CALCULATION OF SOIL HYDRAULIC
CONDUCTIVITY FROM SOIL-WATER
RETENTION RELATIONSHIPS

Battelle

Pacific Northwest Laboratories
Richland, Washington 99352

1973

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SOIL-WATER RETENTION RELATIONSHIPS

by

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Water and Land Resources Department

1973

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RICHLAND, WASHINGTON 99352

SUMMARY

A computer program has been written to solve the modified Millington and Quirk equation for computing the hydraulic conductivity curve for partially saturated soil from the moisture retention versus suction measurements. This document describes the equation and computer programs. It also shows plots of test results and compares them with physically measured data.

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CALCULATION OF SOIL HYDRAULIC CONDUCTIVITY FROM SOIL-WATER RETENTION RELATIONSHIPS

INTRODUCTION

Although rigorous theoretical descriptions of water movement in porous media have been developed in recent years, flow of water in unsaturated porous media is particularly complex and its mathematical description is difficult. The development of numerical methods and modern high-speed computer equipment permits application of the theoretical principles of flow to these complex systems, which include unsaturated flow beneath intermittent streams, waste cribs, leaking tanks or pipelines, and agricultural irrigation. Fundamental to the solution of a boundary value problem in unsaturated flow in porous media is an adequate description of the hydraulic conductivity-suction relationship and the water content-suction relationship for each soil involved.

Available experimental measurement methods for the hydraulic conductivity-suction relationship are both time-consuming and difficult.^{1,2} These involve use of a soil column fitted with tensiometers in which liquid flow is induced by incrementally increasing the negative pressure in the liquid phase. With each decrease in pressure, the column flow must adjust to steady-state conditions prior to recording the hydraulic conductivity at that potential. The problem of holding good soil tensiometer contact at increasingly lower pressures restricts most measurements of this type to the wetter end of the scale. The difficulty of obtaining satisfactory data has been a major deterrent to solving many problems.

Several investigators, recognizing the problem of satisfactorily evaluating the hydraulic conductivity-water suction relationship, have developed procedures for calculating the hydraulic conductivity from the more easily measured water content-suction data.^{3,4,5,6} These methods have recently been reviewed by Bruce⁷ who found that in all cases the technique for calculating the hydraulic conductivity assumes (1) that the pore system contributing to the flow over the desired range of moisture content is adequately modeled and (2) that the moisture content-suction relationship provides adequate data. The accuracy of the results depends to some degree on how well the model fits the real system. There are also conflicting reports in the literature about the accuracy of the data used in the comparison with calculated data.^{8,9,10,11,12} The conclusion drawn by both Bruce⁷ and Jackson⁸ after testing several other methods was that the Millington and Quirk⁵ method with a matching factor gave the best and most reliable results. On the basis of these investigations, this method was adopted for use in this program.

This document describes the mathematical equation for calculating the hydraulic conductivity-suction relationship from moisture content versus suction measurements and the computer program written to solve the equation. A manual for using the program is included as Appendix A. These calculations are used as input to the Partially Saturated Transient Groundwater Flow Model (BNWL-1713) which was developed for the Radionuclides in Soils program. The role of the hydraulic conductivity calculation in relation to other components of the Radionuclides in Soils program is depicted in the schematic diagram below.

HYDROLOGICAL MODELING PROGRAM COMPONENTS

MATHEMATICAL DEVELOPMENT AND COMPUTER PROGRAM

The method originally presented by Millington and Quirk⁵ with a matching factor introduced by Jackson⁸ can be written as:

$$K(\theta)_i = \frac{K_s 30\gamma^2 \theta^{4/3}}{K_{sc} (\rho g \eta) n^2} \sum_{j=i}^n \left[\left(2j + 1 - 2i \right) \right]_{h_j}^{1/2} \quad (1)$$

$$i = 1, 2 \dots n$$

where

$K(\theta)_i$ = calculated conductivity for a specified moisture content or pressure class (cm/min)

K_s/K_{sc} = matching factor (measured saturated conductivity/ calculated saturated conductivity)

γ = surface tension of water (dynes/cm)

g = gravitational constant (cm/sec²)

η = water viscosity (gm/cm-sec)

θ = water-filled porosity (cm³/cm³)

n = total number of pore classes

h = pressure, suction head (cm)

ρ = density of water

The first term of the equation contains the matching factor K_s/K_{sc} and a group of constants which convert the hydraulic conductivity to units of cm/min and the pore radius to pressure potential (h) in millibars, both at a temperature of 27°C. The constants $30\gamma^2/\rho g \eta$ convert to a value of 1.884×10^4 .

The computer program used to solve Equation 1 was written in standard Fortran IV for the Univac 1108. The output from the program is normally a set of punched cards and two Calcomp plots, one showing the calculated hydraulic conductivity-

suction relationship and the other the moisture content-suction relationship interpolated from the input data. Only the near-saturated part of these curves is plotted. The program makes of an interpolation technique known as Aitken's interpolation formula^{13,14} which is used to obtain values of moisture content and suction at specified even increments of moisture content. A four-point interpolation is used which requires that the original data be hand-smoothed to obtain satisfactory results.

RESULTS

Two sets of results are shown in Figures 1 through 12. The first set was done to show the validity of the method for a range of soil material. Included here are Pachappa Loam, G.E. 2 sand, and Touchet Silt Loam. The second set includes three recently sampled soils; one from an experimental lysimeter facility located south of 200 East Area, a soil collected from an excavation north of the 200 East "A" tank farm, and a typical Ringold clay, all from the Hanford Reservation. Table 1 shows the primary data for each soil.

TABLE 1. Saturated Hydraulic Conductivity and Porosity for Six Soils

	<u>Saturated Hydraulic Conductivity</u>	<u>Porosity</u>
Pachappa Loam	1.2×10^{-2} cm/min	.456
Touchet Silt Loam	1.8×10^{-3} cm/min	.496
G.E. 2 Sand	6.77×10^{-1} cm/min	.375
Lysimeter Soil	7.0×10^{-1} cm/min	.330
"A" Tank Farm Soil	1.6×10^{-2} cm/min	.270
Clay	1×10^{-6} cm/min	.372

$$K \text{ (Darcy)} = \text{cm/sec}$$

The computer program was used to calculate the hydraulic conductivity function from measured volumetric water content and potentials. The data points on Figures 1 and 2 were taken from the literature. Figure 1 shows the water content-water potential for the Pachappa Loam; the points are measured values on the desorption curve. Figure 2 compares the computed hydraulic conductivity curve with measured point values. This is the only soil for which a measurement has been made below -1×10^{-5} millibars of water potential. Figure 3 shows the saturation-potential curve as described from the measured points for G.E. 2 Sand, a surface sample from near the 200 East Area patrol headquarters. Figure 4 shows the computed hydraulic conductivity-potential curve and compares it with points measured by King.¹ Figure 5 shows the measured point of saturation-potential and the curve for Touchet Silt Loam used to calculate the hydraulic conductivity-potential curve shown as a line in Figure 6. The measured values, by King,¹ are plotted as points on the graph. The Touchet Silt Loam is representative of soil from Cold Creek Valley near Rattlesnake Mountain. Figure 7 shows the particle size distribution visually indicating the finer texture of the Touchet soil.

Figures 8 through 13, outputs from execution of the computer program, represent recently sampled soils for which no hydraulic conductivity values below that of saturation have been measured. Figure 8 shows the computer calculated hydraulic conductivity curve versus the potential or suction head in millibars for the lysimeter soil. The points are computer generated from water content versus suction head curve shown in Figure 9. Figure 10 shows the hydraulic conductivity-suction head curve for the "A" tank farm soil as computed from the water content-suction head curve presented in Figure 11. Figure 12 shows the hydraulic conductivity curve as computed from the water content-suction head (Figure 13) for a typical Hanford clay soil.

FIGURE 1. Water Potential Versus Water Content Relationship for Pachappa Loam

FIGURE 2. Computed and Measured Hydraulic Conductivity Versus Water Potential for Pachappa Loam

FIGURE 3. Water Potential Versus Water Content Relationship for GE No. 2 Sand

FIGURE 4. Computed and Measured Hydraulic Conductivity Versus Water Potential for GE No. 2 Sand

FIGURE 5. Water Potential Versus Water Content Relationship for Touchet Silt Loam

FIGURE 6. Computed and Measured Hydraulic Conductivity Versus Water Potential for Touchet Silt Loam

FIGURE 7. Particle Size Distribution for Touchet Silt Loam and GE-2 Sand

FIGURE 8. Hydraulic Conductivity Versus Suction Head for the Lysimeter Soil

FIGURE 9. Water Content Versus Suction Head for the Lysimeter Soil

FIGURE 10. Hydraulic Conductivity Versus Suction Head for the "A" Tank Farm Soil

FIGURE 11. Water Content Versus Suction Head for the "A" Tank Farm Soil

FIGURE 12. Hydraulic Conductivity Versus Suction Head for a Typical Clay Soil

FIGURE 13. Water Content Versus Suction Head for a Typical Clay Soil

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APPENDIX A

USER'S MANUAL

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USER'S MANUAL

Use of the computer program requires data for a measured saturated hydraulic conductivity, a measured porosity, and a measured set of water content-suction data through which a smooth best-fit curve has been drawn. The water content-suction data are normally obtained using pressure plate extraction apparatus for the very high negative pressure range and tensiometer manometer measurements on the soil sample at the lower negative pressures near the saturated end of the curve. A good definition of the curve near saturation is needed. From this curve a set of data points is chosen which adequately describes the curve.

The program input consists of the number of input data points chosen from the water content-suction curve, the number of pore classes or points at which a hydraulic conductivity calculation will be made, the list of data points, the saturated hydraulic conductivity, and the porosity of the soil.

The program output lists the input values, followed by a table showing hydraulic conductivity, water content, percent saturation, suction head, and relative permeability. Punched cards with the suction head, the relative permeability, and the percent saturation are produced. A log-log plot of the hydraulic conductivity versus suction head and the water content versus suction head is produced for the near saturated part of the curve. A plot of water content versus capillary pressure is also output.

The input to the program consists of three different card types:

Card 1 contains two fields of five-column integers (2I5).

Field A - Number of input points of moisture content.

Field B - Number of output points interpolated from input points.

Card 2 contains two floating point fields (2F10.0).

Field A - Contains negative pressure value (suction in millibars).

Field B - Contains the corresponding moisture contents.

N number of Type 2 cards will be necessary to complete this list. The points must be in monotonically increasing order of moisture content.

Card 3 contains two floating point fields (2F10.0).

Field A - Contains the saturated hydraulic conductivity.

Field B - Contains the porosity.

APPENDIX B

COMPUTER PROGRAM LISTINGS

APPENDIX B

```

@ RUN CARD
@ ASG, W  A=C, AT)
@ NSG USE FORM 300 PAPER AND FLUID INK PEN
@M FRS HYDCON, HYDCON
C
    DIMENSION SUM(550), WC(550), B(550), WK(550), AH(550), REL(550)
    DIMENSION QH(550), X(550), Y(550), P(550), A(550), C(550), S(550)
    DIMENSION AHC(550), SH(550), XB(550)
    DIMENSION XARRAY(550), YARRAY(550)

C
    EQUIVALENCE (S, XB, WK), (A, AH, REL), (B, AHC, C), (Y, SUM)

C
    10 FORMAT(2F10.0)
    100 FORMAT (2I5)
    500 FORMAT (2F10.0)
    701 FORMAT (1P2E15.4)
    703 FORMAT (25X, 33H HYDRAULIC CHARACTERISTIC ROUTINE )
    704 FORMAT (17HINPUT DATA X Y)
    801 FORMAT(10X1PE15.5, 7XE15.5, 5XE15.5, 5XE15.5, 5XE15.5)
    900 FORMAT (22H THE MATCHING FACTOR = E11.4)
    901 FORMAT (26H CALCULATED HYDRAULIC CONDUCTIVITY WITH JACKSON'S MA
    1TCHING FACTOR 278X22HHYDRAULIC CONDUCTIVITY 5X13HWATER CONTENT 5X
    218HPERCENT SATURATION 3X12HSUCTION HEAD 5X21HRELATIVE PERMEABILITY
    3//)

C
    WRITE (6, 703)
    WRITE (6, 704)
    G=1
    1 READ (5, 100) N, M
    IF(N.EQ.0) GO TO 23
    REHD (5, 500) (X(I), Y(I), I=1, N)
    REHD(5, 18)SHC, POR
    SMC=POR
    Z=FLOAT(M)
    Q=POR/Z
    XB(1)=Q/2
    DO 43 J=2, M
43  XB(J)=XB(J-1)+Q
    J=1
    WRITE (6, 701)(X(I), Y(I), I=1, N)
    10 CONTINUE
    Q=XB(I)
    K=4
    YB=AITINT(X, Y, N, Q, K, P)
    AH(J)=YB
    IF (J-M)40, 50, 50
40  J=J+1
    GO TO 10
50  CONTINUE
    DO 60 J=1, M
        II=M-J+1
        WC(J)=XB(II)
        QH(J)=AH(II)
60  CONTINUE
    J=1
    I=1
    11 SUM(I)=0.
    C(J)=0.0
    DO21 J=1, M
        C(J)=FLOAT (2+J+1-2*I)/QH(J)**2
        SUM(I)=C(J)+SUM(I)
21  CONTINUE
    WK(I)=(1.801E04)/(FLOAT(N)**2) *(SMC**(4./3.))*SUM(I)
    IF(1.EQ.M) GO TO 70
    I=I+1
    GO TO 11

```

```

70  CONTINUE
    DO 82 I=1,M
      II=M-I+1
      A(I)=WC(II)
      B(I)=WK(II)
82  CONTINUE
    YB=ATITNF (A,B,M,SWC,K,P)
    CSHC=YB
    TMF=SHC/CSHC
    WRITE (6,900) TMF
    DO 17 I=1,M
      HHC(I)=TMF*WK(I)
      SAT (I)= WC(I)/SWC
17  REL(I)=HHC(I)/SHC
    WRITE (6,901)
    DO 20 I=1,M
      WRITE(6,901) AHC(I),WC(I),SAT(I),QH(I),REL(I)
      QHT=-QH(I)
    PUNCH 7 QHT,REL(I),SAT(I)
7   FORMAT (1P2E15,5)
20  CONTINUE
    CALL DPLOT(AHC,QH,XARRAY,YARRAY,M)
    CALL WCPLLOT(WC,QH,M,XARRAY,YARRAY)
    GO TO 1
23  CONTINUE
    CALL CPLOT(0,0,0,0,999)
    CALL EXIT
    END

```

```

@M FR5  DPLOT,DPLOT
      SUBROUTINE DPLOT(AHC,QH,XARRAY,YARRAY,MN)
C
      DIMENSION IDATA(1100),XARRAY(550),YARRAY(550),QH(550),AHC(550)
C
70  FORMAT (1P2E15,4)
C
      CALL CPLOTS(IDATA(1),1100,1)
      M=MN
      J=0
C  C ENTER X AND Y VALUES FOR PLOT
C  C DISCARD ANY NEGATIVE VALUES
      DO 25 I=1,MN
26  J=J+1
      IF(J.EQ. (MN+1)) GO TO 22
      XARRAY(I)=QH(J)
      YARRAY(I)=AHC(J)
      II=1
      IF (QH(J)>26,25,25)
25  CONTINUE
22  CONTINUE
      DO 27 M=1,II
      XARRAY(M)=ALOG10(XARRAY(M))
      YARRAY(M)=ALOG10(YARRAY(M))
      K=M+1
27  CONTINUE
C  C CALCULATE BOUNDARIES FOR X AND Y AXIS
      KK = XARRAY(1)
      KK=KK-1
      JJ = YARRAY(II)
      JJ=JJ-1
      MM = XARRAY(II)
      MM=MM+1
      LL=IABS(KK)+MM

```



```

C      C INDICATE UNITS/INCH AND MINIMUM VALUE FOR EACH AXIS
      XARRAY(K)=KK
      XARRAY(K+1)=1.0
      YARRAY(K)=JJ
      YARRAY(K+1)=1.0
      JJ=IABS(JJ)
      KK=IABS(KK)
      A=FLOAT(LL)
      B=FLOAT(JJ)
      AA=A-0.25
      AX=A-0.125
      BB=B-0.25
      BX=B-0.125

C      C CONSTRUCT RECTANGLES FOR AXIS
      CALL CPLUT (0.0,2.0,-3)
      CALL CPLUT(A,0.0,2)
      CALL CPLUT(A,B,2)
      CALL CPLUT(0.0,0.0,3)
      CALL CPLUT(0.0,B,2)
      CALL CPLUT(A,B,2)
      CALL CPLUT (0.0,0.0,3)

C      C MARK OFF LOG @TICE MARKS ON Y AXIS
      DO 100 I=1,JJ
      Y=FLOAT(I)
      CALL CPLUT (0.0,Y,3)
      CALL CPLUT (0.25,Y,2)
      CALL CPLUT(A,Y,3)
      CALL CPLUT(A,Y,2)
      J=1
      YY=FLOAT(I-1)
101  J=J+1
      IF(J.EQ.100) GO TO 100
      ZY = FLOAT(J)
      YZ = ALOG10(ZY) + YY
      CALL CPLUT (0.0,YZ,3)
      CALL CPLUT (0.125,YZ,2)
      CALL CPLUT(AX,YZ,3)
      CALL CPLUT(A,YZ,2)
      IF(J.LT.100) GO TO 101
100  CONTINUE

C      C MARK OFF LOG @TICE MARKS ON X AXIS
      DO 200 N=1,LL
      X=FLOAT(N)
      CALL CPLUT (X,0.0,3)
      CALL CPLUT (X,0.25,2)
      CALL CPLUT(X,B,3)
      CALL CPLUT(X,BB,2)
      N=1
      XX = FLOAT(N-1)
201  N=N+1
      IF(N.EQ.10) GO TO 200
      ZX = FLOAT(N)
      XZ = ALOG10(ZX) + XX
      CALL CPLUT (XZ,0.0,3)
      CALL CPLUT (XZ,0.125,2)
      CALL CPLUT(XZ,B,3)
      CALL CPLUT(XZ,BX,2)
      IF(N.LT.10) GO TO 201
200  CONTINUE

C      C NUMBER Y AXIS
      JJ=JJ+1
      DO 300 I=1,JJ
      Z = FLOAT(I)-1.06
      YXZ = Z + 0.321
      YZX=FLOAT(I-JJ)
      CALL NUMBER(-0.10,Z,0.125,10.0,90.0,-1)
      CALL NUMBER(-0.20,YXZ,0.06,YZX,90.0,-1)
300  CONTINUE

```

```

C   C NUMBER X AXIS
      KK = KK+1
      LL=LL+1
      DO 400 I=1,LL
      X = FLOAT(I)-1.125
      XYZ = X + 0.321
      XZY=FLOAT(I-KK)
      CALL NUMBER(X,-0.25,0.125,10,0,0,0,-1)
      CALL NUMBER(XYZ,-0.121,0.06,XZY,0,0,-1)
400  CONTINUE
C   C LABEL X AND Y AXIS
      YYB=(B-6.0)/2.0
      CALL SYMBOL(-0.5,YYB,0.20,30HHYDRAULIC CONDUCTIVITY(CM/MIN),90,0,3
10)
      XXA=(A-4.5)/2.0
      CALL SYMBOL(XXA,-0.5,0.20,16HSUCTION HEAD(MB),0,0,16)
C   C PLOT DATA POINTS
      CALL LINE(XARRAY(1),YARRAY(1),11,1,1,1)
      CALL CPLOT(11,0,-2.0,-3)
      RETURN
      END

```

```

@M FR5  AITINT,AITINT
      FUNCTION AITINT (A,B,N,CB,K,P)
      DIMENSION A(550),B(550),P(550)
      DO 2 J=1,N
      IF (A(J)-CB)2,1,3
1      AITINT=B(J)
      RETURN
2      CONTINUE
      J=N
3      J=MIN0(MAX0(1,J-(K+1)/2),N-K+1)
      IF (J+K.LE.N.AND.A(J+K)-CB.LT.CB-A(J))J=J+MOD(K,2)
      P(1)=B(J)
      DO 4 I=2,K
      P(I)=B(J+I-1)
      DO 4 L=2,I
      II=J+I-1
      III=J+L-2
      R=A(II)-CB
      T=A(III)-CB
      P(I)=(P(L-1)* R-P(I)*T)/(R-T)
4      CONTINUE
      AITINT=P(K)
      RETURN
      END

```

```

@M FR5  WCPLLOT,WCPLLOT
      SUBROUTINE WCPLLOT(WC,QH,M,XARRAY,YARRAY)
C   THIS ROUTINE PLOTS WATER CONTENT VS. SUCTION HEAD
C
      DIMENSION WC(550),QH(550),IDATA(1100),XARRAY(550),YARRAY(550)
C
      CALL CPLOTS(IDATA(1),1100,1)
C
C   ONLY THOSE VALUES OF QH .LE. 400 WILL BE PLOTTED
C
      KNT=0
      DO 120 I=1,M
      IF(QH(I) .GT. 400.0 .OR. QH(I) .LT. 0.0) GO TO 120
      KNT=KNT+1
      XARRAY(KNT)=WC(I)
      YARRAY(KNT)=QH(I)
120  CONTINUE

```

```

C
C PLOT OUTLINE IS 8 INCHES BY 10 INCHES
C SET ORIGIN
  CALL CPLOT(0.0,2.0,-3)
C BOTTOM LINE
  CALL CPLOT(8.0,0.0,2)
C RIGHT MARGIN
  CALL CPLOT(8.0,10.0,2)
C RETURN TO ORIGIN
  CALL CPLOT(0.0,0.0,3)
C LEFT MARGIN
  CALL CPLOT(0.0,10.0,2)
C TOP LINE
  CALL CPLOT(8.0,10.0,2)
C RETURN TO ORIGIN
  CALL CPLOT(0.0,0.0,3)
C LABEL Y AXIS
  CALL SYMBOL(-.75,2.75,0.20,17HSUCTION HEAD (MB),90.0,17)
C LABEL X AXIS
  CALL SYMBOL(2.25,-0.5,0.20,19HWATER CONTENT (VOL),0.0,19)
  CALL CPLOT(0.0,0.0,3)
C TIC MARKS
  X=0.0
  Y=0.0
C X AXIS
  DO 140 I=1,8
    X=X+1.0
    CALL CPLOT(X,0.0,3)
    CALL CPLOT(X,0.125,2)
140 CONTINUE
C Y AXIS
  CALL CPLOT(0.0,0.0,3)
  DO 160 I=1,19
    Y=Y+0.5
    CALL CPLOT(0.0,Y,3)
    CALL CPLOT(0.125,Y,2)
160 CONTINUE
C
C LABEL TIC MARKS
C X AXIS
  FPN=0.05
  X=.75
  DO 180 I=1,8
    CALL NUMBER(X,-.25,0.125,FPN,0.0,2)
    FPN=FPN+0.05
    X=X+1.0
180 CONTINUE
C Y AXIS
  FPN=10.0
  CALL CPLOT(0.0,0.0,3)
  Y=.437
  DO 200 I=1,20
    CALL NUMBER(-.50,Y,0.125,FPN,0.0,-1)
    FPN=FPN+10.0
    Y=Y+.5
200 CONTINUE
  CALL CPLOT(0.0,0.0,3)
C SET MINIMUM VALUE
  XARRAY(KNT+1)=0.0
  YARRAY(KNT+1)=0.0
C SET UNITS PER INCH
  XARRAY(KNT+2)=.85
  YARRAY(KNT+2)=20.0
C PLOT DATA POINTS
  CALL LINE(XARRAY,YARRAY,KNT,1,1,1)
C MOVE WINDOW
  CALL CPLOT(10.0,-2.0,-3)
  RETURN
  END
@ XQT HYDCON

```

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