.67	56.0	48.4	45.4	63.9	92.3	50.4	56.0	48.4	45.4	63.9	92.3
0.483	37.3	31.6	29.4	45.8	66.3	34.3	5.00	56.7	49.1	46.0	64.5	92.9	50.9	56.7	49.1	46.0	64.5	92.9
0.500	37.6	31.9	29.6	46.0	66.8	34.5	5.33	57.3	49.6	46.6	65.1	93.6	51.3	57.3	49.6	46.6	65.1	93.6
0.533	38.1	32.4	30.0	46.6	67.8	34.9	5.67	57.9	50.1	47.1	65.7	94.1	51.7	57.9	50.1	47.1	65.7	94.1
0.567	38.5	32.9	30.4	47.1	68.7	35.4	6.00	58.5	50.5	47.6	66.2	94.7	52.0	58.5	50.5	47.6	66.2	94.7
0.600	38.8	33.3	30.8	47.9	69.5	35.8	6.33	59.1	51.0	48.2	66.7	95.2	52.4	59.1	51.0	48.2	66.7	95.2
0.633	39.3	33.6	31.1	48.2	70.2	36.2	6.67	59.5	51.2	48.6	66.9	95.7	52.6	59.5	51.2	48.6	66.9	95.7
0.667	39.8	34.0	31.4	48.6	70.7	36.6	7.00	60.0	51.5	49.0	67.4	96.1	53.0	60.0	51.5	49.0	67.4	96.1
0.750	40.7	34.9	32.1	49.5	72.3	37.5	7.50	60.7	52.1	49.6	67.9	96.7	53.3	60.7	52.1	49.6	67.9	96.7
0.833	41.5	35.5	32.8	50.3	73.9	38.4	8.00	61.3	52.6	50.2	68.4	97.2	53.7	61.3	52.6	50.2	68.4	97.2
0.917	42.2	36.2	33.4	51.1	75.0	39.1	8.50	61.9	53.1	50.7	68.8	97.7	54.0	61.9	53.1	50.7	68.8	97.7
1.00	42.9	36.9	34.0	51.6	76.0	39.7	9.00	62.5	53.6	51.3	69.3	98.2	54.4	62.5	53.6	51.3	69.3	98.2
1.08	43.5	37.4	34.5	52.3	76.8	40.3	10.25	63.9	54.4	52.7	70.3	99.6	55.3	63.9	54.4	52.7	70.3	99.6
1.17	44.1	38.0	35.0	52.8	77.7	40.8	11.00	64.5	55.2	53.3	70.7	100.2	55.6	64.5	55.2	53.3	70.7	100.2
1.25	44.6	38.5	35.4	53.3	78.2	41.2	12.00	65.3	55.8	54.1	71.4	100.9	56.1	65.3	55.8	54.1	71.4	100.9
1.33	45.3	38.6	35.9	53.8	78.2	41.8	14.00	66.8	57.2	55.5	72.4	102.1	56.8	66.8	57.2	55.5	72.4	102.1
1.42	45.5	39.3	36.6	54.3	79.8	42.2	16.00	67.8	58.2	56.7	73.3	103.1	57.5	67.8	58.2	56.7	73.3	103.1
1.50	46.0	39.6	36.8	54.7	80.3	42.5	21.75	70.7	60.5	59.3	75.2	105.3	59.0	70.7	60.5	59.3	75.2	105.3
1.58	46.7	40.0	37.3	55.1	80.9	42.9	24.00	71.7	61.4	60.5	76.0	106.3	59.3	71.7	61.4	60.5	76.0	106.3
1.67	46.8	40.4	37.7	55.6	81.4	43.2	28.00	73.2	62.4	61.9	77.0	107.3	60.1	73.2	62.4	61.9	77.0	107.3
1.75	47.3	40.8	38.0	56.1	82.2	43.6	34.00	75.1	63.9	63.5	78.2	108.5	61.1	75.1	63.9	63.5	78.2	108.5
1.83	47.7	41.1	38.3	56.6	82.6	43.9	40.00	76.8	65.0	65.0	79.2	109.6	61.9	76.8	65.0	65.0	79.2	109.6
1.92	48.1	41.5	38.7	56.9	83.1	44.2	46.00	78.3	66.2	66.3	80.1	110.4	62.7	78.3	66.2	66.3	80.1	110.4
2.00	48.4	41.8	39.0	57.2	83.5	44.4	52.00	79.8	67.2	67.4	80.9	111.2	63.4	79.8	67.2	67.4	80.9	111.2
2.17	49.1	42.5	39.5	57.9	84.4	44.8	58.00	81.1	68.0	68.7	81.6	111.7	63.9	81.1	68.0	68.7	81.6	111.7
2.33	49.8	43.1	40.0	58.4	85.1	45.3	64.00	82.2	68.6	69.6	82.3	112.4	64.4	82.2	68.6	69.6	82.3	112.4
2.50	50.4	43.6	40.5	59.0	85.9	45.8	76.00	84.3	69.8	71.2	83.7	113.7	65.3	84.3	69.8	71.2	83.7	113.7
2.67	50.9	43.9	41.0	59.5	86.4	46.2	88.00	86.0	70.8	72.5	84.7	114.3	65.9	86.0	70.8	72.5	84.7	114.3

Table 13. continued.

Time (hrs)	Core #					
	1	2	3	4	5	6
100	87.7	72.2	73.8	85.5	115.3	66.9
112	89.4	73.1	74.9	86.7	115.8	67.9
124	90.9	73.8	76.0	87.4	116.2	68.4
136	91.7	74.5	76.8	88.1	116.6	68.8
148	92.4	75.0	77.5	88.7	116.9	69.3
172	93.9	76.0	78.8	89.9	117.4	70.1
196	95.6	76.9	79.8	90.9	117.6	70.7
220	96.7	77.7	80.6	91.7	118.0	70.9
244	97.5	78.5	81.4	92.6	118.2	71.2
268	98.0	79.1	82.1	93.2	118.3	71.4
292	99.6	79.7	82.9	93.5	118.5	71.6
316	100.3	80.0	83.4	93.7	118.7	71.8
340	100.7	80.4	83.5	93.7	118.7	72.2
364	101.3	80.9	83.8	94.2	118.7	72.5
388	101.8	81.3	84.1	94.7	118.7	72.8
412	102.6	81.5	84.4	95.0	118.7	73.0
436	103.2	81.9	84.7	95.3	118.7	73.2
460	103.7	82.2	84.9	95.6	118.7	73.6
484	104.0	82.5	84.9	96.0	118.7	73.9
508	104.3	83.0	85.4	96.3	118.7	74.3
532	104.6	83.2	85.5	96.6	118.7	74.9
580	105.1	83.9	86.1	97.0	118.7	75.3
604	106.0	84.3	86.1	97.4	118.7	75.3
628	106.5	84.8	86.3	97.4	118.7	75.3
652	107.3	85.2	86.4	97.4	118.7	75.5
748	109.6	86.4	86.9	97.8	118.7	76.5
772	110.2	86.7	87.0	97.8	118.7	76.7
820	110.2	87.2	87.1	98.7	118.8	77.4
892	110.5	87.5	87.6	98.8	118.9	77.7
916	110.8	87.7	88.1	99.0	118.9	77.9
940	111.0	87.8	88.3	99.0	118.9	78.1
964	111.1	88.0	88.3	99.0	119.2	78.2

of the expression to determine values for particular $347.5 \times dW/dt$'s.

One-Step Procedure, Method 1

A statistical analysis determined the Y vs. time relationships for the depths considered as:

$$\begin{aligned} 0-30 \text{ cm} &= Y = 29.548 + 7.904 \ln X & R^2 &= 0.990 \\ 30-122 \text{ cm} &= Y = 36.758 + 7.736 \ln X & R^2 &= 0.995 \\ 122-152 \text{ cm} &= Y = 10.541 + 4.814 \ln X & R^2 &= 0.986 \\ 152-183 \text{ cm} &= Y = 35.640 + 7.678 \ln X & R^2 &= 0.983 \\ 183-213 \text{ cm} &= Y = 43.924 + 8.271 \ln X & R^2 &= 0.974 \end{aligned}$$

where Y was accumulated outflow (ACCOUT) in ml and X was time in hours.

With these relationships of the form $Y = a + b \ln X$, the first derivative was simply the b term. Then dW/dt was $b/347.5$. Water content (W) at a given accumulated outflow was calculated as $W = W_i - \text{ACCOUT}/347.5$. Where W_i is the initial moisture content at saturation. W_f is the final volume water content at the end of the 40 day run, determined gravimetrically. W, W_i and W_f are all expressed as soil moisture content fractions by volume (θ_v). The appropriate values were inserted into Equation 13 and diffusivity calculated for each data point.

Equations for the soil moisture retention curves in the 980 Pa to 1.47 MPa range were obtained from a regression analysis program. The equations followed the general form $Y = c - d \ln X$ and were:

$$\begin{aligned} 0-30 \text{ cm} &= Y = 50.565 - 3.562 \ln X & R^2 &= 0.995 \\ 30-122 \text{ cm} &= Y = 48.364 - 3.260 \ln X & R^2 &= 0.981 \\ 122-152 \text{ cm} &= Y = 48.948 - 2.649 \ln X & R^2 &= 0.992 \\ 152-183 \text{ cm} &= Y = 55.698 - 3.948 \ln X & R^2 &= 0.990 \\ 183-213 \text{ cm} &= Y = 53.895 - 3.893 \ln X & R^2 &= 0.984 \end{aligned}$$

where Y was soil water potential, in cm of water and X was soil moisture content in percent by volume.

Equation 14 required the slope, or first derivative of the moisture retention curve, which in each case was just $(-d)$. Inserting the appropriate values in Equation 14 produced an unsaturated hydraulic conductivity value at the moisture content corresponding to each succeeding accumulated outflow value. The resulting curves are shown in Figure 9, Chapter 2.

Accumulated outflow from the soil core taken from the 91-122 cm depth layer followed a significantly different pattern than was observed in any of the other cores tested in the preliminary or final test runs. When the samples were taken, this core came from a sandy layer present at that location on the bench area. Comparison of the moisture retention curve obtained from this sample and from others taken at the same depth in other locations on the benches suggest that this sample was not representative of the entire area. As a result, the accumulated outflow function for the 30-122 cm range was taken as a composite of the 30-61 and 61-91 cm curves. Because of time limitations, curves were not obtained for the 152-213 cm depths, so the accumulated outflow functions for 61-91 cm were used. Moisture retention curves and a preliminary One-Step Method run showed the physical properties of the 152-213 cm layers to more closely resemble those for the 61-91 cm layer than any other layer tested in the final run. Although not technically correct it was felt that when combined with the correct moisture retention curves, reasonable estimates of unsaturated hydraulic conductivity in these two layers would be obtained.

The final curves obtained by Method 1 calculations are shown in Figure 9, Chapter 2. Corrected curves calculated by Method 2 were all within 5 percent of the Method 1 values in the range plotted so only Method 1 curves are presented.

One-Step Procedure, Method 2

Daily calculation of unsaturated hydraulic conductivity for each of the eight soil layers in the model required a function, or functions that would use an input value of soil moisture content and calculate the corresponding unsaturated hydraulic conductivity. Observing that a simple, continuous function fit the accumulated outflow (ACCOUT) vs. time data rather well (R^2 from 0.974 to 0.995), I chose the following approach.

The general form of the ACCOUT vs. time and soil water potential (TENSION) vs. soil moisture content in percent by volume (W) curves are

$$\text{ACCOUT} = a + b \ln \text{TIME} \quad (15)$$

and

$$W = c + d \ln \text{TENSION} \quad (16)$$

Taking the first derivative of both,

$$dW/d \text{TENSION} = dW/ds \text{ (Doering's notation)} = d/\text{TENSION} \quad (17)$$

and

$$d \text{ ACCOUT}/dt = b/\text{TIME} \quad (18)$$

Since the change in sample moisture content, percent by volume, with time equals the accumulated outflow with time divided by sample volume,

$$dW/dt = b / (\text{TIME} \times 347.5) \quad (19)$$

Doering's (1965) Equation 1 for diffusivity (D) is

$$D = \frac{4 L^2}{-\pi^2 (W-W_f)} \frac{dW}{dt} \quad (13)$$

with terms as previously defined. Hydraulic conductivity (K) is then

$$K = - D dw/ds, \quad (14)$$

Doering's Equation 2. Substituting 19 into 13:

$$D = \frac{4 L^2 b}{-\pi^2 (W-W_f) (347.5) (\text{TIME})} \quad (20)$$

Substituting 17 and 18 into 20 and multiplying by 24 to obtain cm/day;

$$K = \frac{4 L^2 b d (24)}{-\pi^2 (\text{TIME}) (\text{TENSION}) (347.5) (W-W_f)} \quad (21)$$

It is next necessary to be able to express TIME and TENSION in terms of soil moisture. From 15, $\ln \text{TIME} = (\text{ACCOUT}-a)/b$ or $\text{TIME} = \exp (\text{ACCOUT}/b) \times \exp (-a/b)$. Let $\exp (-a/b)$ be a constant, K_1 , so

$$\text{TIME} = K_1 e^{\frac{\text{ACCOUT}}{b}} \quad (22)$$

Soil moisture content (W) at any time is represented by $W = W_i - \text{ACCOUT}/347.5$, so

$$\text{ACCOUT} = (W_i - W) (347.5) \quad (23)$$

Substituting 23 into 22, $\text{TIME} = K_1 e^{(347.5) \times (W_i - W)}$

Let $K_3 = \exp (347.5 W_i)$, so

$$\text{TIME} = K_1 K_3 e^{\frac{-347.5 W}{b}} \quad (24)$$

From 16, $\ln \text{TENSION} = (W - c/d)$ or $\text{TENSION} = e^{\frac{W - c}{d}}$.

Let $K_2 = e^{\frac{-c}{d}}$ so

$$\text{TENSION} = K_2 e^{W/d} \quad (25)$$

Combining equations 21, 23 and 25 gives an expression for K in terms of soil moisture content and several constants:

$$K = \frac{4L^2 b d (24)}{\gamma^2 K_1 K_3 e^{\frac{-347.5 W}{b}} K_2 e^{\frac{W}{d}} (347.5) (W - W_f)}$$

The length of the soil column (L) is 7.62 cm for this set of experiments so combining constants gives

$$K = \frac{1.625 b d}{-K_1 K_2 K_3 (W - W_f) e^{\frac{W}{d}} - \frac{347.5 W}{b}} \quad (26)$$

combining $K_1 K_2 K_3$ into another constant, CON, equation 26 becomes:

$$K = \frac{1.625 \text{ } bd}{\text{CON } (W - W_f) \frac{W}{e} - \frac{347.5 \text{ } W}{b}} \quad (27)$$

where

$$\text{CON} = \frac{-a}{e} \times \frac{347.5 \text{ } W_f}{b} - \frac{c}{d}$$

or

$$\text{CON} = \frac{347.5 \text{ } W_f}{e} - \frac{a}{b} - \frac{c}{d} \quad (28)$$

Equations 25; 27 and 28 are used in the model to calculate soil moisture

Computer runs were made comparing conductivities by Method 1 and Method 2. Method 1 was considered to be the more accurate method because constants obtained from curve fitting of other relationships (a, b, c, and d) were used more times in the argument of exponential functions in Method 2. Percent error was calculated for each point obtained in Method 1 for each core and ranged from 5 percent to 60 percent in the W_f to 38 percent by volume soil moisture range. The errors were graphed vs. soil moisture content and gave figures similar to Figure 18 in most cases. Maximum errors obtained at some depths were smaller than for other depths. The curves calculated by Equations 27 and 28 in the model were corrected with a series of linear correction factors. These corrections gave values within 5 percent of Method 1 results over the W_f to 38 percent by volume range. (Note: field capacity ranged from 30-34 percent by volume so model accuracy was acceptable in the working range of soil moistures encountered.) Due to the method of calculation in both Methods 1 and 2, as the soil moisture approached the final equilibrium water content (W_f) at 196 kPa the conductivity leveled off and then increased sharply. To correct for this, conductivity was assumed to maintain the minimum value reached from that corresponding moisture content to permanent wilting point. This assumption may not be entirely valid but due to experiment conditions was considered acceptable, especially since the

volume of water moving between two adjacent soil layers with an average moisture content below 23 percent by volume is practically negligible. In considering movement from a very wet to a very dry layer, an error of 100 percent or more will produce a negligible difference in the total volume of moisture movement when conductivities for the two layers are averaged.

Although Equation 15 is a very good predictor of accumulated outflow vs. time (R^2 of 0.974 to 0.995), plots of actual and predicted outflow over time showed consistent overpredictions in the dry soil moisture range, tapering to perfect prediction and then increasingly underpredicting outflow as the soil moisture increased farther, giving a somewhat sinusoidal variation about the actual values. Equation 15 or its derivative, Equation 18, was used directly in Method 1 while in Method 2, 18 was used directly in Equation 27 and in two of the three parts of the argument of an exponential. The third part of the argument, (c/d) was also used only directly in Method 1. So, even though Equations 19 and 25 fit the data very well, any errors are magnified by use in the argument of several exponential functions, giving the 50-60 percent errors encountered in Method 2.

While an error of 50 or even 100 percent is not serious in dealing with unsaturated hydraulic conductivities, and could go uncorrected in the model with few noticeable effects, I would recommend an alternate approach. Instead of using Method 2 (the present method used in the model), I believe an equally satisfactory approach would be to calculate the curve coordinates, using Method 1 and approximate each curve by a series of straight lines and simple curves. These simple curves and straight lines would then be substituted for Equations 27 and 28 in calculating daily values of unsaturated conductivity. A generated ACCOUT vs TIME function is still required in this procedure but the complex exponential functions involved in Method 2 are

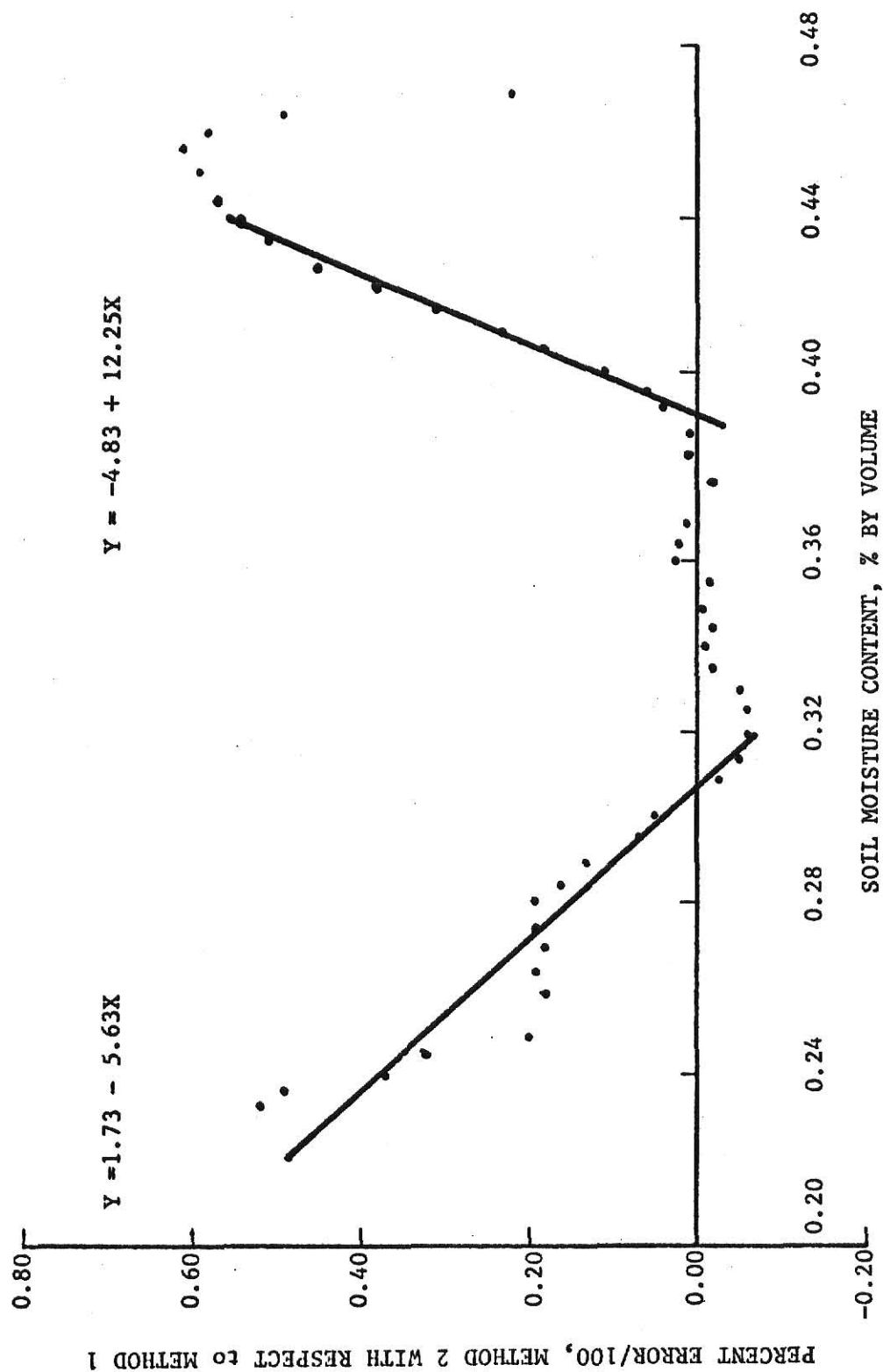


Figure 18. Correction Terms Applied to Modify Method 2 to Equal Method 1 Used in the Calculation of Unsaturated Hydraulic Conductivity.

unnecessary. As a result, the calculated unsaturated conductivities should be easier to evaluate on a daily basis and should be more satisfactory in describing actual unsaturated hydraulic conductivity-soil moisture content relationships.

In following this suggested approach, only a **series** of two or at most four "IF" statements would be necessary to determine unsaturated hydraulic conductivity for each depth, as opposed to passing through Equations 25, 27 and 28 and the necessary correction statements for each depth. This should reduce computer time requirements and the corresponding cost per run considerably, while producing only negligible changes in model results.

Appendix B. Additional Figures and Tables

Table 14. Crop Rotation Codes Used in the Model

1. Continuous grain sorghum
2. Continuous wheat
3. Grain Sorghum-fallow
4. Wheat-fallow

Table 15. Watershed:Bench Area Ratio Codes Used in the Model

- | | |
|---|--------------------------------|
| 0 | 0:1 Watershed:bench area ratio |
| 2 | 2:1 Watershed:bench area ratio |
| 4 | 4:1 Watershed:bench area ratio |

Table 16. Irrigation Design Class Descriptions for Kansas Soils

Irrigation Soil Class	Profile Depth (ft.)	Soil Class Description
1	3'	Deep soils with silt loam or silty clay loam surface layers and slowly to very slowly permeable heavy clay and claypan subsoils.
2	3'	Deep soils with silty clay or clay textures throughout. Surface infiltration and subsoil permeability are very slow when the soil is moist. Shrinkage from drying causes extensive cracking, resulting in high infiltration rates until swelling occurs.
3	5'	Deep soils with silt loam, loam, clay loam, or silty clay loam surface layers and clay loam, silty clay loam, or silty clay subsoils. Subsoil permeability is slow to moderately slow. Shrinkage cracks resulting from drying in the soils with more clayey subsoil textures give a relatively high initial infiltration rate.
4	2.5'	Moderately deep soils with silt loam, clay loam, or silty clay loam surface layers and clay loam or silty clay subsoils with predominately moderately slow permeability.
5	5'	Deep soils with silt loam, loam clay loam, or silty clay loam surface layers and subsoils. Subsoil permeability: moderate to moderately slow.
6	3'	Moderately deep soils with silt loam or loam surface layers and loam, clay loam, or silty clay loam subsoils with moderate to moderately slow permeability.
7	5'	Deep soils with silt loam, loam or very fine sandy loam surface layers and moderately permeable, medium textures subsoils.
8	2.5'	Moderately deep soils with silt loam, loam or very fine sandy loam surface layers and moderately permeable clay loam, loam, or silt loam subsoils.

Table 16. continued.

9	5'	Deep soils with fine sandy loam and loam surface layers and subsoils that have moderately rapid permeability. Available water capacity is moderate to low.
10	5'	Soils are moderately deep over sand with sandy loam to loam surface layers and moderately rapid to rapidly permeable subsoils with low available water capacity.
11	5'	Deep soils with loamy fine sand or loamy sand surface layers and moderately rapid to rapidly permeable subsoils.
12	5'	Deep rapidly permeable soils with sand or fine sand textures throughout.

Table 17. Crop Codes Used in the Model

<u>Reference Number</u>	<u>Crop</u>
1	Wheat
2	Sorghum
3	Corn
4	Soybeans
5	Pasture
6	Alfalfa
7	Fallow Soil

Table 18. SCS Runoff Curve Numbers for Condition II^a Antecedent Soil Moisture, after USDA SCS Handbook, 1964.

Design Soil Group	Crop						
	1	2	3	4	5	6	7
	Wheat	Grain Sorghum	Corn	Soybeans	Pasture	Alfalfa	Fallow Soil
1	83	86	86	84	80	86	84
2	83	86	86	84	80	86	84
3	78	82	82	81	74	82	81
4	78	82	82	81	74	82	81
5	69	75	75	73	61	75	73
6	69	75	75	73	61	75	73
7	69	75	75	73	61	75	73
8	69	75	75	73	61	75	73
9	69	75	75	73	61	75	73
10	69	75	75	73	61	75	73
11	69	75	75	73	61	75	73
12	55	65	65	61	39	65	61

^aCondition II - During the growing season, soil moisture in the top 15.2 cm (6 in) is between 0.4 and 0.8 of field capacity.

Table 19. Summary of Model Results for a Conservation Bench Terrace System at Garden City, Kansas, 1945-1974^a

	Watershed Area					Bench Area					
	Actual	Deep	Change	Actual	Evapo-	Actual	Deep	Change	Actual	Evapo-	
	Evapo-	Perco-	in soil	transpi-	transpi-	Evapo-	Perco-	in soil	transpi-	transpi-	
	ration	lation	Moisture	ration	ration	ration	lation	Moisture	ration	ration	
Year	Inter-	Runoff	Moisture	Runoff	Inter-	Runoff	Perco-	Moisture	Inter-	Runoff	
	ception				ception		lation		ception		
	Storage				Storage				Storage		
1945	43.08	12.07	0.49	-0.43	36.09	-5.55	0.98	12.07	-0.42	35.57	-3.40
1946	62.94	12.95	4.51	1.93	34.05	9.56	9.02	12.95	7.21	38.15	14.10
1947	46.00	12.28	1.13	-0.38	45.30	4.53	2.26	12.28	-0.39	50.19	-13.94
1948	42.42	10.83	1.17	-0.47	29.75	1.41	2.34	10.83	-0.61	32.21	2.59
1949	57.91	12.85	3.27	-0.40	43.47	-1.36	6.54	12.85	-0.35	52.33	-0.38
1950	52.20	12.04	3.01	-0.34	34.07	3.41	6.01	12.04	2.12	38.20	5.84
1951	75.21	15.29	4.54	-0.18	50.96	4.45	9.08	15.29	8.47	59.69	0.85
1952	21.08	9.45	0	-0.11	17.16	-5.58	0.00	9.45	-0.47	22.50	-10.42
1953	38.53	10.44	2.09	-0.14	26.65	-0.49	4.18	10.44	-0.64	27.45	5.70
1954	27.64	7.93	0.62	-0.23	23.32	-4.28	1.24	7.93	-0.46	28.38	-7.22
1955	52.73	8.98	3.67	-0.24	42.39	-1.63	7.34	8.98	-0.45	52.35	-0.38
1956	14.43	6.27	0	-0.27	9.49	-1.16	0.00	6.27	-0.40	10.57	-2.02
1957	54.25	13.94	2.00	-0.30	35.35	3.22	4.00	13.94	-0.41	43.74	1.00
1958	72.06	15.47	2.91	-0.07	45.33	8.07	5.82	15.47	-0.34	55.69	6.93
1959	45.90	13.39	0.28	0.17	37.79	-5.70	0.67	13.39	-0.18	40.35	-6.85
1960	42.62	13.50	0.05	-0.00	29.63	-0.83	0.10	13.40	-0.29	30.32	-0.78
1961	49.25	12.04	0.76	-0.11	33.31	3.14	1.52	12.04	-0.30	34.60	4.49
1962	47.35	13.04	0.34	-0.16	35.89	-1.89	0.68	13.04	-0.20	38.47	-3.35
1963	40.34	8.92	1.60	-0.12	32.12	-3.17	3.20	8.92	-0.12	33.25	0.58
1964	31.70	9.88	0.63	-0.16	24.28	-0.92	1.26	9.88	-0.06	27.08	-1.68

^aWatershed crop rotation is wheat-fallow. Bench crop rotation is continuous wheat. Watershed: Bench rotation is 2:1. Location: Conservation Bench Terrace Area, Garden City, Kansas Branch Agricultural Experiment Station.

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Table 19. continued.

	Watershed Area					Bench Area					
	Actual					Actual					
	Percip-itation	Inter-ception Storage	Runoff	Deep Perco-lation	Evapo-transpi-ration	Change in soil Moisture	Runoff Applied	Inter-ception Storage	Deep Perco-lation	Evapo-transpi-ration	Change in-soil Moisture
1965	70.36	12.94	2.55	-0.14	44.09	10.66	5.10	12.94	-0.11	54.74	7.92
1966	30.68	8.55	0.21	0.04	26.54	-6.64	0.42	8.55	0.05	29.35	-8.84
1967	58.37	12.19	5.35	0.04	42.05	2.94	10.70	12.19	4.90	42.76	13.67
1968	31.99	10.82	0.53	0.04	30.75	-2.42	1.06	10.82	-0.44	39.25	-8.74
1969	65.76	14.34	3.00	-0.00	42.67	5.78	6.00	14.34	0.17	45.58	11.83
1970	38.02	10.13	1.72	0.03	31.46	-5.43	3.44	10.13	-0.26	41.41	-9.86
1971	45.36	12.09	0.63	00.00	34.42	-1.97	1.26	12.09	-0.57	34.50	0.57
1972	68.12	13.37	4.18	0.32	39.31	10.87	8.36	13.37	-0.43	54.31	9.29
1973	42.95	13.59	0.33	0.38	41.21	-12.89	0.66	13.59	-0.15	43.81	-13.77
1974	30.12	8.82	0.01	0.07	22.01	-0.82	0.02	8.82	-0.42	23.26	-1.48
Total	1406.27	348.40	51.58	-1.39	1020.81	5.32	99.16	348.40	14.45	1160.06	-7.75
Average	46.88	11.61	1.72	-0.05	34.03	0.13	3.30	11.61	0.48	38.67	-0.26

Table 19. Summary of Model Results for a Conservation Bench Terrace System at Garden City, Kansas, 1945-1974a

Year	Watershed Area						Bench Area					
	Precip-itation	Inter-ception Storage	Runoff	Deep Perco-lation	Actual Evapo-transpi-ration	Change in soil Moisture	Runoff Applied	Inter-ception Storage	Deep Perco-lation	Actual Evapo-transpi-ration	Change in soil Moisture	
1945	43.08	12.07	0.49	-0.43	36.09	-5.55	0.98	12.07	-0.25	34.47	-2.47	
1946	62.94	12.95	4.51	1.98	34.05	9.56	9.02	12.95	0.02	34.56	14.98	
1947	46.00	12.28	1.13	-0.38	45.30	4.53	2.26	12.28	7.50	40.76	-12.39	
1948	42.42	10.83	1.17	-0.47	29.75	1.41	2.34	10.83	-0.26	38.75	-4.39	
1949	57.91	12.85	3.27	-0.40	43.47	-1.36	6.43	12.85	0.68	47.22	3.70	
1950	52.20	12.04	3.01	-0.34	34.07	3.41	6.01	12.04	-0.07	41.68	4.54	
1951	75.21	15.29	4.54	-0.18	50.96	4.45	9.08	15.29	17.40	50.43	1.16	
1952	21.08	9.45	0	-0.11	17.16	-5.58	0.00	9.45	-0.07	19.41	-7.71	
1953	38.53	10.44	2.09	-0.14	26.65	-0.49	4.18	10.44	-0.38	31.92	0.94	
1954	27.64	7.93	0.62	-0.23	23.32	-4.28	1.24	7.93	-0.51	25.70	-4.44	
1955	52.73	8.98	3.67	-0.24	42.39	-1.63	7.34	8.98	8.34	38.76	4.41	
1956	14.43	6.27	0	-0.27	9.49	-1.16	0.00	6.27	-0.21	11.60	-3.23	
1957	54.25	13.94	2.00	-0.30	35.35	3.22	4.00	13.94	-0.49	41.35	3.46	
1958	72.06	15.47	2.91	-0.07	45.33	8.07	5.82	15.47	-0.23	62.11	0.40	
1959	45.90	13.39	0.28	0.17	37.79	-5.70	0.56	13.39	-0.11	33.77	-0.34	
1960	42.62	13.50	0.05	-0.00	29.63	-0.83	0.10	13.50	-0.30	32.69	-3.12	
1961	49.25	12.04	0.76	-0.11	33.31	3.14	1.52	12.04	-0.37	35.07	4.06	
1962	47.35	13.04	0.34	-0.16	35.89	-1.89	0.68	13.04	-0.32	40.81	-5.53	
1963	40.34	8.92	1.60	-0.12	32.12	-3.17	3.20	8.92	-0.31	36.45	-2.42	
1964	31.70	9.88	0.63	-0.16	24.28	-0.92	1.26	9.88	-0.32	24.95	0.72	

^aWatershed crop rotation is wheat-fallow. Bench crop rotation is continuous grain sorghum. Watershed: Bench ratio is 2:1. Location: Conservation Bench Terrace Area, Garden City, Kansas Branch Agricultural Experiment Station.

Table 19, continued.

	Watershed Area					Bench Area				
	Inter-ception Storage	Runoff	Deep Perco-lation	Actual Evapo-transpi-ration	Change in soil Moisture	Inter-ception Storage	Deep Perco-lation	Actual Evapo-transpi-ration	Change in soil Moisture	
Year	Percip-itation									
1965	70.36	2.55	-0.14	44.09	10.66	12.94	-0.21	47.94	14.77	
1966	30.68	0.21	0.04	26.54	-6.64	8.55	0.02	32.96	-12.38	
1967	58.37	5.35	0.04	42.05	2.94	12.19	3.27	52.86	5.20	
1968	38.99	0.53	0.04	30.75	-2.42	10.82	-0.09	32.82	-2.65	
1969	65.76	3.00	-0.00	47.67	5.78	14.34	-0.40	45.37	112.57	
1970	38.02	1.72	0.03	31.46	-5.43	10.13	-0.11	42.92	-10.87	
1971	45.36	0.63	00.00	34.42	-1.97	12.09	-0.10	32.28	2.33	
1972	68.12	4.18	0.32	39.31	10.87	13.37	0.56	56.27	6.31	
1973	42.95	0.33	0.38	41.21	-12.89	13.59	0.03	38.09	-8.20	
1974	30.12	0.01	0.07	22.01	-0.82	8.82	-0.20	25.79	-4.23	
Total	1406.27	51.58	-1.39	1020.81	5.32	348.40	42.41	1129.76	-4.73	
Average	46.88	1.72	-0.05	34.03	0.18	11.61	1.41	37.66	-0.16	

Table 19. Summary of Model Results for a Conservation Bench Terrace System at Garden City, Kansas, 1945-1974a

	Watershed Area					Bench Area					
	Actual	Deep	Change	Actual	Deep	Change					
Precipitation	Interception Storage	Runoff	Percolation	Evapotranspiration	Interception Storage	Runoff Applied	Percolation	Evapotranspiration	Change in soil Moisture		
1945	43.08	12.07	0.49	-0.43	36.09	-5.55	0.98	12.07	-0.44	36.42	-4.34
1946	62.94	12.95	4.51	1.98	34.05	9.56	9.02	12.95	16.82	23.32	8.22
1947	46.00	12.28	1.13	-0.38	45.30	4.53	2.26	12.28	-0.39	38.81	-12.55
1948	42.42	10.83	1.17	-0.47	29.75	1.41	2.34	10.83	-0.43	30.53	4.10
1949	57.91	12.85	3.27	-0.40	43.47	-1.36	6.54	12.85	-0.24	48.19	3.64
1950	52.20	12.04	3.01	-0.34	34.07	3.41	6.01	12.04	12.16	35.02	-1.01
1951	75.21	15.29	4.54	-0.18	50.96	4.45	9.03	15.29	9.13	53.64	6.22
1952	21.08	9.45	0	-0.11	17.16	-5.58	0.00	9.45	0.10	18.25	-6.71
1953	38.53	10.44	2.09	-0.14	26.65	-0.49	4.18	10.44	-0.52	29.00	4.03
1954	27.64	7.93	0.62	-0.23	23.32	-4.28	1.24	7.93	-0.25	26.64	-5.68
1955	52.73	8.98	3.67	-0.24	42.39	-1.63	7.34	8.98	-0.28	56.36	-4.55
1956	14.43	6.27	0	-0.27	9.49	-1.16	0.00	6.27	-0.34	11.10	02.62
1957	54.25	13.94	2.00	-0.30	35.35	3.22	4.00	13.44	-0.35	41.18	3.40
1958	72.06	15.47	2.91	-0.07	45.33	8.07	5.82	15.47	9.49	45.71	7.08
1959	45.90	13.39	0.28	0.17	37.79	-5.70	0.56	13.39	-0.37	39.18	-5.39
1960	42.62	13.50	0.05	-0.00	29.63	-0.83	0.10	13.40	-0.42	29.91	-0.21
1961	49.25	12.04	0.76	-0.11	33.31	3.14	1.52	12.04	-0.38	45.96	4.22
1962	47.35	13.04	0.34	-0.16	35.89	-1.89	0.68	13.04	-0.27	36.59	-1.41
1963	40.34	8.92	1.60	-0.12	32.12	-3.17	3.20	8.92	-0.10	36.38	-2.57
1964	31.70	9.88	0.63	-0.16	24.28	-0.92	1.26	9.88	-0.19	26.50	-0.97

^aWatershed crop rotation is wheat-fallow. Bench crop rotation is wheat-fallow. Watershed: Bench ratio is 2:1. Location: Conservation Bench Terrace Area, Garden City, Kansas Branch Agricultural Experiment Station.

Table 19. continued.

	Watershed Area					Bench Area				
	Inter-ception Storage	Runoff	Deep Perco-lation	Actual Evapo-transpi-ration	Change in soil Moisture	Runoff Applied	Inter-ception Storage	Deep Perco-lation	Actual Evapo-transpi-ration	Change in soil Moisture
Year										
1965	70.36	2.55	-0.14	44.09	10.66	5.10	12.94	-0.18	52.87	9.80
1966	30.63	0.21	0.04	26.54	-6.64	0.42	8.55	0.02	27.24	-6.66
1967	59.37	5.35	0.04	42.05	2.94	1.70	12.19	8.34	45.51	7.48
1968	38.99	0.53	0.04	30.75	-2.42	1.06	10.82	2.64	31.35	-3.90
1969	65.76	3.00	-0.00	42.67	5.78	6.00	14.34	3.35	47.84	6.36
1970	38.02	1.72	0.03	31.46	-5.43	3.44	10.13	6.41	32.11	-7.18
1971	45.36	0.63	00.00	34.42	-1.97	1.26	12.09	-0.54	38.45	-3.42
1972	66.12	4.18	0.32	39.31	10.37	8.36	13.37	16.06	39.13	7.98
1973	42.95	0.33	0.38	41.21	-12.89	0.66	13.59	-0.44	44.27	-13.94
1974	30.12	0.01	0.07	22.01	-0.82	0.02	8.82	-0.50	22.21	-0.35
Total	1406.27	51.58	-1.39	1020.81	5.32	99.16	348.40	77.79	1099.87	-10.83
Average	46.88	1.72	-0.05	34.03	0.13	3.30	11.61	2.59	36.66	-0.36

Table 19. Summary of Model Results for a Conservation Bench Terrace System at Garden City, Kansas, 1945-1974^a

Watershed Area

Bench Area

Year	Precipitation	Interception Storage	Actual			Change in soil Moisture	Runoff	Interception Storage	Deep Percolation	Actual	
			Evapo-transpiration	Deep Percolation	Evapo-transpiration					Evapo-transpiration	Change in soil Moisture
1945	43.08	12.07	0.49	-0.43	36.09	-5.55	1.95	12.07	-0.25	35.45	-2.47
1946	62.94	12.95	4.51	1.98	34.05	9.56	18.05	12.95	17.69	35.84	14.96
1947	46.00	12.26	1.13	-0.38	45.30	4.53	4.53	12.28	9.76	40.77	-12.39
1948	42.42	10.83	1.17	-0.47	29.75	1.41	4.67	10.83	-0.20	40.10	-3.38
1949	57.91	12.85	3.27	-0.40	43.47	-1.36	13.09	12.85	6.88	47.54	3.72
1950	52.20	12.04	3.01	-0.34	34.07	3.41	12.02	12.04	4.45	42.09	5.64
1951	75.21	15.29	4.54	-0.18	50.96	4.45	18.17	15.29	24.72	50.64	2.71
1952	21.08	9.45	0	-0.11	17.16	-5.58	0.02	9.45	-0.05	22.12	-10.43
1953	38.53	10.44	2.09	-0.14	26.65	-0.49	8.35	10.44	-0.22	34.10	2.77
1954	27.64	7.93	0.62	-0.23	23.32	-4.28	2.48	7.93	-0.31	28.48	-6.19
1955	52.73	8.98	3.67	-0.24	42.39	-1.63	14.68	8.98	16.61	38.78	3.45
1956	14.43	6.27	0	-0.27	9.49	-1.16	0.00	6.27	-0.21	11.60	-3.23
1957	54.25	13.94	2.00	-0.30	35.35	3.22	7.99	13.94	-0.43	42.45	6.39
1958	72.06	15.47	2.91	-0.07	45.33	8.07	11.65	15.47	5.36	63.42	-0.67
1959	45.90	13.39	0.28	0.17	37.79	-5.70	1.12	13.39	-0.13	34.22	-0.21
1960	42.62	13.50	0.05	-0.00	29.63	-0.83	0.20	13.50	-0.43	33.56	-3.77
1961	49.25	12.04	0.76	-0.11	33.31	3.14	3.02	12.04	-0.45	35.88	4.84
1962	47.35	13.04	0.34	-0.16	35.89	-1.89	1.34	13.04	-0.36	42.18	-6.20
1963	40.34	8.92	1.60	-0.12	32.12	-3.17	6.42	8.92	-0.34	39.62	-2.36
1964	31.70	9.88	0.63	-0.16	24.28	-0.92	2.51	9.88	-0.33	26.67	0.27

^aWatershed crop rotation is wheat-fallow. Bench crop rotation is continuous grain sorghum. Watershed: Bench rotation is 4:1. Location: Conservation Bench Terrace Area, Garden City, Kansas Branch Agricultural Experiment Station.

Table 19, continued.

Watershed Area

Bench Area

Year	Actual					Actual					
	Percip-itation	Inter-ception Storage	Runoff	Deep Perco-lation	Evapo-transpi-ration	Change in soil Moisture	Runoff Applied	Inter-ception Storage	Deep Perco-lation	Evapo-transpi-ration	Change in soil Moisture
1965	70.36	12.94	2.55	-0.14	44.09	10.66	10.19	12.94	0.10	48.33	19.17
1966	39.68	8.55	0.21	0.04	26.54	-6.64	0.85	8.55	0.39	34.62	-13.99
1967	53.37	12.19	5.35	0.04	42.05	2.94	21.42	12.19	17.59	52.97	1.47
1968	38.99	10.82	0.53	0.04	30.75	-2.42	2.12	10.82	-0.09	33.78	-2.55
1969	65.76	14.34	3.00	-0.00	42.67	5.78	12.02	14.34	2.16	46.31	15.09
1970	38.02	10.13	1.72	0.03	31.46	-5.43	6.87	10.13	2.88	43.71	-11.84
1971	45.36	12.09	0.63	00.00	34.42	-1.97	2.52	12.09	-0.13	32.99	2.90
1972	68.12	13.37	4.18	0.32	39.31	10.87	16.74	13.37	9.03	56.86	5.63
1973	42.95	13.59	0.33	0.38	41.21	-12.89	1.31	13.59	0.55	38.95	-8.93
1974	30.12	8.82	0.01	0.07	22.01	-0.82	0.04	3.82	-0.22	26.17	-4.58
Total	1406.27	343.40	51.58	-1.39	1020.81	5.32	206.33	348.4	114.02	1160.20	-4.28
Average	46.88	11.61	1.72	-0.05	34.03	0.13	6.88	11.61	3.80	38.67	-0.14

Table 19. Summary of Model Results for a Conservation Bench Terrace System at Garden City, Kansas, 1945-1974^a

Year	Watershed Area					Bench Area					
	Precipitation	Interception Storage	Runoff	Deep Percolation	Actual Evapotranspiration	Change in soil Moisture	Runoff Applied	Interception Storage	Deep Percolation	Actual Evapotranspiration	Change in soil Moisture
1945	43.08	12.07	0.49	-0.43	36.09	-5.55	1.95	12.07	-0.53	36.30	-3.56
1946	62.94	12.95	4.51	1.98	34.05	9.56	18.05	12.95	26.62	34.52	7.35
1947	46.00	12.28	1.13	-0.38	45.30	4.53	4.53	12.28	-0.38	51.29	-12.78
1948	42.42	10.83	1.17	-0.47	29.75	1.41	4.67	10.83	-0.34	30.63	6.25
1949	57.91	12.85	3.27	-0.40	43.47	-1.36	13.90	12.85	1.38	49.32	6.94
1950	52.20	12.04	3.01	-0.34	34.07	3.41	12.02	12.04	23.27	35.11	-6.20
1951	75.21	15.29	4.54	-0.18	50.96	4.45	18.17	15.29	17.77	54.03	6.28
1952	21.08	9.45	0	-0.11	17.16	-5.58	0.02	9.45	0.06	18.29	-6.70
1953	38.53	10.44	2.09	-0.14	26.65	-0.49	8.35	10.44	-0.46	29.10	8.05
1954	27.64	7.93	0.62	-0.23	23.32	-4.23	2.48	7.93	2.22	27.53	-7.80
1955	52.73	8.98	3.67	-0.24	42.39	-1.63	14.68	8.98	1.13	60.81	-3.07
1956	14.43	6.27	0	-0.27	9.49	-1.16	0.00	6.27	-0.30	12.09	-3.65
1957	54.25	13.94	2.00	-0.30	35.35	3.22	7.99	13.94	-0.42	45.14	3.60
1958	72.06	15.47	2.91	-0.07	45.33	8.07	11.65	15.47	16.44	47.10	4.56
1959	45.90	13.39	0.28	0.17	37.79	-5.70	1.12	13.39	-0.47	39.15	-4.79
1960	42.62	13.50	0.05	-0.00	29.63	-0.83	0.20	13.40	-0.41	30.06	-0.27
1961	49.25	12.04	0.76	-0.11	33.31	3.14	3.02	12.04	-0.36	35.53	5.15
1962	47.35	13.04	0.34	-0.16	35.89	-1.39	1.34	13.04	-0.10	36.67	-0.98
1963	40.34	8.92	1.60	-0.12	32.12	-3.17	6.42	8.92	0.17	37.25	-0.50
1964	31.70	9.88	0.63	-0.16	24.28	-0.92	2.51	9.88	-0.01	27.41	-0.80

^aWatershed crop rotation is wheat-fallow. Bench crop rotation is wheat-fallow. Watershed: Bench rotation is 4:1. Location: Conservation Bench Terrace Area, Garden City, Kansas Branch Agricultural Experiment Station.

Table 19. continued.

	Watershed Area					Bench Area					
	Actual					Actual					
Year	Percip-itation	Inter-ception Storage	Runoff	Deep Perco-lation	Evapo-ration	Change in soil Moisture	Runoff Applied	Inter-ception Storage	Deep Perco-lation	Evapo-ration	Change in soil Moisture
1965	70.36	12.94	2.55	-0.14	44.09	10.66	10.19	12.94	1.26	57.62	8.70
1966	39.68	8.55	0.21	0.04	26.54	-6.64	0.85	8.55	1.03	27.32	-7.33
1967	53.47	12.19	5.35	0.04	42.05	2.94	21.41	12.19	20.21	46.73	4.09
1968	34.99	10.82	0.53	0.04	30.75	-2.42	2.12	10.82	3.71	31.35	-3.92
1969	65.76	14.34	3.00	-0.00	42.67	5.78	12.02	14.34	9.03	48.15	6.37
1970	38.02	10.12	1.72	0.03	31.46	-5.43	6.87	10.13	9.83	32.13	-720
1971	45.36	12.09	0.63	00.00	34.42	-1.97	2.52	12.09	-0.54	38.82	-2.53
1972	68.12	13.37	4.18	0.32	39.31	10.87	16.74	13.37	24.30	39.15	8.09
1973	42.95	13.59	0.33	0.38	41.21	-12.89	1.31	13.59	-0.44	45.89	-14.90
1974	30.12	9.82	0.01	0.07	22.01	-0.82	0.04	9.82	-0.50	22.23	-0.36
Total	1406.27	348.40	51.58	-1.39	1020.81	5.32	206.33	348.4	153.17	1127.72	-10.91
Average	46.88	11.61	1.72	-0.05	34.03	0.18	6.88	11.61	5.11	37.59	-0.35

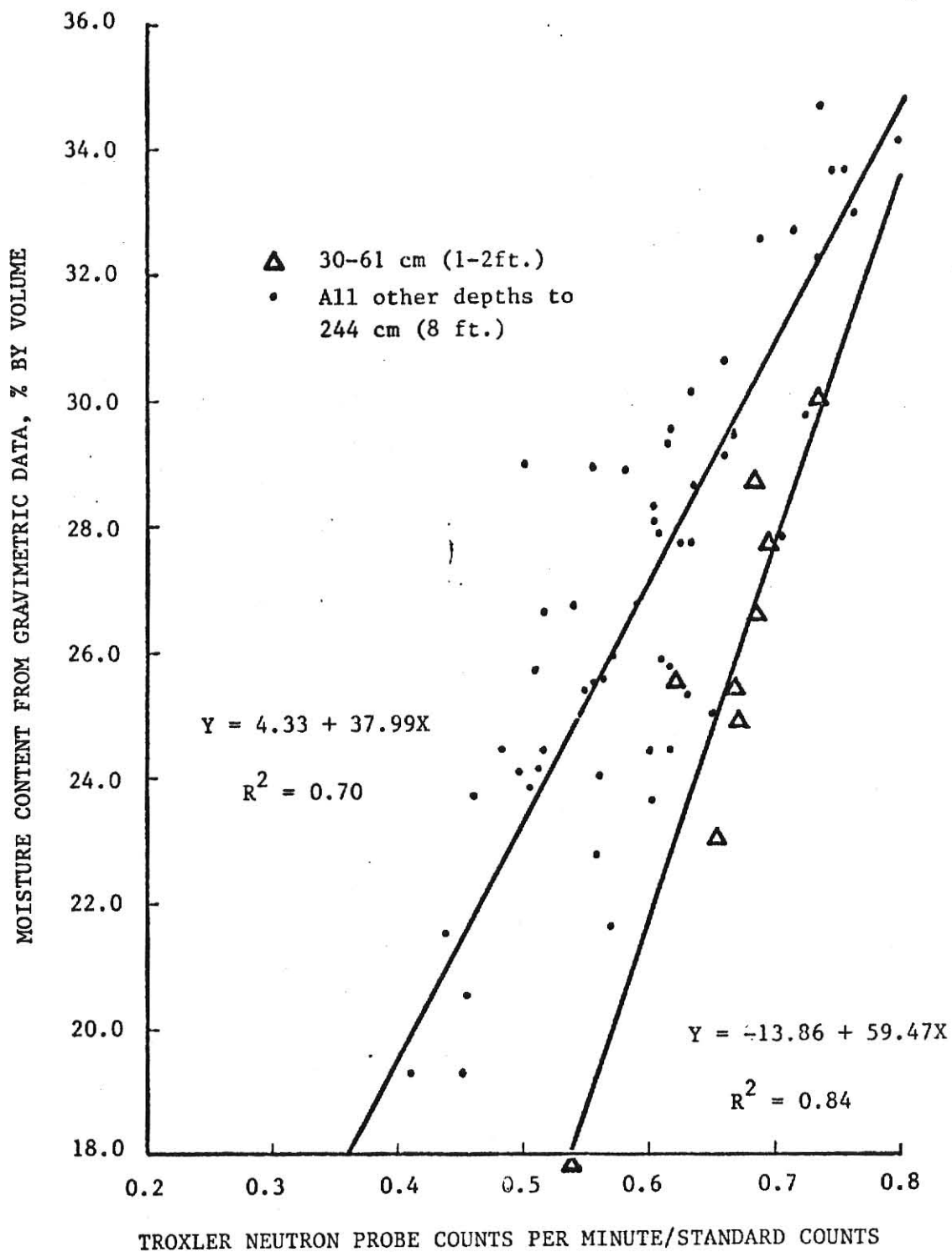


Figure 19. Neutron Probe Calibration Curve, Probe # 1257,
Serial no. 222.

Appendix C. Computer Printouts

SWMTD1 HOWARD NEIRLING KANSAS STATE UNIVERSITY JUNE 1976

THIS PROGRAM MODELS SOIL MOISTURE DISTRIBUTION AND MOVEMENT WITHIN THE
TOP 182.9 CM (6 FEET) OF THE SOIL PROFILE. RUNOFF, INTERCEPTION,
EVAPORATION FROM THE SOIL SURFACE, PLANT ROOT WATER EXTRACTION PATTERNS
AND SOIL MOISTURE MOVEMENT BETWEEN ADJACENT SOIL LAYERS DETERMINE THE
DISPOSITION OF RAINFALL AND THE WATER STORAGE IN EACH LAYER. THE PROFILE
IS DIVIDED INTO A 15.24 CM (6 INCH) SURFACE LAYER, A 15.24 CM LAYER
IMMEDIATELY BELOW IT, AND 6 30.5 CM (12 INCH) LOWER DEPTH INCREMENTS.
182.9 CM IS TREATED AS THE BOUNDARY BETWEEN THE ACTIVE ROOT ZONE AND THE
GROUNDWATER ZONE.

INTEGER DAY(2)
INTEGER NDAY(12), ROTAT1, ROTAT2, T(2)
INTEGER YSTART, YEARS, YEAR, PDAYS, PDAYW, HDAYS, HDAYW, MSBRAT
INTEGER DAY(2), SOIL, CROP, ROTATE, ADFAR
REAL LA, LAFT, LAADD, FO, MA, MO, M, MPX, LAI, KC(7,12), INEIL(9), LEN(8)
REAL LAIC(2), KSI(8)
DIMENSION AVEFC(8), AVELSM(8)
DIMENSION PSUNS(12), PWD(12), PA(12), WIND(12), REACCT(11,3)
DIMENSION DECT(11), TMAX(11), TMIN(11), TAVG(11), AWDPTH(11)
DIMENSION TRAVSR(1), SW(3,5,2), SMP(8,6,2), EXTRA(7), SWAVL(7)
DIMENSION SWSAT(7), Z(7), H(8), CUMM(8), PCN(12,7), RCM(12,7)
DIMENSION SUT(R), U(12), CC(12), FCU(8), PWP(8), WSACCT(13,9)
DIMENSION MCROR(2), BONDI(2), NCNM(2), NCNM(2), NCYEAP(2)
DIMENSION A(9), R(8), C(8), Z(8), WF(8), KROP(70,2), REFF(2)

C *** INITIALIZATION OF VARIABLES

DATA LAIC(2)*0.0/
DATA LEN(2)*15.24, 6*30.49/
DATA DECT, PDAYS, TOPREC, TONPR, EXCESS, MET, PCHG, PCHGR, SC465/9*0.0/
DATA AFT, LA, LAFT, LAADD, ED, LAI, ABTTOT, SMOIST, POT/8*0.0, 37.5/
DATA SWSAT, PACK, MA, MO, M, MPX, PX, PACKPY/8*0.0/
DATA DAY, SOIL, IDAY/2*0.3, 3/
DATA CUMM, M, PDUN(8)*.005, 8*1500.0, 2*0.0/
DATA TMIN, TRANS, POUT, EXTRA/9*0.0, 8*0.0, 8*0.0, 2*0.0, 7*0.0/
DATA NDAY/31, 28, 31, 30, 31, 30, 31, 30, 31, 30, 31, 30, 31/
DATA AWDPTH/JAN, FEB, MAR, APR, MAY, JUNE, JULY,
1 AUG, SEPT, OCT, NOV, DEC, TOT/
DATA "/3.47, 3.47, 3.47, 3.47, 3.47, 3.47, 3.47, 3.47, 3.47, 3.47, 3.47, 3.47, 3.47,
10.24/
DATA CC/0.2, 0.2, 0.177, 0.177, 0.177, 0.177, 0.159, 0.159, 0.139, 0.138,
10.134, 0.131/
DATA FCU/2*1.89, 3.69, 3.59, 3.62, 4.13, 4.04, 3.70/
DATA SW, REACT, SMOIST, WSACCT/9*3.5, 10*0.0, 2*22.35, 10*0.0/
DATA PWP/2*1.00, 2.13, 2.06, 2.24, 2.24, 2.24, 2.24, 2.10/
DATA A/2*29.549, 36.759, 36.759, 35.759, 10.541, 35.540, 43.924/
DATA P/2*7.004, 7.736, 7.736, 7.736, 4.914, 7.679, 8.271/
DATA C/2*0.50545, 0.48364, 0.48364, 0.48364, 0.48364, 0.55598, 0.53895/
DATA P/2*0.03562, -0.03260, -0.03260, -0.03260, -0.03260, -0.03549, -0.03948,
1-0.03893/
DATA WF/2*0.2206, 0.2098, 0.2098, 0.2098, 0.2093, 0.2126, 0.2139/
NAMELIST/ALPHA/CROP, PDAYS, HDAYS, PDAYW, HDAYW, MSTART, YSTART, YEND
NAMELIST/BETA/ALPH, ROTAT1, ROTAT2, MSBRAT
READ INPUT DATA

C *** READ INPUT DATA
19 READ(5,19) ((RCN(I,K), K=1,7), I=1,12)
20 FORMAT(7F2.2,1X)
21 READ(5,18) ((KCI(I,K), K=1,12), I=1,7)
22 FORMAT(12F3.2,1X)

```

      READ(5,20) (PSUNS(I),RHO(I),RA(I),WIND(I),I=1,12)
20  FORMAT(5X,F2.2,F2.0,F4.2,F3.1)
      READ(5,ALPHA)
      WRITE(6,ALPHA)
      READ(5,RETA)
      WRITE(6,RETA)
      XYZ=0.0
      YEARS=YEND-YSTART+1
      DO 1776 AREA=1,2
      DO 1011 K=1,8
1011 SW(K,1,AREA)=FCU(K)
1776 CONTINUE
C *** ESTABLISH CROP ROTATIONS
C
C CROP CODE: 1=ALFALFA, 2=CORN, 3=GRAIN SORGHUM, 4=WHEAT, 5=PASTURE
C 6=STYREANS, 7=FALLOW
C *** CROP ROTATION CODE: 1 = CONT. G.S., 2 = CONT. WHEAT, 3 = G.S. - FALLOW,
C 4 = WHEAT - FALLOW
C *** AREA VALUES ARE: 1=WATERSHED,2=BENCH AREA
      DO 17 LL=1,2
      ROTATE=ROTAT1
      IF(LL.EQ.2) ROTATE=ROTAT2
      GO TO (421,422,423,425),ROTATE
C *** WHEAT-FALLOW
425 DO 510 K=1,YEARS,2
610 KROP(K,LL)=1
      DO 615 K=2,YEARS,2
615 KROP(K,LL)=2
      GO TO 17
C *** GRAIN SORGHUM-FALLOW
423 DO 600 K=1,YEARS,2
600 KROP(K,LL)=3
      DO 605 K=2,YEARS,2
605 KROP(K,LL)=4
      GO TO 17
421 DO 526 K=1,YEARS
606 KROP(K,LL)=5
      GO TO 17
422 DO 607 K=1,YEARS
607 KROP(K,LL)=6
17 CONTINUE
C
C *** ENTER YEARLY LOOP *****
      DO 1000 NY=1,YEARS
      DO 10 I=1,13
      DO 9 J=1,8
      WSACCT(I,J)=0.0
      REACT(I,J)=0.0
10 CONTINUE
      IF(NY.GT.1) MSTART=1
      NDAY=0
      NCROP(1)=0
      NCROP(2)=0
      WRITE(6,12)
12 FORMAT('1',4X,'***** ANNUAL SUMMARY *****')
C
C ***** ENTER MONTHLY LOOP *****
C

```

```

01 2000 NM=NMSTART,12
04 00 REAT(1,60,END=5000) KAN,STING,AEAR,MONTH,(PREC(1),1=1,31),
10 TMAX(1),1=1,31),TMIN(1),1=1,31)
60 0000 REAT(12,14,212,314,2,62F3,0)
IF(YEAR,LT,AVSTAPT) GO TO 40
IF(YEAR,GT,AVEND) GO TO 5000
IF(MONTH,LT,MSTART,AND,AEAR,EQ,YSTART) GO TO 40
R=0.23
NDIM(2)=28
IF(NM,FO,2,AND,TMAX(29),LT,900) NDIM(2)=29
NDAYS=NDIM(NM)

C ***** ENTER DAILY LOOP *****
00 3000 ND=1,NDAYS

C *** CALCULATION OF POTENTIAL EVAPOTRANSPIRATION BY MEANS OF PENMAN COMBINATION
      EQUATION ***

TMAX(ND)=TMAX(ND)-100.
TMIN(ND)=TMIN(ND)-100.
TAVG IS THE AVERAGE DAILY AIR TEMPERATURE, DEGREE FAHRENHEIT
TAVG(ND)=(TMAX(ND)+TMIN(ND))/2.0
THE FOLLOWING STATEMENTS CORRECT FOR MISSING DATA ON INPUT TAPE
IF(TAVG(ND),GT,900) TAVG(ND)=900
IF(PREC(ND),GT,99.97) PREC(ND)=0.0
THE NEXT TWO LINES CONVERT TAVG TO ABSOLUTE, DEGREE KELVIN
CENT=(TAVG(ND)-32.0)/1.8
ABST=CENT+273.16
FSA=33.9*(1.0-0.0738*CENT+0.4072)**9-0.00019*ABST(1.8*CENT+49)
1 +0.00136)
FSA=ES*RHOMW/100.0
FSA IS THE DAILY CALCULATED SATURATED VAPOR PRESSURE, IN MILLIBARS
RN IS THE DAILY CALCULATED ACTUAL VAPOR DEFECT, IN MILLIBARS
RN IS THE CALCULATED DAILY NET RADIATION, IN MM OF WATER
PN=(1-0.1)*RN*(0.22+0.54*PSUNS(NM))-2.010E-09*ABST**4
1 (0.98-0.77+0.0275*PSUNIESA))*0.1+0.9*PSUNS(NM))
C *** WIND0 IS THE MONTHLY AVERAGE WINDSPEED, MILES/DAY AT 2 METERS HEIGHT
WIND0=(WIND(NM)*24)/0.55
FA IS THE CONVECTIVE LOSSES, MM WATER
FA=0.35*(0.5+0.01*WIND0)*ES-FSA
IF(TAVG(ND)) 65,65,70
65 DELTA=0.0
GO TO 75
70 DELTA=0.310-TAVG(ND)+0.673
75 GAMMA=1-DELTA
PET=((DELTA*RN)+(GAMMA*FA))/25.39098
C *** PET IS THE CALCULATED DAILY POTENTIAL EVAPOTRANSPIRATION, INCHES
PET=TAVG(ND)
IF(TAVG(ND),LT,20.0) PET=0.0
IF(PET,LT,0.0) PET=0.0
IF(PET-IAADD) 1013,1013,1014
1013 IAADD=IAADD-PET
IF(IAADD,LT,0.0) IAADD=0.0
PET=0.0
GO TO 1015
1014 PET=PET-IAADD
C

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```

C
C
1015 W=0.0
      AETSND=0.0
      DDF=10*DDPREC(N)
      RAIN=PRECIP
      TRANS=0.0
      IF (TAVG(ND)-37.4E-0.0.AND.PACK.GT.0.0) AETSND=0.5*PET
      IF (AETSND.GT.PACK) AETSND=PACK
      IF (TAVG(ND)-32) 900,900,910
900 IF (PRECIP) 970,970,920
910 IF (PACK) 990,990,930
920 PACK=PACK+PRECIP-AETSND
      RAIN=0.0
      GO TO 900
C*** MA IS SNOWMELT DUE TO ATMOSPHERIC CONDITIONS
930 MA=0.05*(TAVG(ND)-34)
      IF (MA.LT.0.0) MA=0.0
      IF (PACK-MA) 960,960,940
C*** MP IS SNOWMELT DUE TO RAIN
940 MP=(PRECIP*(TAVG(ND)-20))/144
      M=MP+MA
      IF (PACK-M) 960,970,970
960 M=PACK
      PACK=0.0
      GO TO 980
970 PACK=PACK-M-AETSND
980 RAIN=M+PRECIP
C
C
C *** EVALUATION OF SOIL MOISTURE AND CALCULATION OF ACTUAL
      EVAPOTRANSPIRATION ON THE WATERSHED AND BENCH AREAS ***
C
990 DO 4000 AREA=1,2
      AP=AREA
      DETERMINATION OF CROP GROWN ON EACH AREA EACH YEAR
      ROTATE=ROTAT1
      IF (APFA.EQ.2) ROTATE=ROTAT2
      GO TO (580,585,590,593), ROTATE
C *** CONTINUOUS GRAIN SORGHUM
580 CROP=3
      IF (NDAY.GT.PDAYS.AND.NDAY.LT.HDAYS) GO TO 620
      CROP=7
      DAY(AP)=0
      FDAY(AP)=FDAY(AP)+1
      REFF(AP)=(1252.-FDAY(AP))/252.)*0.29+0.08
      GO TO 620
C *** CONTINUOUS WHEAT
585 CROP=4
      IF (NDAY.LT.HDAYW.OR.NDAY.GT.PDAYW) GO TO 620
      CROP=7
      DAY(AP)=0
      FDAY(AP)=FDAY(AP)+1
      REFF(AP)=(1092.-FDAY(AP))/092.)*0.36+0.22
      GO TO 620
590 ICROP=KROP(NY,AREA)
C *** ICROP CODE: 1=WHEAT PLANTING,2=WHEAT HARVEST,3=SORGHUM FALLOW YEAR
C *** 4=SORGHUM CROP YEAR
      GO TO (616,617,618,619), ICROP
C *** WHEAT-FALLOW

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615 CROP=4
   IF (NDAY.GE.0DAYW) GO TO 620
   CROP=7
   DAY(AR)=0
   FDAY(AR)=FDAY(AR)+1
   REFF(AR)=(1/458.-FDAY(AR))/458.)*0.46*0.22
   GO TO 620
617 CROP=4
   IF (NDAY.LT.HDAYW) GO TO 620
   CROP=7
   DAY(AR)=0
   FDAY(AR)=FDAY(AR)+1
   REFF(AR)=(1/458.-FDAY(AR))/458.)*0.46*0.22
   GO TO 620
C *** GRAIN STORAGE--FALLOW
619 CROP=7
   DAY(AR)=0
   FDAY(AR)=FDAY(AR)+1
   REFF(AR)=(1/616.-FDAY(AR))/616.)*0.40*0.08
   GO TO 620
619 CROP=3
   IF (NDAY.GT.0DAYS.AND.NDAY.LT.HDAYS) GO TO 620
   CROP=7
   DAY(AR)=0
   FDAY(AR)=FDAY(AR)+1
   REFF(AR)=(1/615.-FDAY(AR))/615.)*0.40*0.08
620 SWUZ=SW(1,1,AREA)
   IF (DAY(AR).NE.0) FDAY(AR)=0
   IF (DAY(AR).NE.0) REFF(AR)=0.
   IF (RAIN.LE.0) GO TO 205
C *** CALCULATE SURFACE RUNOFF VOLUME BY SCS METHOD
   IF (SWUZ.LT.0.4*FCU(SOIL)) GO TO 193
   IF (SWUZ.GT.0.8*FCU(SOIL)) GO TO 185
   GO TO 180
180 PCM(SOIL,CROP)=PCM(SOIL,CROP)*0.3*EXP(0.009*PCM(SOIL,CROP))
   GO TO 210
185 PCM(SOIL,CROP)=PCM(SOIL,CROP)*1.95*EXP(-0.00653*PCM(SOIL,CROP))
   GO TO 202
190 PCM(SOIL,CROP)=PCM(SOIL,CROP)
200 IF (ICROP.EQ.3) PCM(SOIL,CROP)=PCM(SOIL,CROP)*1.05
   SI=1000.0/PCM(SOIL,CROP)-10.0
   PF=RAIN-0.2*SI
   IF (PF.LT.0.0) GO TO 204
   PHOS=PF**2/(RAIN+0.8*SI)
   GO TO 208
205 RNOF=0.0
C *** CALCULATE INTERCEPTION LOSSES
   IA=0.0
   GO TO 206
204 RNOF=0.0
209 IA=0.1
   IF (IA.GT.RAIN) IA=RAIN
   IF ((IA+IAADD).GE.0.1) IA=0.1-IAADD
206 IACT=IA+IAADD
   POND(AR)=POND*WSPAT
   IF (AREA.EQ.1) GO TO 207
   RAIN=RAIN+POND(1)
   RNOF=0.0
207 PFC=RAIN-RNOF-IA
   UFEVAP=0.0

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C*** CALCULATE EVAPORATION FROM BARE SOIL SURFACE (U7EVAP)
ACTU7=0.0
K=1
TAU=EXP(-0.398*LAIC(AR))
U12=FCU(1)-U(SOIL)
IF(SM17.LF.1L2+0.01) GO TO 242
CALCULATE STAGE 1 SOIL EVAPORATION
U7EVAP=PET*(TAU/ALPH)*(1.-RSEFF(AR))
EVAPMX=SM17-(FCU(1)-U(SOIL))
IF(EVAPMX.LT.0.0) EVAPMX=0.0
IF(U7EVAP.GT.EVAPMX) U7EVAP=EVAPMX
T(18)=0
GO TO 243

C*** CALCULATE STAGE 2 SOIL EVAPORATION
242 T(AR)=T(AR)+1
U7EVAP=(CC(SOIL)*(T(AR)**0.5)-CC(SOIL))*(T(AR)-1)**0.5))*TAU/ALPH
1+U7EVAP
243 IF(U7EVAP.GT.(PET-TAET)) U7EVAP=PET-TAET
IF(U7EVAP.LT.0.0) U7EVAP=0.0
IF(SM17.LF.(0.5*PWP(K))) U7EVAP=0.0
TAAD=TAET-PET
IF(TAAD.LT.0.0) TAAD=0.0
IF(DAY(AR).LT.0) GO TO 125
IF(CROP.EQ.7) GO TO 125
IF(CROP.EQ.4) GO TO 110
GO TO 120

C *** WHEAT LEAF AREA INDEX FUNCTION
110 IF(DAY(AR).LT.3) LAI=0.0
IF(DAY(AR).GE.3.AND.DAY(AR).LT.37) LAI=0.0106*(DAY(AR)-3)
IF(DAY(AR).GE.37.AND.DAY(AR).LT.53) LAI=0.26-8.125E-03*(DAY(AR)-37)
IF(DAY(AR).GE.53.AND.DAY(AR).LT.153) LAI=0.23-1.5E-03*(DAY(AR)-53)
IF(DAY(AR).GE.153.AND.DAY(AR).LT.189) LAI=0.08+0.014*(DAY(AR)-153)
IF(DAY(AR).GE.189.AND.DAY(AR).LT.199) LAI=0.60*(DAY(AR)-189)
IF(DAY(AR).GE.199.AND.DAY(AR).LT.217) LAI=0.62-0.028*(DAY(AR)-199)
IF(DAY(AR).GE.217.AND.DAY(AR).LT.239) LAI=0.31-0.014*(DAY(AR)-217)
IF(DAY(AR).GE.239) LAI=0.0
GO TO 140

C *** SODGROW LEAF AREA FUNCTION
120 IF(DAY(AR).GE.0.AND.DAY(AR).LT.29) LAI=0.006571*DAY(AR)
IF(DAY(AR).GE.29.AND.DAY(AR).LT.35) LAI=0.23+0.09*(DAY(AR)-29)
IF(DAY(AR).GE.35.AND.DAY(AR).LT.42) LAI=0.77+0.10*(DAY(AR)-35)
IF(DAY(AR).GE.42.AND.DAY(AR).LT.49) LAI=2.10+0.796*(DAY(AR)-42)
IF(DAY(AR).GE.49.AND.DAY(AR).LT.56) LAI=4.10+0.119*(DAY(AR)-49)
IF(DAY(AR).GE.56.AND.DAY(AR).LT.77) LAI=4.93-0.0928*(DAY(AR)-56)
IF(DAY(AR).GE.77.AND.DAY(AR).LT.115) LAI=2.57-0.0142*(DAY(AR)-77)
IF(DAY(AR).GE.115) LAI=0.00
140 TRANS=PET-U7EVAP
181 K=1
L=1
TRANS=TRANS*KC(CROP,NM)
IF(CROP.EQ.3) GO TO 220
C *** WHEAT ROOT EXTRACTION PATTERN
K=1
ROOT(K)=(172.0-0.104*(DAY(AR)-55))/100.
IF(DAY(AR).GE.0.AND.DAY(AR).LT.55) ROOT(K)=(100.-0.509*DAY(AR))/100.
K=2
ROOT(K)=(120.0-0.0469*DAY(AR))/100.
IF(DAY(AR).GE.0.AND.DAY(AR).LT.55) ROOT(K)=(10.363*DAY(AR))/100.
K=3

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ROOT(K)=0.145*DAY(AR)/100
IF (DAY(AR).GE.55) ROOT(K)=0.08*(0.0448*(DAY(AR)-55))/100
K=4
ROOT(K)=0.0
IF (DAY(AR).GE.193) ROOT(K)=0.09
K=5
ROOT(K)=0.0
IF (DAY(AR).GE.193) ROOT(K)=0.08
K=6
ROOT(K)=0.0
IF (DAY(AR).GE.218) ROOT(K)=0.03
K=7
ROOT(K)=0.0
K=8
ROOT(K)=0.0
GO TO 240
C *** SORGHUM ROOT EXTRACTION PATTERN
220 K=1
ROOT(K)=(56.0-0.391*DAY(AR))/100.
IF (DAY(AR).GE.0.AND.DAY(AR).LT.61) ROOT(K)=(100.0-1.456
1*DAY(AR))/100.
K=2
ROOT(K)=(23.0-0.174*DAY(AR))/100.
IF (DAY(AR).GE.0.AND.DAY(AR).LT.61) ROOT(K)=(0.766*DAY(AR))/100.
K=3
ROOT(K)=0.334*DAY(AR)/100
IF (DAY(AR).GE.61.AND.DAY(AR).LT.63) ROOT(K)=0.21
IF (DAY(AR).GE.63.AND.DAY(AR).LT.73) ROOT(K)=(21.0-1.1*
1*DAY(AR)-63)/100
IF (DAY(AR).GE.73) ROOT(K)=0.19
K=4
ROOT(K)=0.0
IF (DAY(AR).GE.73) ROOT(K)=0.13
K=5
ROOT(K)=0.0
IF (DAY(AR).GE.104) ROOT(K)=0.10
K=6
ROOT(K)=0.0
IF (DAY(AR).GE.104.AND.DAY(AR).LT.119) ROOT(K)=0.05
IF (DAY(AR).GE.119) ROOT(K)=0.10
K=7
ROOT(K)=0.0
IF (DAY(AR).GE.130) ROOT(K)=0.05
K=8
ROOT(K)=0.0
GO TO 240
125 K=1
L=1
LAI=0.0
TRANS=0.0
TRANSM=0.0
LAIC(AR)=LAI
GO 250 K=1,R
KS(K)=1.0
AVLECK(K)=FCU(K)-PWP(K)
AVLSM(K)=SM(K,L,AREA)-PWP(K)
IF (AVLSM(K).LT.0.0) AVLSM(K)=0.0
IF (AVLSM(K).LT.0.3*AVLECK(K)) KS(K)=AVLSM(K)/10.3*AVLECK(K)
IF (K.LT.2) GO TO 244
IF (ROOT(K).LT.0.) GO TO 244

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      IF (XS(K-1).LT.1.) ROOT(K)=ROOT(K)+(ROOT(K-1)-(1.-XS(K-1)))
244  TRANS(K)=TRANS(K)+ROOT(K)
      IF (SM(K,1,AREA).LT.0.0) TRANS(K)=0.0
      IF (PERC.LT.0.0) SM(K,5,AREA)=SM(K,1,AREA)
250  CONTINUE
251  K=1
      L=1
      AETU7=UZEVAP+TRANS(1)
C *** DISTRIBUTION OF WATER ADDED TO AREA
C
      TNFIL(K)=PERC
      SMAVL(K)=SQU(K)-SM(K,L,AREA)
      IF (SMAVL(K).LT.0.0) SMAVL(K)=0.0
      EXTRA(K)=TNFIL(K)-SMAVL(K)
      IF (EXTRA(K).LT.0.0) EXTRA(K)=0.0
      SM(K,L,AREA)=SM(K,L,AREA)+TNFIL(K)-EXTRA(K)
      TNFIL(K+1)=EXTRA(K)
      K=K+1
      IF (K.LT.8.AND. TNFIL(K).GT.0.0) GO TO 340
      RCHGR=TNFIL(K)
      DO 1001 K=1,8
      DO 1002 L=1,6
      SMP(K,L,AREA)=SM(K,L,AREA)/12.
      IF (K.LE.2) SMP(K,L,AREA)=SM(K,L,AREA)/6.
      IF (SMP(K,L,AREA).GT.1.) SMP(K,L,AREA)=1.
1002 CONTINUE
1001 CONTINUE
      K=1
      L=1
      DTIME=0.1667
      IF (PERC.LT.0.0) DTIME=1.0
      IF (PERC.LT.0.0) L=5
C *** CALCULATE UNSATURATED HYDRAULIC CONDUCTIVITY
      DO 270 K=1,8
      XY7=(SMP(K,L,AREA)-C(K))/D(K)
      H(K)=EXP(XYZ)
      IF (H(K).GT.15000) H(K)=15000
      IF (H(K).LT.0.0) H(K)=0.0
      XXX=SMP(K,L,AREA)-WF(K)
      IF (XXX.LT.0.0) SMP(K,L,AREA)=WF(K)+0.01
      GO TO (272,273,274,275,276,277),K
272  COND(K)=1.1036E-14*(EXP(72.039*SMP(K,L,AR))) / (SMP(K,L,AR)-WF(K))
      GO TO 278
273  COND(K)=1.6204E-14*(EXP(75.595*SMP(K,L,AR))) / (SMP(K,L,AR)-WF(K))
      GO TO 278
274  COND(K)=1.2887E-21*(EXP(109.94*SMP(K,L,AR))) / (SMP(K,L,AR)-WF(K))
      GO TO 278
275  COND(K)=2.174E-16*(EXP(70.589*SMP(K,L,AR))) / (SMP(K,L,AR)-WF(K))
      GO TO 278
276  COND(K)=1.7193E-14*(EXP(70.599*SMP(K,L,AR))) / (SMP(K,L,AR)-WF(K))
277  COND(K)=1.7193E-14*(EXP(70.599*SMP(K,L,AR))) / (SMP(K,L,AR)-WF(K))
278  IF (COND(K).GT.10.0) COND(K)=10.0
279  IF (COND(K).LT.1.0E-07) COND(K)=1.0E-07
C *** CALCULATE FLUX BETWEEN ADJACENT SOIL LAYERS USING DARCY'S LAW
1004  DO 270 K=1,7
      Q(K)=(COND(K)+COND(K+1))/2*DTIME*(H(K+1)-(H(K)-LEW(K)))/LEN(K)
C *** Q IS FLOW IN CM PER TIME PERIOD. H IS SOIL MOISTURE TENSION
C *** IN CM. DELTA Z=30.48 CM. COND(K) IS UNSATURATED HYDRAULIC
C *** CONDUCTIVITY IN CM PER DAY.
      Q(K)=Q(K)/72.54

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[illegible]

ANNUAL SUMMARY

WATER BALANCE (IN CM) IN THE WATERSHED AREA - 1945

INPUTS				OUTPUTS				CHANGE IN SM
MONTH	PRECIPITATION	INTERCEPTION	SURFACE RUNOFF	PERCOLATION	AET			
JAN.	1.07	2.04	0.0	0.02	1.64			-1.33
FEB.	1.12	0.70	0.0	0.01	1.03			-0.88
MAR.	0.38	1.23	0.0	0.01	1.67			-1.43
APR.	10.49	2.62	0.08	0.01	9.49			-1.50
MAY	1.16	2.51	0.0	-0.01	6.65			-6.35
JUNE	7.24	1.75	0.33	-0.05	2.00			3.65
JULY	8.92	2.13	0.38	-0.08	4.39			1.95
AUG.	2.40	1.07	0.0	-0.08	2.64			-0.23
SEPT.	5.56	1.47	0.0	-0.07	3.33			0.87
OCT.	1.83	0.99	0.0	-0.07	1.07			-0.19
NOV.	0.03	0.33	0.0	-0.06	0.69			-0.63
DEC.	1.78	0.52	0.0	-0.06	0.60			0.52
TOT.	43.08	12.24	0.49	-0.43	36.05			-5.55

ICRDP= 2

WATER BALANCE (IN CM) IN THE RENCH AREA - 1945

INPUTS				OUTPUTS				CHANGE IN SM
MONTH	PRECIPITATION	RUNOFF APPLIED	INTERCEPTION	PERCOLATION	AET			
JAN.	1.07	0.0	0.04	0.01	1.66			-1.34
FEB.	1.12	0.0	0.47	0.01	1.95			-0.84
MAR.	0.38	0.0	0.33	0.00	1.68			-1.44
APR.	10.49	0.32	2.62	0.00	9.59			-1.19
MAY	1.16	0.0	0.51	-0.02	7.09			-6.77
JUNE	7.24	0.11	1.75	-0.07	2.02			3.76
JULY	8.92	1.52	2.13	-0.10	4.40			3.83
AUG.	2.40	0.0	1.07	-0.09	2.69			-0.28
SEPT.	5.56	0.0	1.47	-0.08	3.22			0.39
OCT.	1.83	0.0	0.99	-0.07	1.09			-0.21
NOV.	0.03	0.0	0.33	-0.06	0.69			-0.64
DEC.	1.78	0.0	0.52	-0.06	0.60			0.65
TOT.	43.08	1.55	12.07	-0.53	36.80			-3.56

ICRDP= 2

PACK ON DECEMBER 31 = 0.12

CHANGE IN SNOW STORAGE = 0.18

WATERSHED:RENC AREA RATIO=4:1

ICRDP CODE : 1 = WHEAT PLANTING YEAR
 2 = WHEAT HARVEST YEAR
 3 = SORGHUM FALLOW YEAR
 4 = SORGHUM CROD YEAR
 5 = CONTINUOUS GRAIN SORGHUM
 6 = CONTINUOUS WHEAT

***** ANNUAL SUMMARY *****

WATER BALANCE (IN CM) IN THE WATERSHED AREA - 1951

MONTH	INPUTS				OUTPUTS				CHANGE IN SM
	PRECIPITATION	INTERCEPTION	SURFACE RUNOFF	PERCOLATION	AEI				
JAN.	2.62	0.71	0.0	-0.01	1.23				0.49
FEB.	2.26	0.70	0.0	-0.01	1.04				0.68
MAR.	1.52	0.53	0.0	-0.01	0.05				-0.02
APR.	3.00	1.64	0.0	-0.01	7.04				-5.43
MAY	12.33	2.74	0.46	-0.01	11.85				4.46
JUNE	24.69	3.33	1.78	-0.01	14.74				4.38
JULY	1.52	1.32	0.0	-0.02	2.49				-2.41
AUG.	9.09	1.17	1.00	-0.02	3.93				3.00
SEPT.	7.70	1.32	1.30	-0.02	2.84				2.13
OCT.	2.31	1.12	0.0	-0.02	0.64				0.26
NOV.	1.14	0.86	0.0	-0.02	1.72				-1.41
DEC.	0.05	0.0	0.0	-0.02	0.24				-0.78
TOT.	75.21	13.44	4.54	-0.18	50.86				4.45

ICROP= 2

WATER BALANCE (IN CM) IN THE BENCH AREA - 1951

MONTH	INPUTS				OUTPUTS				CHANGE IN SM
	PRECIPITATION	RUNOFF APPLIED	INTERCEPTION	PERCOLATION	AEI				
JAN.	2.62	0.0	0.62	0.01	1.41				0.48
FEB.	2.26	0.0	0.70	0.01	1.15				0.55
MAR.	1.52	0.0	0.53	0.01	2.23				-1.12
APR.	3.00	0.0	1.54	0.00	7.85				-6.54
MAY	19.39	1.84	2.74	-0.03	17.83				5.72
JUNE	24.69	7.12	3.33	1.36	15.59				11.04
JULY	1.52	0.0	1.32	0.01	7.48				-7.34
AUG.	9.09	4.91	1.17	7.49	3.93				0.74
SEPT.	7.70	5.30	1.32	8.51	2.94				-0.30
OCT.	2.31	0.0	1.12	0.01	9.64				0.23
NOV.	1.14	0.0	0.86	0.01	1.78				-1.45
DEC.	0.05	0.0	0.0	0.01	0.85				-0.32
TOT.	75.21	18.17	10.29	17.77	54.93				6.33

ICROP= 2

PACK ON DECEMBER 31 = 0.0

CHANGE IN SNOW STORAGE = 0.0

WATERSHED:BENCH AREA RATIO=4:1

ICROP CODE : 1 = WHEAT PLANTING YEAR
 2 = WHEAT HARVEST YEAR
 3 = SORGHUM FALLOW YEAR
 4 = SORGHUM CROP YEAR
 5 = CONTINUOUS GRAIN SORGHUM
 6 = CONTINUOUS WHEAT

Estimating Groundwater Recharge
From Conservation Bench Terraces

by

William H. Neibling

B. S., Kansas State University, 1975

AN ABSTRACT OF A MASTER'S THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree

MASTER OF SCIENCE

Department of Agricultural Engineering
Kansas State University
Manhattan, Kansas

1976

ABSTRACT

A continuous water budget type of computer model was developed and calibrated for use in western Kansas. Daily potential evapotranspiration (PET), actual ET and soil moisture changes in a 213 cm soil profile were calculated from inputs of crop and soil moisture characteristics and daily meteorological observations. Interception-storage evaporation, evaporation from the soil surface and plant transpiration were computed and combined to give the actual ET estimate for the day. Soil moisture was redistributed by tension and conductivity-soil moisture relationships developed from laboratory tests on a Richfield silt loam soil. The model was calibrated with one year's data from a fallow watershed. Model calculated soil moisture contents averaged within 5.3% of the measured moisture content in the 0-31 cm soil layer. Predicted total moisture content in the 213 cm profile averaged within 2.4 percent and ranged from 1.2 to 3.4 percent over the one-year test period.

The model was used to evaluate the potential for groundwater recharge from conservation bench terraces for the Garden City, Kansas area. Computer runs were made using historical weather records for the period 1945 to 1974. Watershed:bench area ratios of 2:1 and 4:1 were used. A wheat-fallow rotation was used on the watershed areas. Continuous wheat, continuous grain sorghum or wheat-fallow rotations were used on the bench areas for both 2:1 and 4:1 watershed:bench area ratios.

Recharge was assumed to be the net water movement downward below the 183 cm depth. A large portion of total deep percolation to ground-

water recharge occurred any time water was applied to an area when the 183 cm profile was at field capacity. The remaining fraction of deep percolation was calculated as the summation of water movement, downward taken as positive, between adjacent 30.4 cm soil layers across the 183 cm boundary, using the Darcy equation.

Groundwater recharge on the watersheds under a wheat-fallow was estimated as 0.33 cm per year for the period 1945 to 1974. Recharge rates, for the rotations used, in order of increasing amounts were continuous wheat, continuous grain sorghum and wheat-fallow, for both 2:1 and 4:1 watershed:bench area ratios. All bench areas, regardless of watershed:bench area ratio or the crop rotation used showed a larger recharge rate than was calculated for the sloping watershed conditions. It would appear that conservation bench terraces do have the potential for groundwater recharge when used on Richfield silt loam or soils with similar permeabilities with the effectiveness as a recharge structure dependent on the choice of crop rotations and watershed:bench area ratio.