Natural Resources Conservation Service
Wetland Science Institute

DRAINMOD REFERENCE REPORT

CHAPTER 5

INPUT DATA

The input data requirements for the water management model are discussed in this section. Data are required for soil properties, crop inputs, water management system parameters and climatological input data. The purpose of this chapter is to identify required inputs, discuss methods of measuring or calculating these data and identifying published and unpublished sources of data for different soils, crops, and locations.

In many cases, all of the input data needed in the model will not be available from conventional data sources. Furthermore, it may not be possible to measure, or otherwise directly determine, the data, and the needed inputs will have to be approximated. Where possible, methods of approximating the various input data are given in the chapter. When relationships, such as the hydraulic conductivity or upward flux have to be estimated from a meager amount of information, it is a good idea to test the sensitivity of the objective function to the relationship estimated. Some sensitivity analyses are presented in Chapter 7, but, when possible, such analyses should be conducted for the specific case of interest. If the objective function is not sensitive to the estimated inputs, the approximations may be used. When the results are sensitive to the estimations, it may be desirable to invest more time and money in determining the needed inputs.

Soil Property Inputs

The first step in obtaining soil property input data for a given area is to refer to a good soils map of the fields involved. The soils map will identify the different soil types and certain of the required input data can be obtained or estimated from the soil survey interpretations. The soil survey data will also serve as a guide for identifying layers, etc., and for making additional soil property measurements.

The model should be used to make a separate analysis for each major soil type involved in a given water management system design or analysis.

Hydraulic Conductivity - K.

The saturated hydraulic conductivity of each horizon above the restricting layer is an important input. Since artificial drainage and subirrigation usually involve lateral flow to and from drains, the effective horizontal K values are used. A rough estimate of K can be obtained from the SCS soil survey interpretations (Form #5 - blue sheets). These data are usually based on soil texture and structure and the judgment of soil scientists. The K values are normally not determined from measurements and are approximations of the vertical hydraulic conductivity. Field or laboratory measurements of K are occasionally made for a soil series by the SCS National Soil Survey Lab personnel or at universities in the various states. These data may be in the file for the given soil series at the state SCS office or at the respective National Technical Centers. They may also be available in publications from the state universities, usually from the departments of soil science or agricultural engineering. Hydraulic K data may also have been measured for a few locations by the SCS National Soil Mechanics Lab in Lincoln, Nebraska. These measurements would have been made on cores form dam site locations and would represent deep horizons. Such data would be available from the state SCS office.

In some cases, detailed in situ K measurements have been made for selected soil types (e.g., Schwab, et al, 1978) so a good estimate of saturated hydraulic conductivity can be made from knowledge of the soil type. K values have also been determined in the lab from undisturbed samples and tabulated by soil type and horizon for many soils. Some of the sources for these data, as well as for some field measurements of K are given in Table 5-1. K values determined from cores tend to be smaller than field effective values because the cores usually do not contain cracks, worm holes, etc., that may have a big effect on K. Also, care should be taken in using values from cores, in that these values usually represent vertical K while drainage rates depend more on horizontal K. Effective vertical and horizontal K values may be different by a factor of 10 for field soils. Furthermore, K values may very considerably within a given soil type. Therefore, on-site measurements should be made whenever possible.

Numerous methods have been developed for determining saturated hydraulic conductivity in the field (Bouwer and Jackson, 1974). They include the auger hole method (van Bavel and Kirkham 1949, Boast and Kirkham 1970, van Beers 1970); the slug test (Bouwer, 1978) the two-well method (Childs, et al, 1953); the four-well method (Kirkham 1955, Snell and van Schilfgaarde 1964); and the piezometer method (Kirkham 1946). Shady, et al, (1977) reported on experience in Canada with field production scale hydraulic measurements using the auger hole method. This method is the most commonly used and is described in the SCS-NEH (Section 16, Chapter 2). These methods offer the advantage of a rapid, relatively easy measurement, but the resulting K value represents a single point in the field and several measurements may be needed to determine a field effective K value (Dylla and Guitjens, 1970); Hore 1959).

Methods for determining field effective K values from water table drawdown measurements were presented by Hoffman and Schwab (1964) and Skaggs (1976, 1979). These methods are currently being used by Schwab, et al, (1978) to determine K for several soils in the midwest. The ratio of K to drainable porosity, f, is obtained by matching measured drawdown rates to those predicted from theoretical equations. By calculating f from drain outflow measurements (e.g. Hoffman and Schwab 1964) or from soil water characteristic data (Duke 1972; Skaggs, et al, 1978), hydraulic conductivity can be obtained from the K/f determinations. A major advantage of determining K/f from drawdown measurements is that the effects of profile heterogeneities, nonuniformities, and anisotropy tend to be lumped in such a way that they are properly represented in ultimate drain spacing calculations. In addition, errors made in estimating the effects of soil layering and determining the depth to the impermeable layer are incorporated in the K values obtained and result in smaller errors in predicted drain spacings than when K is measured independently. The main disadvantage is that these measurements require more time and effort than do the point methods.

Soil Water Characteristic $h(\theta)$.

This property is a measure of how tightly water is held in the soil matrix in the unsaturated state. In addition to being an input to DRAINMOD, $h(\theta)$ is used in determining other inputs such as the relationship between water table depth and drainage volume, upward flux, etc. When the water table depth-drainage volume relationship is not read in, it is computed in DRAINMOD from the $h(\theta)$ data. The soil water characteristic is a basic soil property which is second in importance to only hydraulic conductivity in modeling soil water movement.

The soil water characteristic is usually determined in the laboratory using tension tables or pressure plates. Details of apparatus and procedure are given by L. A. Richards (1965), Tanner, and Elrick (1958) and others. Soil water characteristics for soils representing several textural classes are plotted in Figure 5-1. Data are available for many soils from several sources and a national data set on soil water characteristics is being compiled by Rayls and Brakensiek (1979). A list of their data sources is given in Table 5-1. Holtan, et al, (1968) compiled a data set for $h(\theta)$ for several hundred soil horizons. Some of these data are plotted in Figure 5-2 (from Baver, et al, 1972). However the lowest tension represented in these data is 0.1 bar so they are not complete in the range needed for drainage modeling applications. They can still be used to get an approximation of the soil water characteristic. However, it will only be an approximation for drainage purposes. Additional $h(\theta)$ data may be available from the SCS Soil Survey Investigations Reports (SSIR) from each state. The SSIR's are available from the National Technical Centers and from individual state offices. The user should be aware that the data in the SSIR for a given soil type may be incomplete (e.g. volumetric water contents for only 2 or 3 tensions), or it may not be available at all. On the other hand, additional $h(\theta)$ data may be tabulated in the file that is maintained for each soil type at the SCS National Technical Centers, the National Soil Survey Lab, the state SCS offices, or in soil science departments at cooperating universities in various states. Because of the need for $h(\theta)$ data at low tensions in drainage modeling, it is desirable to increase the number of pressure steps that are used in standard tests run by the SCS National Soil Survey Lab. Water contents could be obtained at tensions of 5 cm, 50 cm, and 100 cm without much additional effort or expense. Such data would be extremely valuable for applications discussed herein, as well as in other water management uses.

The soil water characteristic relationship for only one layer is used as input data in the model. These data should represent the thickest layer between the surface and the drain line depth. Soil water characteristics for all the layers are needed to determine other required inputs.

Soil water characteristics for a given site should be measured whenever possible. The next best alternative is the tabulated $h(\theta)$ data in the literature (Table 5-1). If data for the soil is not available, $h(\theta)$ can be approximated for each horizon by matching the textural classes with those of soils that are tabulated. If possible, data should be obtained from soils in the same series and from the same geographic area. While $h(\theta)$ depends on texture, it is also heavily dependent on structure. So a well aggregated soil should be matched with a soil in the literature that is also well aggregated. Once $h(\theta)$ is determined for each horizon other inputs can be obtained.

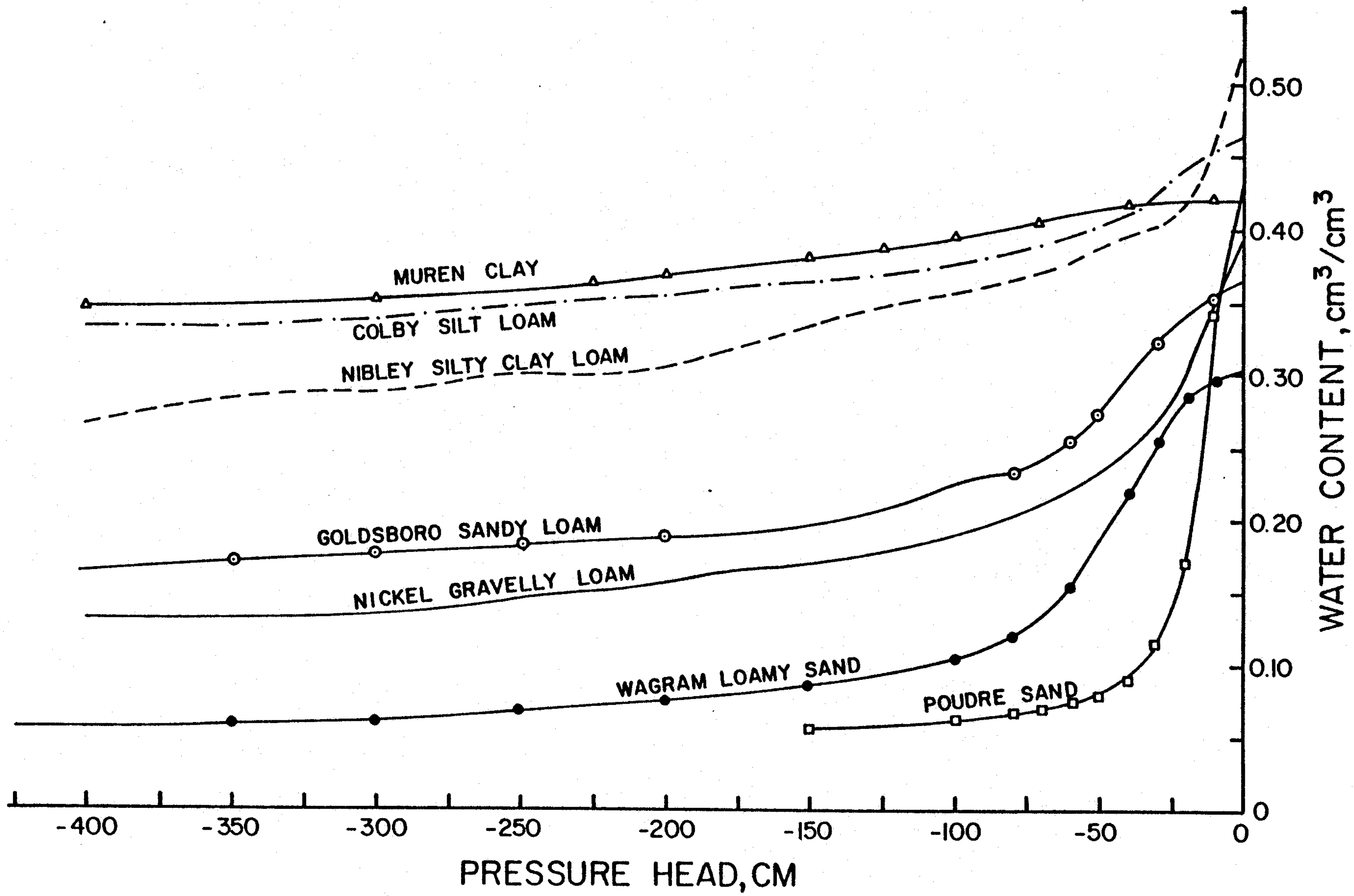

Figure 5-1. Soil water characteristics for 7 soils. Data for the Muren, Colby, Nibley, Nickel and Poudre soils were obtained from Smith (1972). Wagram and Goldsboro data are from Skaggs (1978a).

Methods for determining input h(θ) data may be ranked as follows:

1. Measurement of h(θ) from undisturbed field samples taken from each layer of the major soil types on the sites to be considered.

2. Obtain tabulated h(θ) data for the given soil types from literature sources.

3. Estimate h(θ) for each profile horizon by matching according to texture and structure with similar soils that have published or otherwise available h(θ) data.

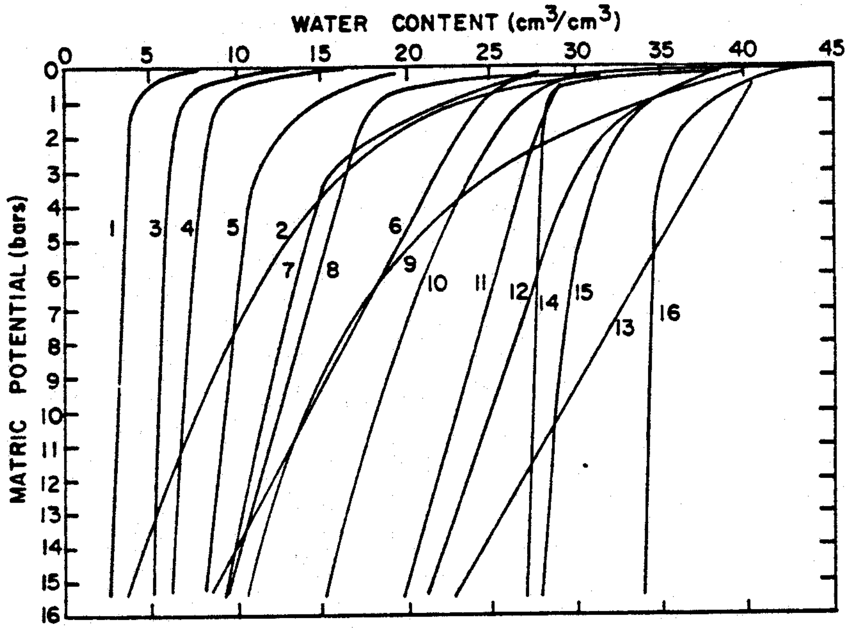

Figure 5-2. Desorption curves for various soils sketched from data at 0.1, 0.3, 0.6, 3, and 15 bars tension given by Holtan, et al, 1968.

1. Continental gravelly sandy loam, Arizona.
2. Sassafras sandy loam, Maryland.
3. Progresso fine sandy loam, New Mexico.
4. Vaucluse sandy loam, Georgia.
5. Albion loam, Oklahoma.
6. Abilene clay loam, Texas.
7. Hartsells loam, Ohio.
8. Palouse silt loam, Washington.
9. Fayette silt loam, Wisconsin.
10. Nellis gravelly loam, New York.
11. Lard-like silty clay loam, South Dakota.
12. Memphis silt loam, Mississippi.
13. Drummer silty clay loam, Illinois.
14. Auston silty clay, Texas.
15. Marshall silty clay loam, Iowa.
16. Bascom-like clay, South Dakota (from Baver, et al, 1972). Note that the curve between tensions of 0.0 and 9.1 bars may be very important for drainage applications and these data are missing in this data set.

Table 5-1. Sources of published soil water characteristic (or moisture tension), hydraulic conductivity and other soil property data (obtained by personal communication from Walter J. Rawls, USDA-SEA-AR).

Author or Investigator and Date	Location of Soils	Title of Article	Source
1. Holtan, et al, 1968	U.S.A.	Moisture tension data for selected soils on experimental watersheds	USDA, ARS Bulletin ARS 41-144, 609 pages
2. University of Illinois and USDA-ARS, 1979	North Central Region	Water infiltration into representative soils of the North Central Region	Illinois Agricultural Experiment Station Bulletin 760 and North Carolina Region Research Pub. 259 Urbana, Illinois, 119 pages
3. Long, et al, 1963	Lower Coastal Plains-Atlantic Coat	Soil moisture characteristics of some lower Coastal Plains soils	USDA, ARS Bulletin ARS 41-82, 22 pages
4. Elkins, et al, 1961	Southern Piedmont	Soil moisture characteristics of some Southern Piedmont soils	USDA, ARS ARS 41-54, 22 pages
5. Long, et al, 1969	Atlantic Coast Flatwoods	Morphological, chemical, and physical characteristics of eighteen representative soils of the Atlantic Coast Flatwoods	USDA, ARS, and University of Georgia Agriculture Experiment Station, Research Bulletin 59, Athens, Georgia, 74 pages
6. Lutz, J. F. 1970	North Carolina	Movement and storage of water in North Carolina soils	North Carolina State University Agricultural Research Service Soils Information Series No. 15, Raleigh, North Carolina, 29 pages
7. Carlisle, et al, 1978	Florida	Characterization data for selected Florida soils	IFAS, University of Florida, USDA, SCS, Soil Science Research Report No. 78-1, Gainesville, Florida, 335 pages

(Continued)
Table 5-1. Sources of published soil water characteristic (or moisture tension), hydraulic conductivity and other soil property data (obtained by personal communication from Walter J. Rawls, USDA-SEA-AR).

Author or Investigator and Date	Location of Soils	Title of Article	Source
8. Lund, Z. F. and Lofton, L. L., 1960	Louisiana	Physical characteristics of some Louisiana soils	USDA, ARS, ARS-41-33, 83 pages
9. Lund, et al, 1961	Louisiana	Supplement to physical characteristics of some Louisiana soils	USDA, ARS, ARS-41-33-1, 43 pages
10. Longwell, et al, 1963	Tennessee	Moisture characteristics of Tennessee soils	University of Tennessee Agr. Experiment Station and USDA, SCS Bulletin 367, Knoxville, Tennessee, 46 pages
11. Holt, et al, 1961	Minnesota	Soil moisture survey of some representative Minnesota soils	USDA, ARS Bulletin ARS 41-48, 43 pages
12. Hermsmeier, 1966	Minnesota	Hydraulic conductivity and other physical characteristics of some "wet" soils in SW Minnesota	USDA, ARS Bulletin ARS 41-127, 17 pages
13. Cassel and Sweeney, 1974	North Dakota	In situ soil water holding capacities of selected North Dakota soils	Bulletin 495, Agr. Experiment Station, North Dakota, State University, Fargo, North Dakota, 25 pages
14. Olson, 1970	South Dakota	Water storage characteristics of 21 soils in eastern North Dakota	USDA, ARS Bulletin ARS-41-166, 69 pages
15. Mathers, et al, 1963	Southern Great Plains	Some morphological physical, chemical, and mineralogical properties of 7 Southern Great Plains soils	USDA, ARS Bulletin ARS-41-85, 63 pages

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Table 5-1. Sources of published soil water characteristic (or moisture tension), hydraulic conductivity and other soil property data (obtained by personal communication from Walter J. Rawls, USDA-SEA-AR).

Author or Investigator and Date	Location of Soils	Title of Article	Source
16. Krother, et al, 1960	Missouri	Soil moisture survey of some representative Missouri soil types	USDA, ARS Bulletin ARS-41-34, 57 pages
17. Post, et al, 1978	Arizona	Soils of the University of Arizona Experiment Station: Marana	USDA, SCS, Agri. Eng. & Soil Science, 78-1, University of Arizona, Tucson, Arizona
18. Kelley and Edwards 1975	Ohio	Soils of the North Appalachian experimental watershed	USDA, ARS, and SCS, Ohio Agri. Research & Development Center, M.S. Publication No. 1296, Washington, D.C., 145 pages
19. Epstein, et al, 1962	Maine	Soil moisture survey of some representative Maine soil types	USDA, ARS, ARS-41-57, 57 pages
20. Rourke, et al, 1969	Maine	Chemical and physical properties of the Charlton, Sutton, Paxton, and Woodbridge soil series	Maine Agr. Experiment Station Technical Bulletin 34, University of Maine, Orono, Maine, 8 pages
21. Rourke, et al, 1971	Maine	Chemical and physical properties of the Allagarh, Hermon, Howland, and Marlow soil mapping units	Agr. Experiment Station Technical Bulletin 46, University of Maine, Orono, 73 pages
22. Rourke and Bangs 1975	Maine	Chemical and physical properties of the Bangor, Dixmont, Caribou, Conant, Perhan, and Daigle soil mapping units	Agr. Experiment Station Technical Bulletin 75, University of Maine, Orotha, 102 pages

Drainage Volume - Water Table Depth Relationship

This relationship is used in the model to determine how far the water table falls or rises when a given amount of water is removed or added. The volume of water drained at various water table depths (sometimes called the water yield) can be measured directly from large soil cores (Skaggs, eta al. 1978). However, it is usually not convenient to collect a large core and the drainage volume - water table depth relationship may be calculated from the soil water characteristic.

In calculating the water yield from $h(\theta)$, it is assumed that the water table recedes such that the vertical hydraulic gradient above the water table is zero and the unsaturated zone is essentially 'drained to equilibrium' with the water table at all times. That is, it is assumed that the water content distribution at any time is the same as that which would result if the water table was stationary at a given position and the profile drained to equilibrium. Theoretical studies (Tang and Skaggs, 1978; Skaggs and Tang, 1976) indicate that this assumption is valid for most field scale drainage systems. Then, the volume drained per unit area, V_d, when the water table drops from the surface to depth y_1, may be expressed as,

$$V_d = \int_o^{y_1} (\theta_o(y) - \theta(y))\, dy, \tag{5-1}$$

Where $\theta_o(y)$ is the soil water content prior to drainage, usually assumed to be constant and equal to the saturated value*, and $\theta(y)$ is the equilibrium water content distribution which is obtained from the soil water characteristic for a water table depth of y_1. The water content distribution and V_d are shown schematically in Figure 5-3a for a uniform soil V_d is calculated for any depth, y, by numerically integrating the cross-hatched area in Figure 5-3a.

For layered profiles θ_o and $\theta(y)$ are obtained from the soil water characteristics for the respective layers, the drained volume for a layered profile is schematically shown in Figure 5-3b. If the water yield relationships of the soils in the top layer, $V_{d1}(y)$, and in the bottom

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*Soils are rarely completely saturated in the field because of entrapped air. Thus, θ_o is the volumetric water content at residual air saturation which is usually not more than 90 to 95 percent of total porosity.

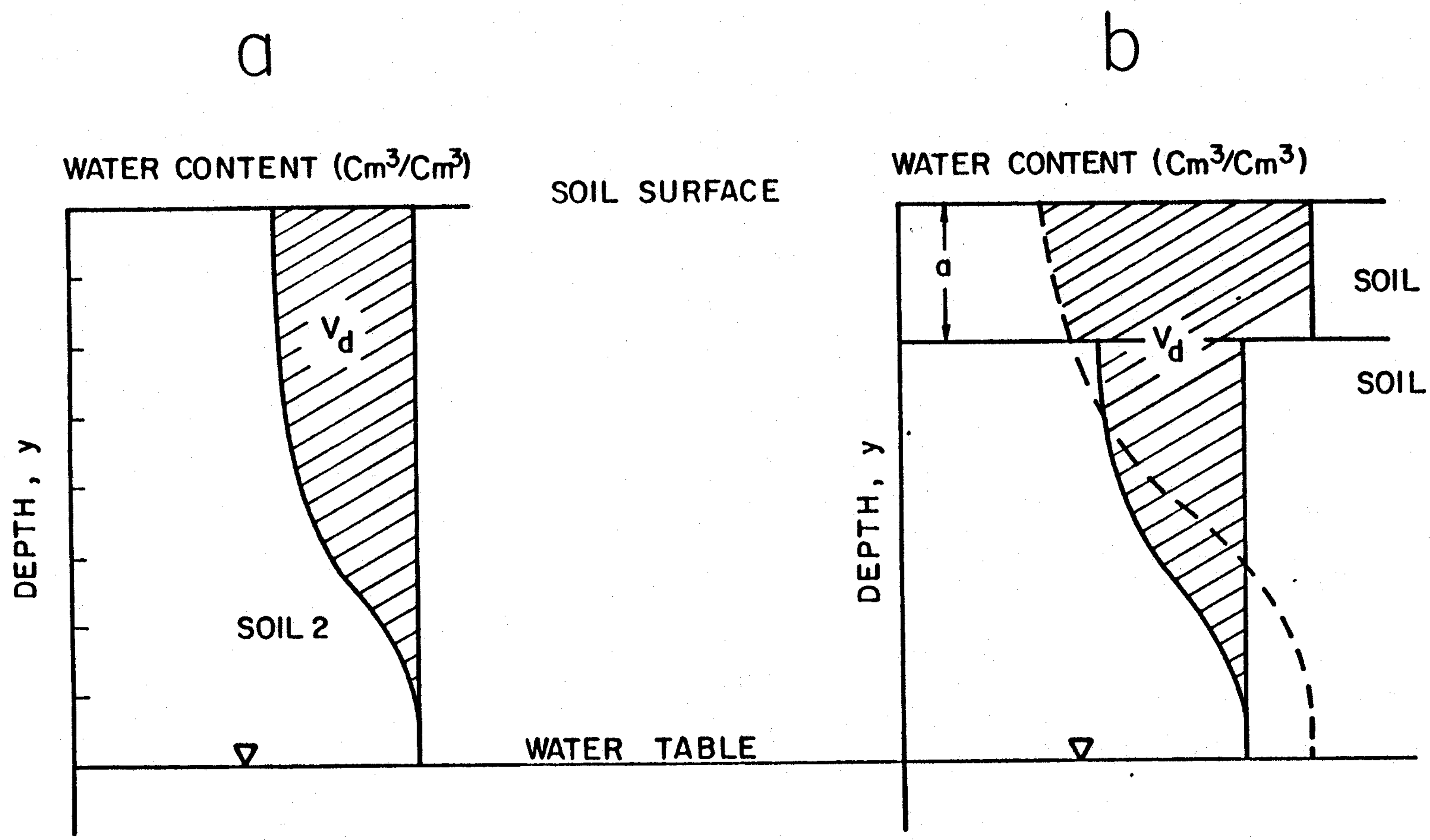

Figure 5-3. Soil water distribution for a uniform soil [a] and a layered soil [b] drained to equilibrium to a water table. The broken curve in [b] represents the soil water distribution for a uniform soil 1.

layer, V_{d2} (y), are first determined from the soil water characteristics, V_d can be easily computed for the layered soil as follows. For water table depths less than the depth, a, of the top layer,

$$V_d(y) = V_{d1}(y) \tag{5-2}$$

For greater depths,

$$V_d(y) = V_{d1}(y) - V_{d1}(y-a) + V_{d2}(y-a) \tag{5-3}$$

If the profile has a third layer starting at depth b, the water yield for depths greater than b may be computed by,

$$V_d(y) = V_{d1}(y) - V_{d1}(y-a) + V_{d2}(y-a) - V_{d2}(y-b) + V_{d3}(y-b) \tag{5-4}$$

Where $V_{d3}(y)$ is the water yield relationship for the third layer.

A computer program to calculate the $V_d(y)$ relationship from the soil water characteristics of a soil profile with up to 5 layers was developed by Badr (1978) and is given, along with example input data and program results, in Appendix D.

Drainage volume - water table depth relationships are given in Figure 5-4 for 7 North Carolina soils. Others can be calculated from soil water characteristic data which are available for many soils as discussed in the previous section. The slope of a plot of drainage volume versus water table depth is the drainable porosity, f, also called the specific yield. So if f is known or can be approximated for each soil horizon $V_d(y)$ can be estimated. For example, consider a soil with a well aggregated surface layer (0 - 30 cm) which has a drainable porosity of approximately f = 0.12. The subsurface layer (B horizon; 30-120 cm deep) is a silt loam with f = 0.04. These drainable porosities imply the water yield relationships plotted in Figure 5-5 (broken lines) for each layer. Once the $V_d(y)$ relationships are estimated for each layer, the water yield for the entire profile can be obtained from equations 5-2 and 5-3. This relationship is plotted as the solid curve in Figure 5-5.

There are a number of methods of obtaining the input data for drainage volume versus water table depth as discussed above. These methods are ranked as follows with the most exact or best method listed first, the next best listed second, etc.

1. Measurement of $V_d(y)$ from large undisturbed soil cores. (Probably impractical for most situations.)

2. Calculation of $V_d(y)$ from soil water characteristics, $h(\theta)$, for each soil horizon.

3. Determination of $V_d(y)$ from estimated drainable porosities of each layer (e.g. Figure 5-5).

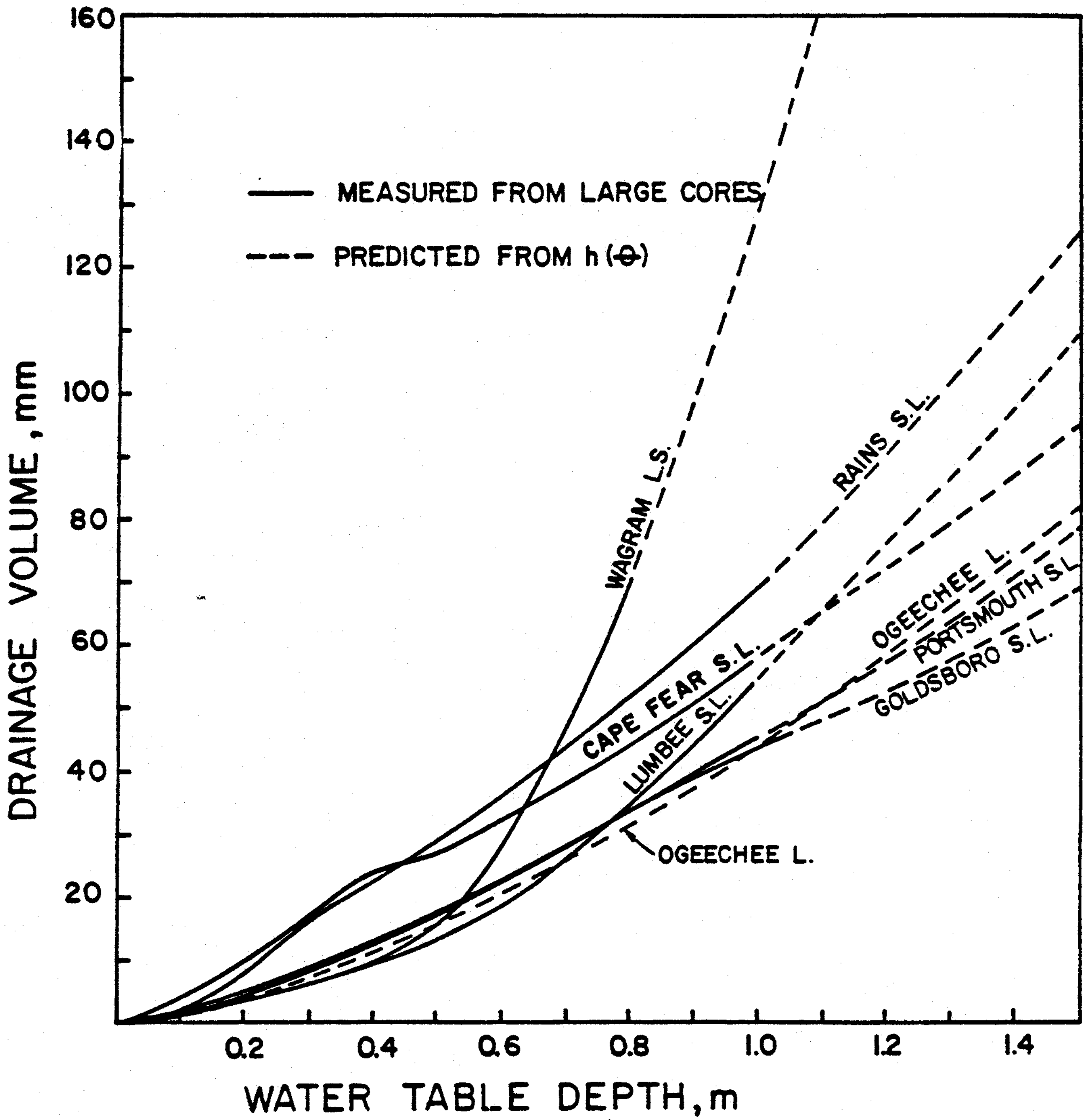

Figure 5-4. Drainage or air volume (mm^3/mm^2) as a function of water table depth for 7 North Carolina soils.

Upward Flux

There are several ways of estimating the relationship between upward flux and water table depth. The entire concept is approximate, as discussed in Chapter 2 because the relationship is defined for steady state conditions while the actual upward water movement process is transient. The easiest method is to obtain upward flux relationships directly from the literature. Such relationships are plotted for 8 North Carolina soils in Figure 5-6. Gardner (1958) obtained explicit unsaturated flux solutions for a given form of the unsaturated hydraulic conductivity function. Generally, however, upward flux relationships are not available and must be calculated from more basic soil properties. Numerical procedures may be used to calculate the water table depth for a given steady upward flux.

The equation for upward flux, at any point below the root zone, may be written from the Darcy-Buckingham equation as,

$$q = - K(h) \frac{dh}{dz} + K(h) \tag{5-5}$$

Where q is flux, z is the vertical position coordinate which is positive in the downward direction, h is pressure head, and K(h) is the unsaturated hydraulic conductivity. By dividing the soil profile into increments of Δz (Figure 5-7), Equation 5-5 can be written in finite difference form as,

$$q = - K(h_i) \frac{h_i + 1 - h_i}{\Delta z} + K(h_i) \tag{5-6}$$

Solving for h_{i+1} yields,

$$h_{i+1} = h_i + \Delta z - q \frac{\Delta z}{K(h_i)} \tag{5-7}$$

For a given surface (or bottom of root zone) boundary condition h_1, say $h_1 = -500$ cm, and an assumed value of q, h_2 can be calculated from Equation (5-7) by looking up the K value corresponding to $h_1 = -500$ cm. Then, h_3 can be determined from (5-7) and so on for the entire column. The water table depth for the q value assumed is that depth at which h = 0. By repeating the solution for a range of q values, the relationship between upward flux and water table depth can be defined. The K(h) value for each node is obtained from the unsaturated hydraulic conductivity function of the appropriate layer. A computer program to solve Equation 5-7 for a profile with up to 5 layers is given together with example input and output data in Appendix E.

The most critical condition for upward water movement is when available water in the root zone has been used up. Then, the upper boundary is effectively at the bottom of the root zone. Since the root zone depth changes with time during the growing season, an average root depth should be defined and used as the surface boundary for calculating the upward flux. For example, if the root zone depth of corn varies from 2 to 28 cm, the upper boundary condition should be applied at a depth of (2 + 28)/2 = 15 cm. Then, if the soil profile has three layers: 0 - 25 cm with $K_1(h)$; 25-75 cm with $K_2(h)$; and 75-120 cm with $K_3(h)$, the solutions given above should be

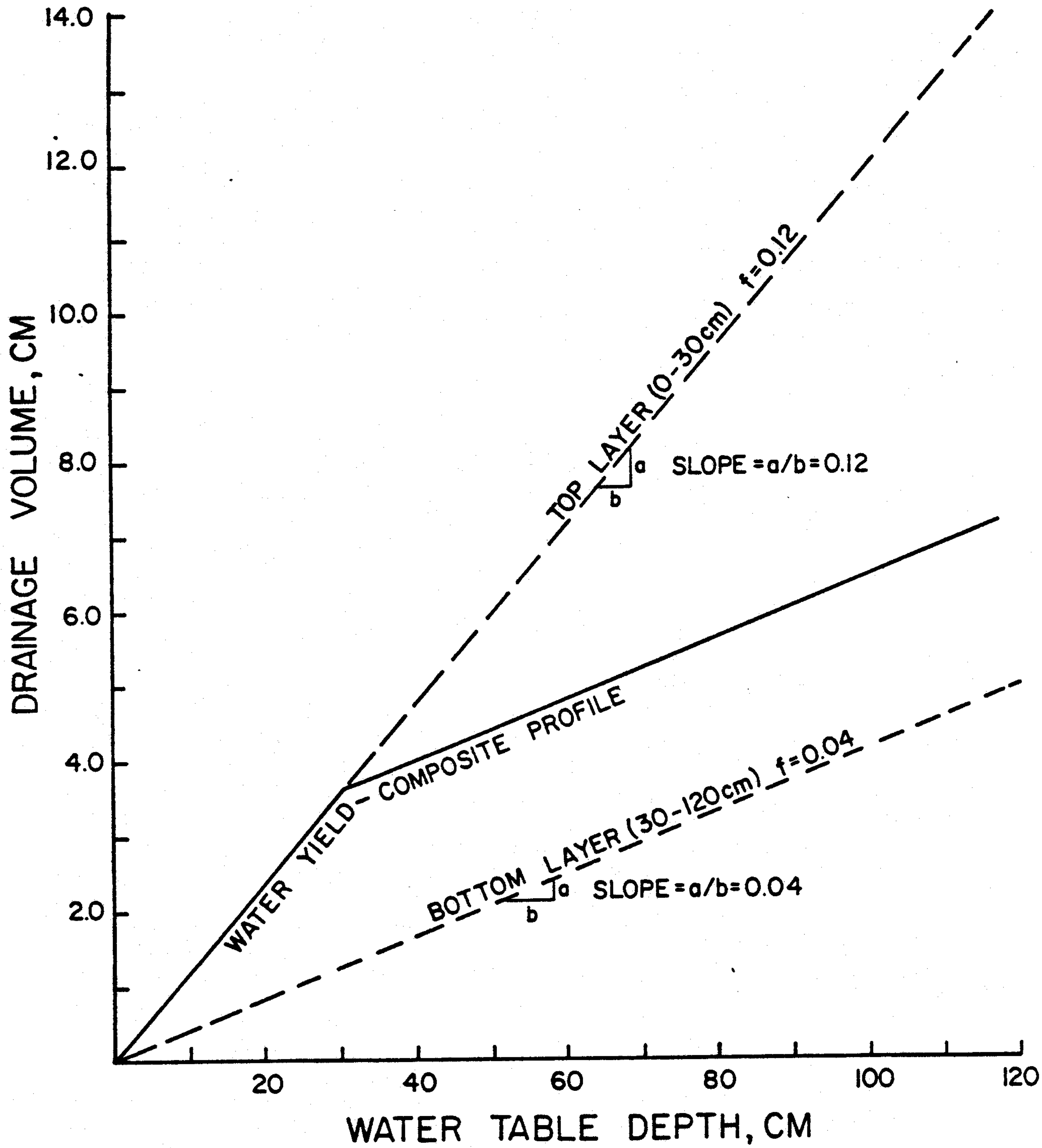

Figure 5-5. Drainage volume - water table depth relationships may be determined from estimated drainable porosity values.

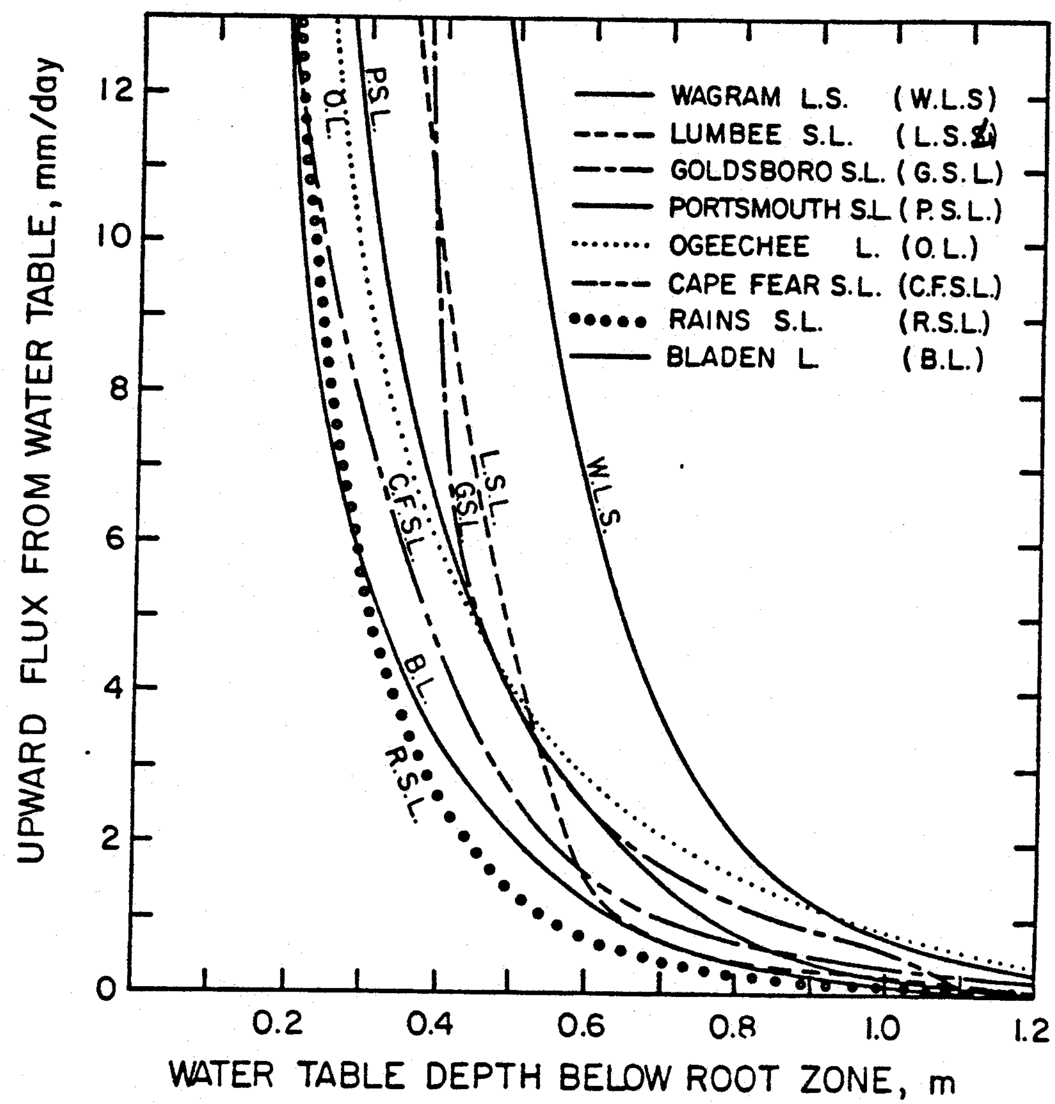

Figure 5-6. Upward flux - water table depth relationships for eight North Carolina soils.

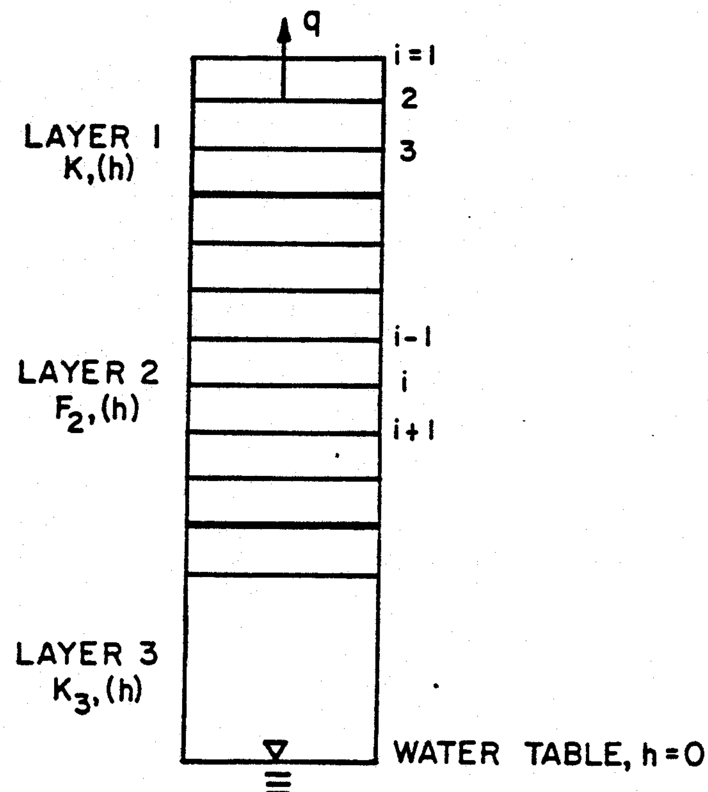

Figure 5-7. Finite difference grid for numerical solution for upward flux in a layered soil.

obtained for a profile starting at the 15 cm depth. That is, a profile with layer 1, 0 - 10 cm - $K_1(h)$; layer 2, 10-60 cm - $K_2(h)$; and layer 3, 60 - 105 cm - $K_3(h)$.

It is generally difficult to apply the above methods to determine upward flux relationships because of the unavailability of unsaturated hydraulic conductivity, K(h), data. Measured data are available for a few soils. Mualem (1978) cited sources of data for 50 soils. Other conductivity data may be obtained from some of the sources listed in Table 5-1. Unsaturated hydraulic conductivity, soil water characteristics and other properties are being measured in the field in several locations throughout the United States. The measurements are being made primarily by soil physicists at the Land Grant universities in the various states. A regional project entitled "Movement and Storage of Water and Solutes in Selected Southern Region Field Soils" is being conducted by researchers in 12 southern states. The project is sponsored by the Environmental Protection Agency and the Agricultural Experiment Stations in the individual states. The results from all states will be published in a bulletin when the project is completed (in 1982). Data may be published or available from individual researchers prior to that time.

What do you do if K(h) data are not available? Probably the next best alternative is to calculated K(h) from the soil water characteristic and saturated K. A number of prediction methods have been proposed and were reviewed by Bouwer and Jackson (1974). Experimental evaluations of the prediction methods have shown that best results are obtained when a matching factor is used to force the calculated and measured conductivities to agree at a given water content, usually saturation. Among the most frequently used methods are those predicted by Millington and Quirk (1961) and Marshall (1958). When the matching factor is based on the saturated conductivity, both the Millington and Quirk and Marshall equations can be written in the following form (Jackson, 1972).

$$K(\theta_i) = K_s \left(\frac{\theta_i}{\theta_s}\right)^p \frac{\sum_{j=1}^{m} (2j + 1 - 2i)/h_j^2}{\sum_{j=1}^{m} (2j - 1)/h_j^2} \qquad (5\text{-}8)$$

Where $K(\theta_i)$ is the calculated conductivity at water content θ_i, K_s is the saturated conductivity, θ_s is the water content at saturation, m is the number of water content increments used in the computation and j and i are indicies. The exponent p is 0 for the Marshall formulation and 4/3 for Millington and Quirk. A value of p = 1 can be used for most cases (Kunze, et al, 1968; Jackson 1972). Figure 5-8 shows a soil water characteristic divided into m equal water content increments. Usually m taken between 10 and 20 is adequate. The pressure head h_i is obtained from the midpoint of each increment. The water content, θ_i is the highest water content for the increment. A computer program to calculate $K(\theta)$ from Equation 5-8 is given in Appendix F. Once the K(h) relationship is defined, the numerical methods discussed above and in the computer program given in Appendix E can be used to determine the upward flux - water table depth relationship.

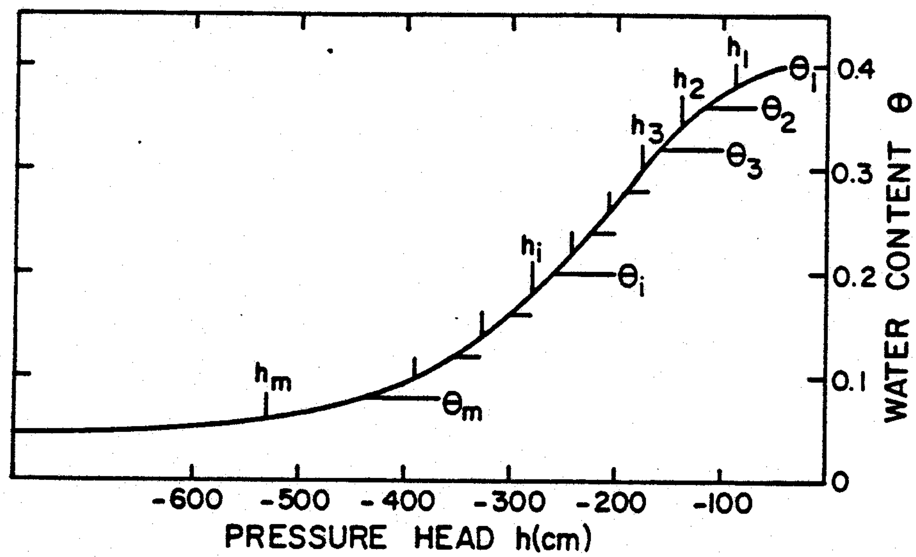

Figure 5-8. Hypothetical pressure head-water content relation showing equal water-content increments and corresponding pressure heads used to calculate the unsaturated conductivity by the methods of Marshall and of Millington and Quirk (after Bouwer and Jackson, 1974).

Often the soil water characteristic will not be known. Then, how do you determine the upward flux? It should be obvious that the less we know about the soil properties, the more approximate will be the inputs and the results. In the case where we know neither $K(h)$ or $h(\theta)$, upward flux relationships can be estimated in terms of the soil texture and saturated hydraulic conductivity by assuming a form of the hydraulic conductivity function and selecting equation parameters based on the soil texture. Gardner (1958) suggested the following equation for the relationship between the hydraulic conductivity, $K(h)$, and the pressure head, h.

$$K(h) = a\ [(-h)^n + b]^{-1} \tag{5-9}$$

Where a, b, and n are parameters that depend on the soil. Raats and Gardner (1974) wrote the equation as:

$$K(h) = K_s\ [(h/h_{0.5})^n + 1]$$

Where K_s is the vertical saturated hydraulic conductivity and $h_{0.5}$ is the pressure head at which $K(h) = K_s/2$.

Gardner (1958) solved Equation 5-5 for n values between 1.5 and 4 and expressed the maximum upward flux in terms of the water table depth and the parameters a, b, and n. Raats and Gardner (1974) showed that the solution for maximum upward flux could be written as,

$$q_{max} = K_s \left[\frac{-\pi\ h_{0.5}}{n\ \mathrm{Sin}\pi/n}\right]^n \quad y^n \tag{5-10}$$

Where y is the depth of the water table below the surface. For our purposes, we would assume that y is the depth below the root zone, as discussed on pages 5-20.

An equation similar to 5-10 was derived by Anat, et al, (1965) by assuming the Brooks and Corey (1964) form of the hydraulic conductivity function, which may be written as,

$$K = K_s \quad , \qquad h > h_b \tag{5-11a}$$

$$K = K_s \left(\frac{h_b}{h}\right)^\eta \qquad h < h_b \tag{5-11b}$$

Where η is a dimensionless constant for a given soil and h_b is the bubbling pressure head (remember that the pressure head is negative for unsaturated conditions, so $h < h_b$ corresponds to tensions greater than $-h_b$). Anat's equation for maximum upward flux may then be written as,

$$q = K_s \left[h_b + \frac{1.89\ h_b}{\eta^2 + 1}\right]^\eta /y^\eta \tag{5-12}$$

Brooks and Corey (1964) related η to the pore size distribution index, λ, as,

$$\eta = 2 + 3\lambda \tag{5-13}$$

They described graphical methods of determining λ from the soil water characteristic. It can be shown that $\eta = n$ in Equations 5-9 and 5-10.

The difficult part in applying either Equation 5-10 or Equation 5-12 is determination of the parameters η, h_b, and $h_{0.5}$. When better information cannot be obtained the parameters can be approximated in terms of the soil texture using results recently reported by Brakensiek, et al, (1980). These results build on the work of Clapp and Hornberger (1978) and Brakensiek (1979) to present, for textural classes of sand, sandy loam, silt loam, etc., average values of η, h_b, and other parameters that will be discussed in the section on infiltration. Values for η and h_b are given in Table 5-5. The values given by Brakensiek, et al, (1980) were derived from analyses of desorption data. Because upward flux may involve both desorption and imbibition processes (Anat, et al, 1965), estimates for the imbibition cycle should probably be used. Bouwer (1969) suggested that the bubbling pressure head for imbibition, which he called the water entry section, could be approximated as one-half the desorption h_b.

Another method of estimating the upward flux is to employ the results of Clapp and Hornberger (1978). They used a power curve to model the soil water characteristic and a relationship for K(h) originally derived by Cambell (1964). By examining soil properties for many soils, they obtained average parameters for various textural classes. Their results were used to calculate normalized upward flux relationships for each textural class using Equation 5-7 and the computer program in Appendix E. These normalized relationships are plotted in Figure 5-9. An input upward-flux relationship for a given soil can be estimated by multiplying the flux values on the approximate curve in Figure 5-9 by the saturated conductivity. A note of caution is necessary in using the values given in Table 5-5 and Figure 5-9. In both cases, the results are based on soil water characteristic data obtained by Holtan, et al, (1968). As already mentioned (page 5-4), these data are not complete for low tensions. Inaccuracies in this range may cause significant errors in predicting upward flux relationships so the results in Figure 5-9 and the data in Table 5-5 should only be used when measurements on the specific soils considered cannot be obtained.

For layered soils, the maximum upward flux-water table depth relationships can be constructed for each soil layer using Equation 5-10, Equation 5-12, or Figure 5-9. Then, a composite curve can be constructed, as shown in the example below.

Example. Analyses are to be conducted for a soil having the following profile description:

0 - 15 cm sandy loam, $K_s = 2.0$ cm/hr

15 - 55 cm sandy clay loam, $K_s = 0.5$ cm/hr

55 - 135 cm sandy clay, $K_s = 0.2$ cm/hr

Corn, with a time-average rooting depth of 15 cm is to be grown. Therefore, the upward flux relationship will be defined from profile characteristics from the 15 to 135 cm depth. Multiplying the ordinate values of the sandy clay loam and sandy clay curves in Figure 5-9 by 0.5 and 0.2 cm/hr,

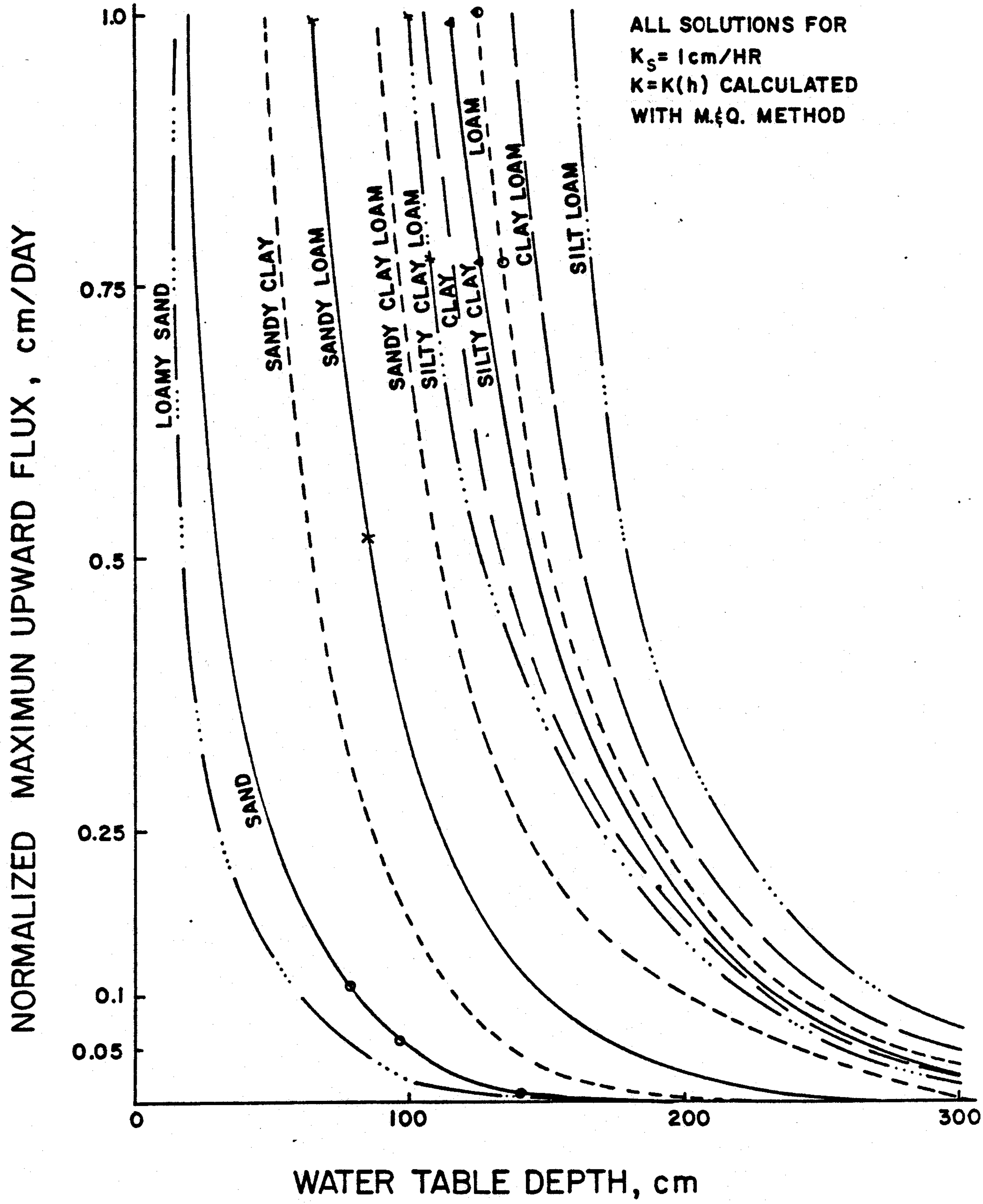

Figure 5-9. Approximate upward flux relationships for a range of textural classes. Upward flux was determined for saturated K of 1 cm/hr in all cases. Average h(θ) relationships were obtained from the results of Clapp and Hornberger (1978). K(h) was predicted from the Millington and Quirk method with K_s = 1.0 cm/hr and upward flux computed numerically (Equation 5-7 and Appendix E).

respectively, gives the broken curves in Figure 5-10. The sandy clay loam curve will represent the relationship for water table depths from 0 to 55 - 15 = 40 cm and the sandy clay curve for deeper depths. A transition curve is sketched in to smoothly connect the two relationships giving an approximate upward flux - water table depth relationship for the profile. If an upward flux relationship is to be calculated from Equation 5-12 or chosen from Figure 5-9 for a single layer, it should be based on the texture and K of the zone from the bottom of the plow layer to a depth of about 1 m.

The simplest (and most approximate) method of handling the upward flux is to define a critical limiting depth, CRITD, below which water will not be transferred to the root zone. That is, it is assumed that water will move upward from the water table at a rate equal to the potential ET rate until the distance between the water table and the root zone becomes greater than CRITD. The parameter CRITD can be approximated from a soil profile description based on the texture and hydraulic conductivity of each horizon. In some cases, this option may be preferable to approximating an upward flux - water table depth relationship. Consider the field description of an Oldsmar sand profile given in Table 5-2. For this particular case, the soil properties are given by Hammond, et al, (1971) and the upward flux relationship could be calculated using the numerical methods discussed above. However, if these data were not available, we would assume that upward water movement would be severely restricted by the tight layer at a depth of 86 cm. Then, subtracting the average root zone depth of 15 cm gives CRITD = 86 - 15 = 71 cm.

Alternative methods for determining input data for upward flux may be ranked as follows:

1. Obtain upward flux - water table depth relationship from plots or tables in the literature (e.g. Figure 5-6) or from explicit solutions such as those given by Gardner (1957). Such relationships are not available for many soils at this time, but could be developed for future use.

2. Calculate the relationship from K(h) using numerical methods (Equation 5-7 and Appendix F).

    a. With measured or tabulated K(h) for the given soils.

    b. With K(h) of each horizon computed from Millington and Quirk or other prediction methods (Appendix G). This requires the soil water characteristic, $h(\theta)$, and saturated K of each horizon.

3. Use the normalized relationships for different soil textures given in Figure 5-9 with saturated K for each horizon. Approximate for layered soils, as discussed in relation to Figure 5-10, <u>or</u> choose approximate η and h_b values from Table 5-5. Calculate upward flux relationship using Equations 5-10 or 5-12.

4. Use the critical depth concept. CRITD should usually not be greater than 90 cm and may be less depending on location of restricting horizons.

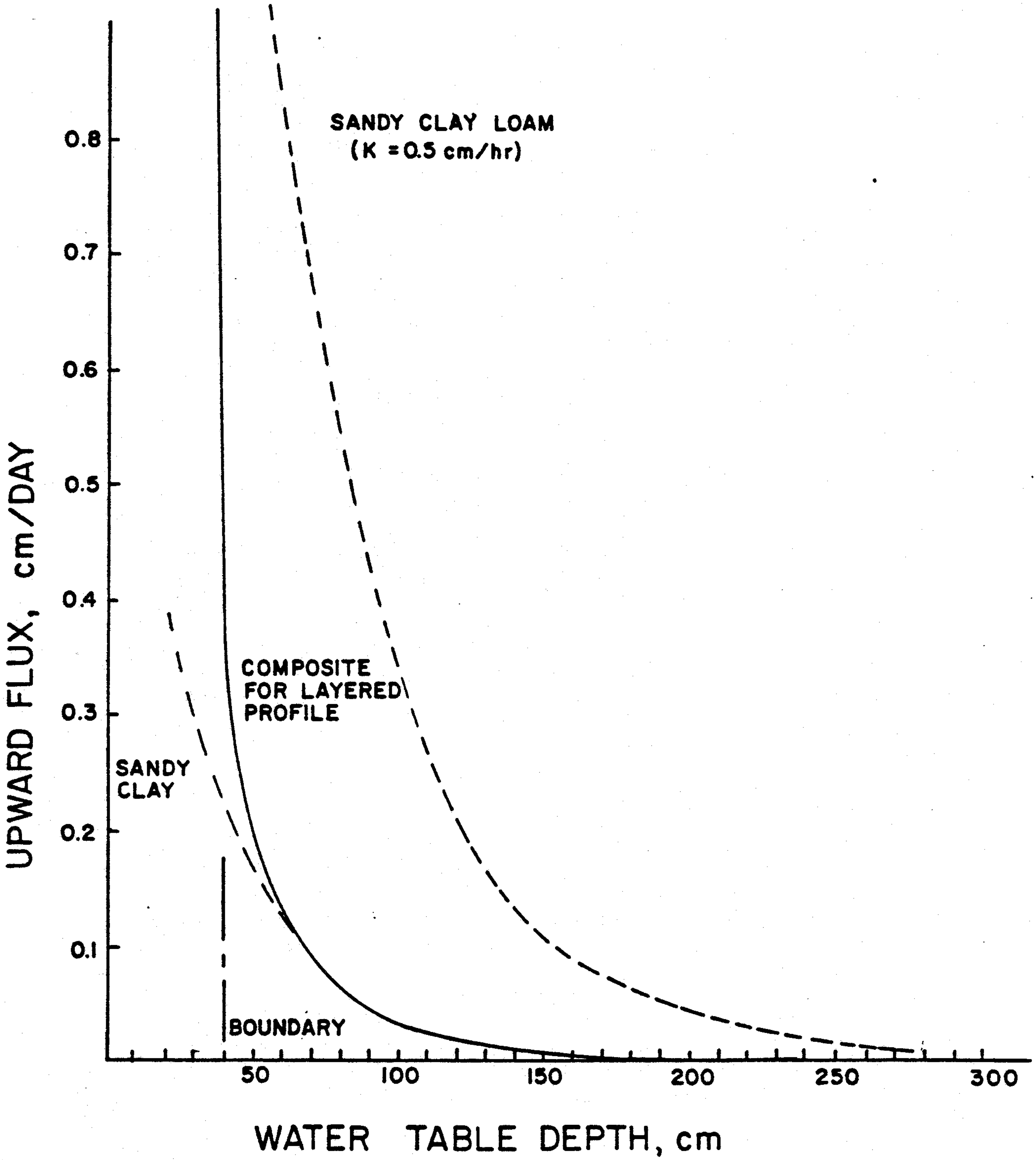

Figure 5-10. Upward flux relationships for a layered profile. The curves were approximated using the relationships in Figure 5-9, as explained in the example.

Table 5-2. Field description of an Oldsmar sand profile at the SWAP Experimental site at Fort Pierce (after Hammond, et al, 1971).

Horizon	Depth, cm	Morphology	K(cm/hr)
A1	0-13	Very dark gray (10 YR 3/1) sand; single grain structure; loose; gradual smooth boundary.	30.
A21	13-30	Gray (10 YR 5/1) sand; single grain structure; loose; gradual smooth boundary.	10.
A22	30-86	Light gray (10 YR 7/) sand; single grain structure; loose; abrupt wavy boundary.	10.
B2h	86-107	Black (10 YR 2/1) sand; massive structure; weekly cemented; gradual wavy boundary.	0.01
B21	107-127	Very dark grayish brown (10 YR 3/2) loamy sand; single grain structure; loose; gradual wavy boundary.	18.
B22tg	127-152	Very dark grayish brown (10 RY 3/2) sandy clay loam; sub-angular block structure; friable; gradual wavy boundary.	1
B23tg	152-218	Grayish brown (2.5 Y 5/2) to gray (10 YR 5/1) sandy clay loam; massive structure; friable; undetermined boundary.	0.1

Green-Ampt Equation Parameters

The flexibility of the Green-Ampt equations for describing infiltration under varied initial, boundary, and soil profile conditions makes it an attractive method for field applications. The fact that the equation parameters have physical significance and can be computed from soil properties is an added advantage. In practice, however, it will nearly always be advantageous to determine the equation parameters from field measurements by fitting measured infiltration data or from measurements such as those proposed by Bouwer (1966). Field infiltration measurements tend to lump the effects of such factors as heterogeneities, worm holes, and crusting in the equation parameters. This results in more reliable infiltration predictions than if the parameters are determined from basic soil property measurements.

Methods for measuring infiltration in the field are discussed briefly in Section 15, Chapter 1 of the SCS-NEH. Parr and Bertrand (1960) published a thorough review of field methods for measuring infiltration capacity. Basically, two types of devices have been used - sprinkling infiltrometers and flooding infiltrometers. While it would be advantageous to use a sprinkling infiltrometer to simulate rainfall conditions, the flooding devices are far more frequently used because they require less equipment and are easier to install and operate than the sprinkling type.

The most commonly used infiltrometer is probably the ring or cylindrical infiltrometer which was described in detail by Haise, et al, (1956). Bouwer (1963) and Wooding (1968) discussed methods of reducing and correcting for errors caused by lateral flow from the cylindrical infiltrometer. There are many types of sprinkling infiltrometers, as discussed by Parr and Bertrand (1960). Construction and operation of one such infiltrometer was presented, in detail, by Dixon and Peterson (1964). Sprinkling or spray infiltrometers usually consist of a plot surrounded by partially buried sheet metal barriers with facilities for measuring the rate of surface runoff. Water is sprinkled onto the plot surface at a constant intensity and the infiltration rate is determined from recorded runoff measurements. In most cases, the infiltration rate is determined by simply subtracting the runoff rate from the application intensity. However, the rate of surface storage during the initial stages of runoff should also be considered, as shown by Skaggs, et al, (1966) and Smith (1976). Another sprinkler irrigation method of measuring infiltration rates was described by Tovey and pair (1966). A shielded rotating sprinkler head is used to apply water to a circular section of soil at various rates depending on location. Application rates are measured and notes made as to whether the water is applied too fast, too slow, or equal to the infiltration capacity. The results can be used to plot a curve of infiltration capacity versus cumulative infiltration.

Regardless of the method used to measure the infiltration relationship, the next step is to determine the Green-Ampt equation parameters from the infiltration measurements. From Equation 2-7, the Green-Ampt equation may be written as,

$$f = A/F + B \tag{2-7}$$

Where $A = K_s M S_{av}$ and $B = K_s$. A simple method for determining A and B is demonstrated in the example given below.

<u>Example</u>. Results of field infiltration measurements on a sandy loam soil are tabulated in Table 5-3 and plotted in FIgure 5-11. The infiltration rates were determined by drawing a smooth curve through the observed cumulative infiltration data and taking the slope at various times along the curve. The parameters A and B can be estimated from these data by first defining a variable G = 1/F such that Equation 2-5 may be written,

$$f = AG + B \tag{5-14}$$

The variable G is also tabulated in Table 5-3. Then, A and B can be determined from a plot of f vs. G (Figure 5-12) by simply drawing a straight line (eyeball fit) through the data and determining the slope and intercept. In this example, $A = 1.25\ cm^2/hr$ and $B = 0.50$ cm/hr.

Table 5-3. Results of sprinkler infiltrometer measurements on a sandy loam soil. The application rate was 5.0 cm/hr.

Time min	Cumulative Infiltration, F (cm)	Infiltration Rate, f (cm/hr)	$G = 1/F$ cm^{-1}
0	0	5.0	0
3 (time of surface ponding)	0.25	5.0	4.0
5	0.45	3.6	2.22
10	0.60	2.4	1.67
20	1.0	1.7	1.0
40	1.55	1.2	0.645
60	1.80	1.08	0.555
90	2.25	0.95	0.444
120	3.0	0.88	0.333
150	3.25	0.81	0.308
180	3.75	0.78	0.267
210	4.10	0.75	0.244

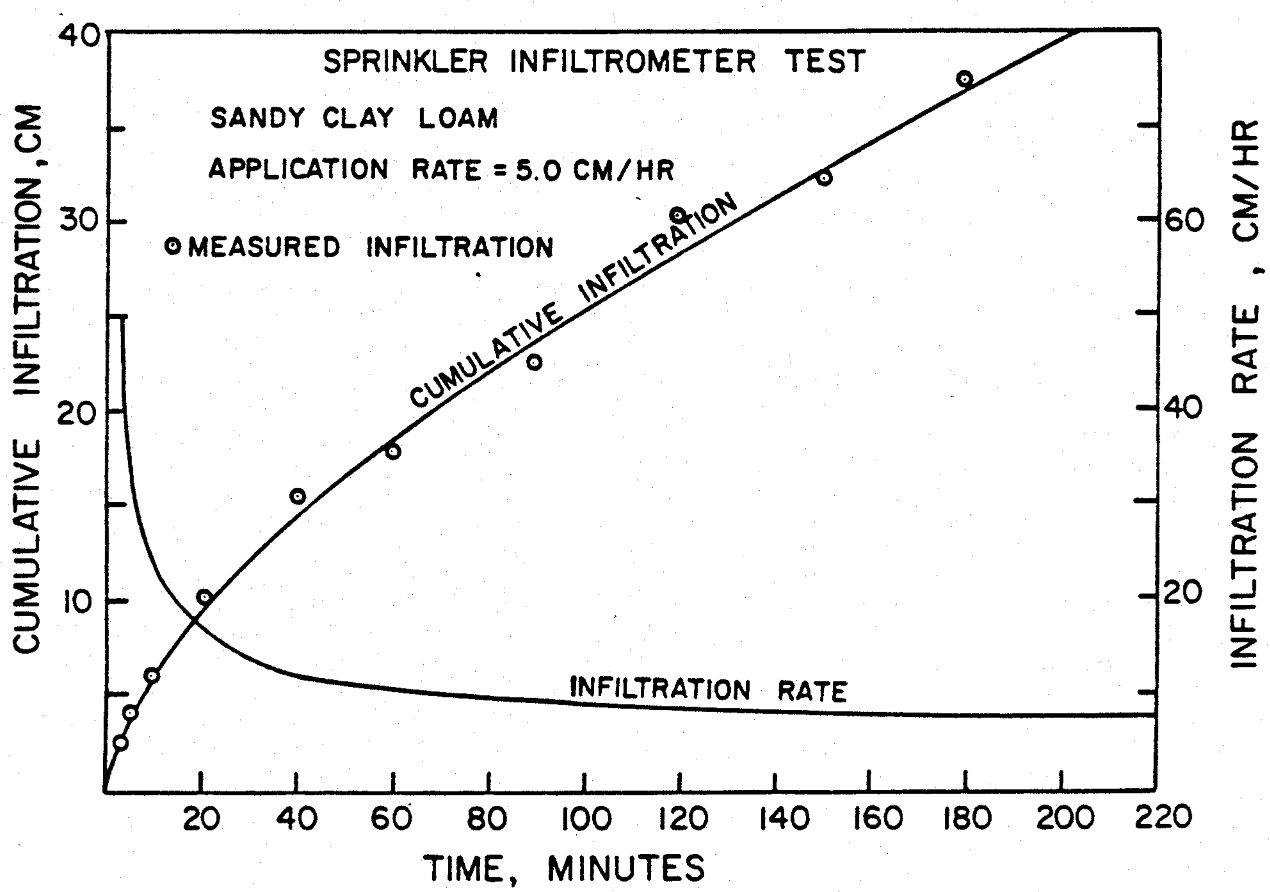

Figure 5-11. Cumulative infiltration determined from sprinkler infiltrometer measurements and calculated infiltration rates as a function of time.

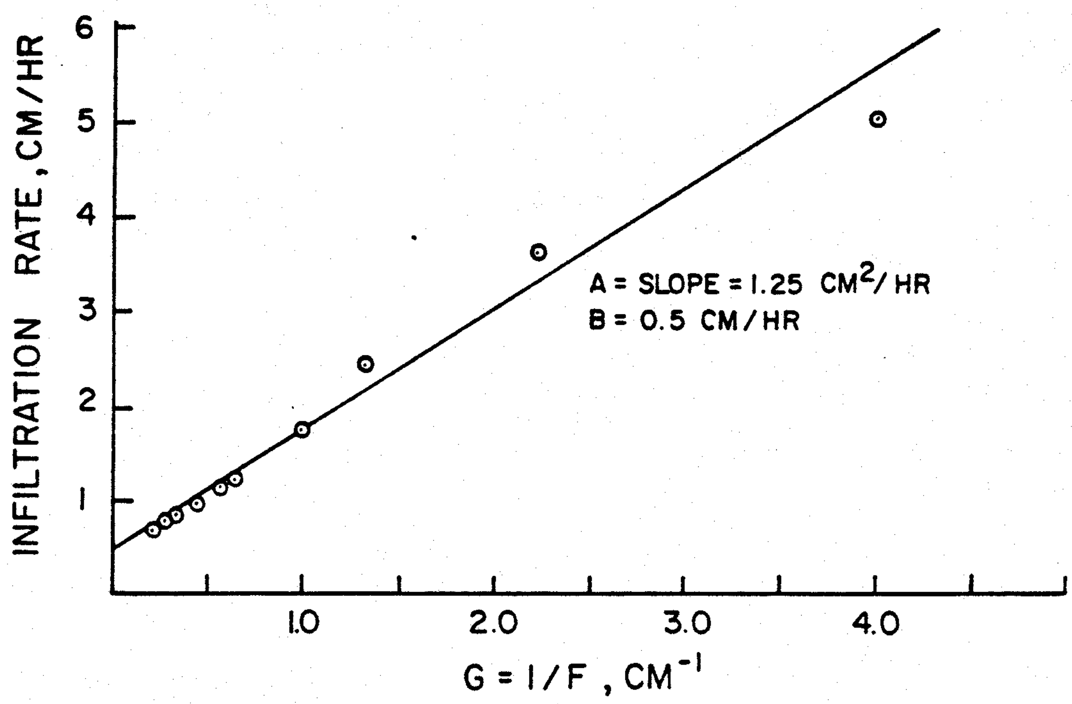

Figure 5-12. Graphical procedure for estimating parameters A and B from measured infiltration data.

Nothing has been said so far about the initial conditions for the above test. Let us assume that the water table was at a depth of 150 cm when the above test was run and the water content at the soil surface was $\theta_i = 0.25$ cm^3/cm^3. The maximum water content (saturation less entrapped air) is $\theta_s = 0.45$ cm^3/cm^3. Therefore, $M = 0.45 - 0.25 = 0.20$ and since $K_s = B = 0.5$ cm/hr, $S_{av} = A/K_sM = 12.5$ cm. The values of A and B can be determined for other initial water table depths by repeating the experiment for the different conditions. Alternatively, B can be assumed constant at 0.5 cm/hr and A can be estimated by determining the appropriate value of M for each water table depth. For example, if the initial water table depth is 50 cm, the water content at the surface may be obtained from the soil water characteristic (corresponding to h = -50 cm) as, say 0.36 cm^3/cm^3. Then, M = 0.45 - 0.36 = 0.09 and A = 0.5 X 0.09 X 12.5 = 0.56 cm^2/hr.

More sophisticated methods for determining A and B by fitting infiltrometer data using regression methods were presented by Brakensiek and Onstad (1977). They considered spatial variation of the estimated parameters and presented methods for averaging the values to give lumped parameter values for watershed modeling. A sensitivity analysis for the equation parameters showed that predicted infiltration and runoff amounts and rates were most sensitive to the errors in fillable porosity, M, and K_s, and less sensitive to errors in S_{av}.

When field infiltration measurements are not available, the Green-Ampt equation parameters can be estimated from basic soil properties. Bouwer (1966, 1969) showed that the hydraulic conductivity parameter in the Green-Ampt equation should be less than the saturated value, K_o, because of entrapped air. He described an air-entry permeameter which can be used in the field for measuring K_s, the conductivity at residual air saturation, and the air entry suction. When measured values are not available, Bouwer (1966) suggested that K_s may be approximated as $K_s = 0.5\ K_o$. Thus, an estimate of K_s can be obtained from K_o values in the standard soil survey interpretation forms.

The effective suction at the wetting front, S_{av}, is somewhat more difficult to determine. Bouwer (1969) used the water entry suction, h_{ce}, for S_{av} in Equation 2-7 and suggested that it can be approximated as one-half of the air entry value. Main and Larson (1973) used the unsaturated hydraulic conductivity as a weighting factor and defined the average suction at the wetting front as,

$$S_{av} = \int_o^1 h\ dk_r = -\int_o^{h_i} k_r\ dh \qquad (5\text{-}15)$$

Where h is the soil water pressure head, h_i is the pressure head at the initial water content, θ_i, and k_r is the relative hydraulic conductivity, $k_r = K(h)/K_s$. The effective matric drive, H_c, introduced by Morel-Seytoux and Khanji (1974) is dependent on the relative conductivities of both air and water. However, for most cases, the value of S_{av} given by Equation 5-15 is a reasonable approximation of H_c (Morel-Seytoux and Khanji, 1974).

One of the problems of using Equation 5-15 to obtain S_{av} is the requirement of the unsaturated hydraulic conductivity function K(h). Some investigators have used prediction methods (e.g. Equation 5-8 and Appendix G) to estimate K(h) and then determine S_{av} from Equation 5-15. Brakensiek (1977) used methods of Brooks and Corey (1964) and Jackson (1972) to determine S_{av} for the five soils originally investigated by Mein and Larson (1973). He showed that, for the Brooks and Corey (1964) model, Equation 5-15 may be integrated to give,

$$S_{av} = h_{ce}\ \eta/(\eta-1) \qquad (5\text{-}16)$$

Where h_{ce} is approximately one-half the bubbling pressure. The bubbling pressure, P_b, and the parameter η may be obtained from the soil water characteristic by using graphical procedures given by Brooks and Corey (1964). The procedures are demonstrated in an example given below. Brakensiek (1977) found that S_{av} values computed from Equation 5-16 and from Equation 5-15 with k_r given by Equation 5-8 were in good agreement with the original values of Mein and Larson for actual k_r data and with the H_c values computed by Morel-Seytoux and Khanji (1974) for the same five soils. Brakensiek (1977) also found that the simple equation,

$$S_{av} = 0.76\ P_b, \qquad (5\text{-}17)$$

Where P_b is the desorption bubbling pressure, is an acceptable approximation for the soils he investigated.

Example. The soil water characteristic for a sandy clay loam soil is plotted in Figure 5-13. To use the method of Brooks and Corey (1964), we first define saturation as $S = \theta/\theta_s$ where θ_s = saturated water content. The residual saturation, S_r is determined from Figure 5-13, or a similar plot of S vs. h, as the horizontal asymptote. In this case, $\theta_r = 0.21$ and $S_r = 0.21/\ 0.42 = 0.50$. Then, the effective saturation,

$$S_e = \frac{S - S_r}{1 - S_r}$$

is calculated for a number of points as shown in Table 5-4. Then, log S_e is plotted versus log (-h) on log-log paper (Figure 5-14).

The value of P_b is determined from the straight line intercept of the -h axis. From Figure 5-14, P_b = 32 cm and $\eta = 2 + 3\lambda = 2 + 3 \times 0.57 = 3.71$. Then, the value of S_{av} may be estimated from Equation 5-16 as,

$$S_{av} = \frac{32}{2} \times 3.71/(3.71 - 1) = 21.9 \text{ cm.}$$

Using Equation 5-17 gives $S_{av} = 0.76 \times 32 = 24.3$ cm. Thus, S_{av} can be estimated from the soil water characteristic when it is available.

Table 5-4. Effective saturation and pressure head values for a sandy clay loam. ($S_r = 0.50$).

θ cm^3/cm^3	S_e $(S-S_r)/(1-S_r)$	h cm
0.42	1.0	0.0
0.41	0.95	-30
0.40	0.90	-40
0.38	0.81	-61
0.36	0.71	-92
0.34	0.62	-138
0.32	0.52	-200
0.30	0.43	-295
0.28	0.33	-550
0.26	0.24	-1,000

When the soil water characteristic cannot be obtained for a given soil, it may be estimated by matching the soil texture with that of a soil for which $h(\theta)$ is known, as discussed earlier in this chapter. Then, S_{av} could be estimated using the methods discussed above. The results of Brakensiek, eta al. (1980) and Clapp and Hernberger (1978) can be used to estimate soil property values for various textural classes as discussed earlier in this chapter. Brakensiek's, et al, (1980) results for saturated water content, θ_s, η, h_b, and S_{av} are given in Table 5-5. Brakensiek's (1979) estimates for S_{av} are also given in the table.

Table 5-5. Average values of θ_s, η, h_b, and S_{av} for 10 textural classes of soils (after Brakensiek, et al, 1980). Note: There may be wide variation of S_{av} within a textural class and these values should be regarded, as approximate.

Soil Texture	Average θ_s	(Std. Dev.)	η	h_b (cm)	S_{av} (cm)	Average S_{av}* (cm)
Sand	0.35	(0.11)	3.6	17	10	10
Loamy sand	0.41	(0.06)	3.3	10	7	7
Sandy loam	0.42	(0.08)	3.1	17	12	18
Silt loam	0.48	(0.06)	2.6	43	35	64
Loam	0.45	(0.07)	2.7	23	18	39
Sandy clay loam	0.41	(0.05)	3.0	26	19	25
Silty clay loam	0.47	(0.05)	2.5	37	30	31
Clay loam	0.48	(0.05)	2.8	28	21	55
Sandy clay	0.42	(0.06)	2.7**	28**		14
Silty clay	0.48	(0.06)	2.5	27	20	44
Clay	0.48	(0.05)	2.5	33	26	36

* From Brakensiek's (1979) comment on the Clapp and Hornberger (1978) paper.

** Estimated.

Note: The values given in Table 5-5 are average values and that $h(\theta)$ (and hence S_{av}) depends on soil structure and other factors, as well as texture. Therefore, the values tabulated in Table 5-5 should be treated, as estimates, to be used only when better data cannot be obtained.

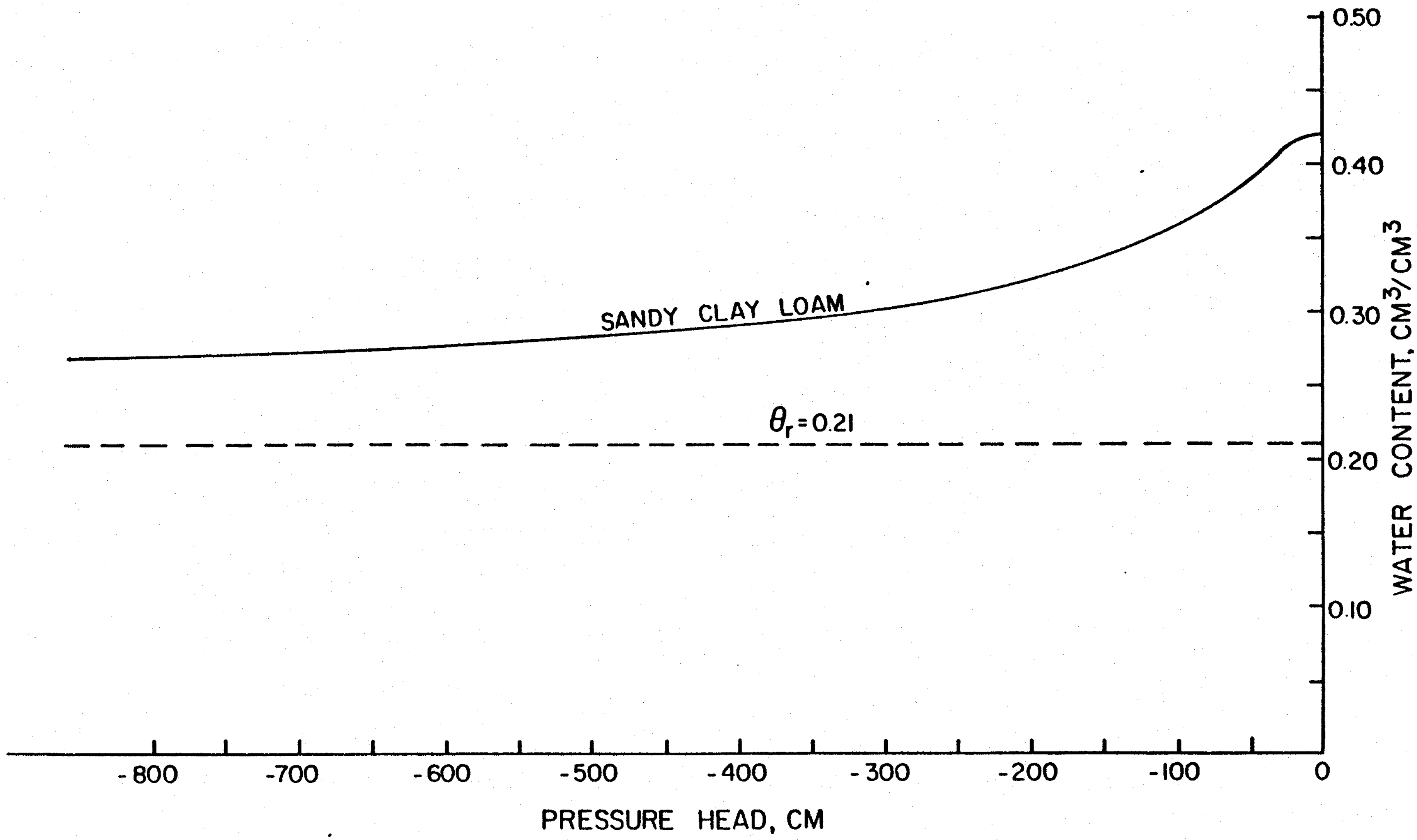

Figure 5-13. Soil water characteristic for a sandy clay loam.

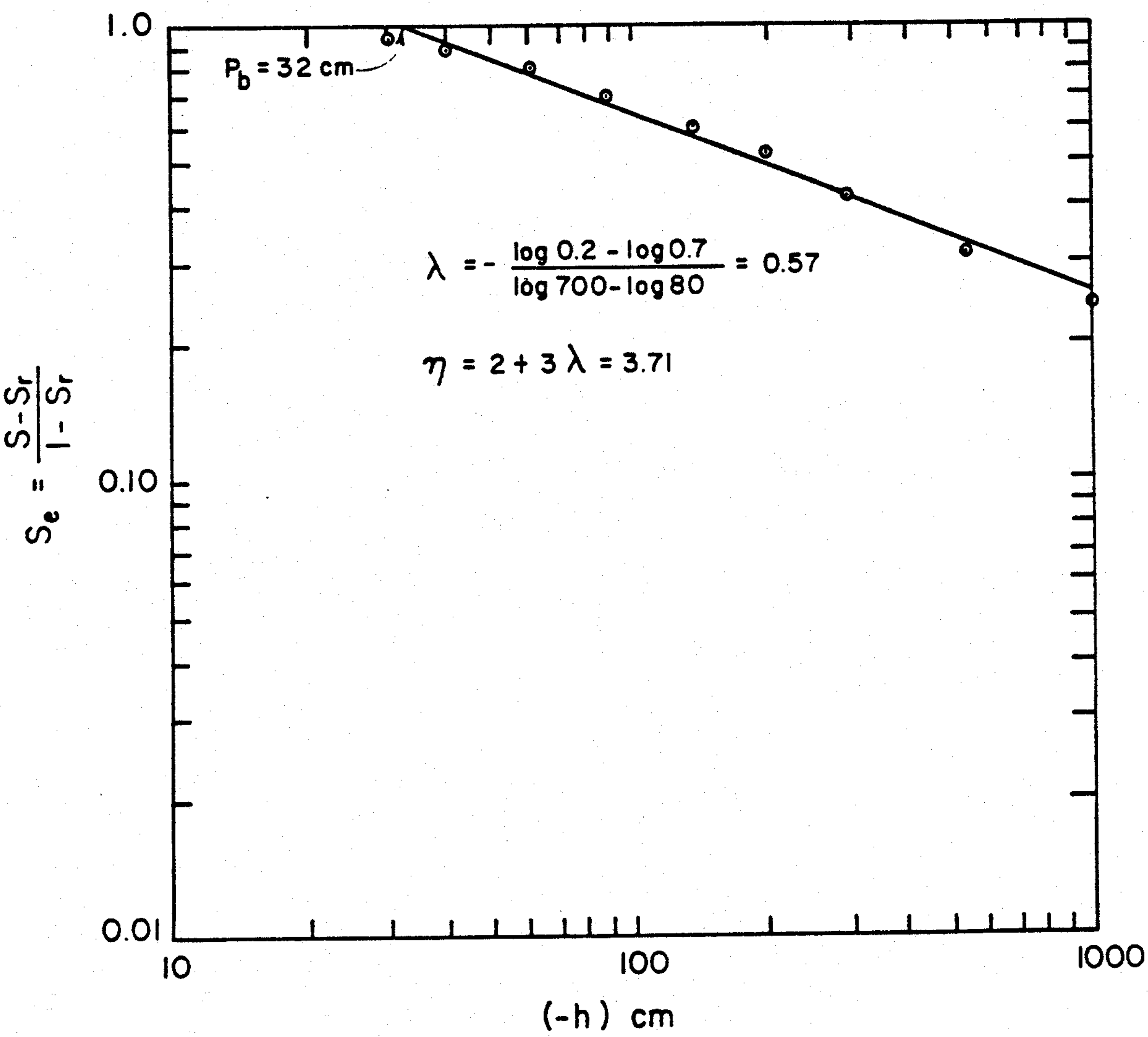

Figure 5-14. Determination of bubbling pressure, P_b, and η from the effective saturation, S_e, - pressure head relationship.

For a layered soil, S_{av} should usually be based on properties of the surface horizon. The value of K_s in the surface layer may be used for shallow initial water table depths, while K_s of underlying layers or average K_s values may be used when the water table is deeper. Consider a profile made up of 30 cm of the sandy clay loam of the above example (with K_s = 2 cm/hr) over 170 cm of silty clay loam with K_s = 1 cm/hr. We need input data for DRAINMOD for a range of initial water table depths (IWTD). From above S_{av} = 22 cm.* For IWTD = 30 cm, K_s = 2 cm/hr. From Figure 5-13, $\theta_s = 0.42$ and $\theta_i = 0.41$ (corresponding to $h = -30$ cm). Then, $M = 0.42 - 0.41 = 0.01$, $A = 0.01 \times 2$ cm/hr $\times$ 22 cm = 0.44 cm^2/hr and $B = K_s = 2.0$. For IWTD = 120 cm, $\theta_i = .345$ (Figure 5-13), $M = .075$, $K_s = (30 \times 2 + 90 \times 1)/120 = 1.25$ cm/hr so B = 1.25 cm/hr and A = 1.25 x 0.075 x 22 = 2.06 cm^2/hr. For water table depths greater than 150 cm, a dry zone normally develops at the surface with an assumed $\theta_{\ell\ell} = 0.22$. Then, $M = 0.42 - 0.22 = 0.20$, B = 1.25 cm/hr and A = 5.28 cm^2/hr. Using these methods for other IWTD values, the input data for infiltration parameters could then be written as follows:

IWTD (cm)	A(cm^2/hr)	B cm/hr
0	0.	2.0
30	0.44	2.0
60	1.32	1.5
120	2.06	1.25
150	5.28	1.25
500	5.28	1.25

Methods for determining the Green-Ampt equation parameters may be ranked as follows:

1. Determination from field infiltration measurements.

2. Field measurement of S_{av} and K_s using methods such as those proposed by Bouwer (1966).

3. Calculation of S_{av} from measured k_r (h) and h(θ) data.

4. Calculation of S_{av} using prediction equations for k_r and measured h(θ) data. That is, use of Equations 5-16, 5-17, 4-18, and others. Obtain K_s from field measurements or estimate from soil survey interpretations.

5. Estimate S_{av} based on soil texture from Table 5-5. Get K_s from soil survey interpretations.

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* S_{av} = 22 cm was obtained from data for this specific soil and is used rather than the value for sandy clay loam in Table 5-5. If h(θ) data were not available, S_{av} = 11.7 cm could have been estimated from Table 5-5.

Trafficability Parameters

Three parameters are used in DRAINMOD to determine if field conditions are suitable for tillage or harvesting operations. The parameters are: (1) minimum water free pore volume (air volume) (cm) required for trafficability, AMIN; (2) minimum precipitation (cm) required to stop field operations, ROUTA; and (3) minimum time after rain before field operations can begin (days), ROUTT. Two sets of the parameters are read in DRAINMOD; one set represents values required for tillage operations (seedbed preparation, etc.) in the spring and the other set is for harvesting conditions in the fall. Spring conditions are called working period 1 and the trafficability inputs are designated as AMIN1, ROUTA1, and ROUTT1, while AMIN2, etc., are used for working period 2 in the fall. Times that the working day begins and ends are also inputs to the model in order to determine fractional working days as discussed in Chapter 3.

Trafficability parameters were approximated for several research sites in North Carolina by field observations during the spring period of seedbed preparation. Field conditions were monitored by experienced technicians in coordination with farmers and research station personnel. When the soil reached a condition that was just dry enough to plow and prepare seedbed, samples were taken at 10 and 20 cm depths and the water contents determined. Drainage volumes corresponding to the measured water contents were estimated from the soil water characteristics and drainage-volume water table depth relationship. For example, the volumetric water content for Goldsboro s.l. was 0.23 at the point that it was just dry enough to plow. This corresponds to a pressure head of -75 cm (Figure 5-1). A suction head of at least 75 cm at the surface would result from a 75 cm water table depth. This would give a water free pore volume (air volume) of 3.2 cm (Figure 5-4). Thus, AMIN1 = 3.2 cm for Goldsboro s.l. soil. Trafficability parameters for the seedbed preparation period are given in Table 5-6 for eight North Carolina soils.

Table 5-6. Trafficability parameters for plowing and seedbed preparation for some North Carolina soils.

Soil	Water content in plow layer* (cm^3/cm^3)	Corresponding pressure head in plow layer (cm)	AMIN (cm)	ROUTA (cm)	ROUTT (days)
Cape Fear l.	0.395	-65	3.3	1.2	2
Lumbee s.l.	0.265	-70	2.8	1.5	1
Coxville-Ogeechee l.	0.39	-80	3.4	1.2	2
Goldsboro s.l.	0.23	-80	3.2	1.5	1
Rains s.l.	0.25	-70	3.9	1.2	2
Wagram l.s.	0.15	-65	3.5	1.5	1
Bladen s.l.	0.40	-60	3.0	1.0	2
Portsmouth s.l.	0.32	-75	3.0	1.2	2

* Water content in plow layer when soil is just dry enough for plowing and seedbed preparation.

The water contents given in Table 5-6 corresponded to pressure heads between -60 and -80 cm of water. For a 10 cm depth at the point of measurement, these pressure heads would result for water table depths between 70 and 90 cm from the surface. Grossman (1979)* measured the minimum water tension at which tillage operations could be initiated in the spring. He measured the tension at a 15 cm depth in a Sharpsburg (typic Argiudall, fine) in southeastern Nebraska and a Mexico (Udollic Ochraqualf, fine) in central Missouri. The tensions ranged from 40 to 170 cm with most below 100 cm of water. These results are consistent with those given in Table 5-6. Similar measurements are needed on many more soils throughout the humid region to provide a data base for predicting trafficability. In the absence of specific data, it is suggested that suitable conditions for seedbed preparation may be assumed when the soil tension at the 15 cm depth is at least 60 cm. This will occur for a profile drained to equilibrium to a water table 75 cm deep. Then, AMIN1 can be obtained directly from the drainage volume - water table depth relationship.

The other trafficability parameters, ROUTA and ROUTT, can be selected by a technician or farmer who is familiar with the soil being analyzed. Assuming very dry initial conditions, ROUTA is the minimum amount of rain that would prohibit field operations because of wet or slick soil conditions. The air volume in the profile may be greater than AMIN at that time, but field operations would be limited because the surface soil is too wet. Then, ROUTT is the time (in days) required for the soil water at the surface to redistribute in the profile so that field operations can resume.

Crop Input Data

Crop input data include the relationship between effective rooting depth and time and the dates to initiate and stop SEW and Dry Day computation. The main input is the effective rooting depth-time relationship which was discussed in some detail in Chapter 2 (pages 2-47 through 2-52). Data of the type given in Figures 2-22 and 2-23 will not be available for most crops so the relationships will have to be approximated from other data. Depths of roots that extract soil water at the peak stage of growth are given for several crops and locations in Table 1-4 of the SCS-NEH, Section 15, Chapter 1. The depth of plant feeder roots for various crops is also given in the Sprinkler Irrigation Handbook published by Rain Bird Manufacturing Corporation and listed in Table 5-7.

Because most of the water will be extracted near the surface, as discussed in Chapter 2, the maximum effective root depth used in DRAINMOD should be approximated as 50 to 60 percent of the depth given in Table 5-7 or in Table 1-4 of the SCS-NEH. The maximum rooting depth depends on factors such as physical and chemical barriers to root growth, as well as soil water conditions. Values given in the tables may require modification because of the influence of such factors.

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* Unpublished data obtained by personal communication from R. B. Grossman, Research Soil Scientist, SCS National Soil Survey Laboratory, Lincoln, Nebraska.

Table 5-7. Plant feeder root depths* (from Sprinkler Irrigation Handbook, Rain Bird Manufacturing Corporation, Glendora, California).

Crop	Root Depth	Crop	Root Depth
Alfalfa	3 to 6 feet	Nuts	3 to 6 feet
Beans	2 feet	Onions	1 1/2 feet
Beets	2 to 3 feet	Orchard	3 to 5 feet
Berries (Cane)	3 feet	Pasture (Grasses only)	1 1/2 feet
Cabbage	1 1/2 to 2 feet	Pasture (with Clover)	2 feet
Carrots	1 1/2 to 2 feet	Peanuts	1 1/2 feet
Corn	2 1/2 feet	Peas	2 1/2 feet
Cotton	4 feet	Potatoes	2 feet
Cucumbers	1 1/2 to 2 feet	Soy Beans	2 feet
Grain	2 to 2 1/2 feet	Strawberries	1 to 1 1/2 feet
Grain, Sorghum	2 1/2 feet	Sweet Potatoes	3 feet
Grapes	3 to 6 feet	Tobacco	2 1/2 feet
Lettuce	1 foot	Tomatoes	1 to 2 feet
Melons	2 1/2 to 3 feet		

* Majority of feeder roots.

The change in the effective root depth with time can be estimated by Crop Growth Stage Coefficients (K_c) given in the SCS Technical Release No. 21, "Irrigation Water Requirements." The K_c was introduced to account for the growth stage in predicting ET by the Blaney-Criddle method. K_c values are plotted as a function of percent of growing season for several crops in the SCS-TR 21. Because K_c indicates the rate that the crop can use water, it should also be proportional to the stage of development of the plant and root growth. Use of the K_c to estimate the change in effective root depth with time is demonstrated in the following example. Note that the K_c was not derived for this purpose. Further, the procedure has not been verified experimentally and should be viewed only as a method of obtaining a rough estimate of the root depth distribution with time.

Example. Irish potatoes are to be planted on March 10 and harvested June 28 in eastern North Carolina. Estimate the root depth-time relationship during that period. From Table 5-7, the maximum depth of feeder roots for potatoes is 2 feet. Taking an effective depth of 50 percent of maximum gives 0.5 x 2 ft = 1 ft = 30 cm. We can estimate the root depth at any time during the growing season by assuming that it is linearly related to K_c as, $R_d = aK_c + b$ where R_d is root depth and a and b are coefficients. K_c values for Irish potatoes are given as curve No. 18 in the SCS-TR 21. Assuming that water may be removed from the surface 3 cm by evaporation when the soil is fallow implies an effective root depth of 3 cm at the beginning of the growing season when $K_c = 0.33$ (curve No. 18). The maximum effective root depth of 30 cm would correspond to a maximum K_c of 1.37. Substituting these values in the above equation and solving for a and b gives $R_d = 26\ K_c - 5.62$. After 20 percent of the growing season (growing season length = 110 days, so 20 percent = day 22), $K_c = 0.51$. Then, $R_d = 7.6$ cm 22 days after planting. Repeating this procedure for several times during the growing season gives the following values for root depth versus time:

Table 5-8. Effective root depth versus days after planting for potatoes, as estimated from published crop growth stage coefficients.

Percent of Growing Season	Days after Planting	K_c	Root Depth
0 percent	0	0.33	3 cm
10	11	0.40	4.8
20	22	0.51	7.6
30	33	0.72	13.1
40	44	0.96	19.3
50	55	1.18	25.1
60	66	1.31	28.4
70	77	1.37	30.0
80	88	1.36	30.0
90	99	1.30	28.1
100	110	1.22	26.1

Drainage System Parameters

Surface Drainage

Most of the input data for drainage system parameters such as drain spacing and depth are easy to define. The depressional storage parameter used to quantify surface drainage is somewhat more difficult. Depressional storage has been measured under various field conditions in eastern North Carolina (Gayle and Skaggs, 1978). The following subjective guidelines are offered for estimating surface storage:

Table 5-9. General guidelines for estimating field surface depressional storage.

Field Surface Drainage Quality	Field Description	Depressional Storage
Good	Surface relatively smooth and on grade so that water does not remain ponded in field after heavy rainfall. No potholes - adequate outlets.	0.1 - 0.5 cm
Fair	Some shallow depressions, water remains in a few shallow pools after heavy rainfall. Micro-storage caused by disking or cultivation may cause surface drainage to be only fair, even when field surface is on grade.	0.6 - 1.5 cm

Table 5-9. General guidelines for estimating field surface depressional storage. (continued)

Field Surface Drainage Quality	Field Description	Depressional Storage
Poor	Many depressions or potholes of varying depth. Widespread ponding of water after heavy rainfall <u>or</u> inadequate surface outlets, such as berms around field ditches <u>or</u> very rough surface, such as directly after plowing.	1.6 - 2.5 cm or greater

Effective Drain Radius

The effective drain radius, r_e, is used in Equation 2-13 to calculate the equivalent depth from the drain tube to the impermeable layer. The effective radius is considerably smaller than the actual drain tube radius to account for the resistance to inflow due to a finite number of openings in an otherwise impervious wall, as discussed in Chapter 2. The determination of r_e is based on research by Bravo and Schwab (1977). They used an electric analog to determine the effect of openings on radial flow to corrugated drain tubes. Envelopes increase the effective size of the drain by allowing free movement of water to the drain openings. When gravel envelopes are placed around the drain in a cylindrical shape, the effective radius may be taken as the outside radius of the envelope. For a more commonly used square envelope cross-section of length 2a on each side, r_e can be approximated from the results of Kirkham and Selin (1973) as r_e = 1.77a. Fabric wrap envelopes tend to prevent drain tube corrugations from filling with soil and therefore increase the effective radius to some degree. However, the effective radius with a fabric wrap material would still be less than the actual tube radius. The effective radii of some conventional drain tubes are given in Table 5-10. These values were approximated from Bravo and Schwabs (1977) work and from related work by Skaggs (1978a). Research is continuing in this subject and the values given in Table 5-10 are subject to revision.

Table 5-10. Effective radii for various size drain tubes.

Drain	Diameter (O.D.)	r_e
3-in corrugated*	89 mm	3.5 mm
4-in corrugated*	114	5.1
5-in corrugated*	140	10.3
6-in corrugated*	165	14.7
4-in clay - 1/16 in crack between joints	127	3.0
4-in clay - 1/8 in crack between joints	127	4.8
Drain tube surrounded by gravel envelope with square cross-section of length 2a on each side	2a	1.177a

* Based on 5 rows of slots with total opening amount to 1.5 to 2 percent of the wall area.