A Study of Infiltration Trenches in Unsaturated Soil

by

Joonghoon Kim

Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Master of Science

in

Civil Engineering

APPROVED:

Chin Y. Kuo, Chairman

James M. Wiggert

G.V. Loganathan

December 1986

Blacksburg, Virginia

A Study of Infiltration Trenches in Unsaturated Soil

by

Joonghoon Kim

Chin Y. Kuo, Chairman

Civil Engineering

(ABSTRACT)

Interest in infiltration structures to control peak runoff in urban areas has increased in recent years. The work reported here is a study of infiltration trenches in unsaturated soil. The infiltration rates and the water content distributions in soil calculated by Fok's model and a finite difference model are compared for both the Ida silt loam soil and the Webster clay loam soil considering the capillary zone effect due to groundwater table. A computer program for hydrologic routing in infiltration trenches has been developed with the infiltration rate calculated based on a 3-dimensional cumulative infiltration equation. The 3-D cumulative infiltration equation developed in this study is recommended for the analysis and practical design of infiltration trenches, since it is easy to use and inexpensive in computation. An infiltration trench with overflow has been examined allowing the overflow not to exceed an allowable discharge to downstream. It has been found that the surface infiltration due to overland flow does not significantly alter the infiltration rate from a trench. It has also been found that a long narrow trench is more effective for water to infiltrate into soil than a short wide trench for the same trench area(length × width). The hydraulic conductivity of a soil is an important factor in the design of an infiltration trench, whereas the porosity and the effective capillary potential have minor effects.

Acknowledgements

I wish to express my sincerest appreciation to my committee chairman, Dr. Chin Y. Kuo, for his valuable advice and guidance throughout this study. I would also like to thank Dr. James M. Wiggert and Dr. G.V. Loganathan for serving on my committee and for their assistance.

Special thanks are due to my wife, Jeongnam, whose patience and love have been major source of motivation to me. Many thanks to my parents in Korea for their continuing love and guidance.

Thanks are also due to my fellow graduate students and friends at Virginia Tech.

Table of Contents

List of Illustrations

List of Tables

List of Variables

a --- drainage area

A --- gross cross-sectional area through which flow occurs

A_s --- saturated zone of depth y_s

A_t --- area of trench bottom

b --- sectional length of trench

C --- runoff coefficient

d --- depth of trench

D --- diffusivity of soil

f_p --- infiltration capacity of soil

F --- cumulative infiltration of rain from soil surface

h --- head loss in transmission zone, $h = h_o + h_c - h_w$

h_o --- water depth on soil surface

h_c --- capillary potential head at wetting front

h_w --- pressure potential loss in wetting zone

h_e --- effective capillary potential, $h_e = h_c - h_w$

H = water depth in trench

i --- rainfall intensity

I --- cumulative infiltration from trench

I_i --- infiltration rate

I_n --- flow rate into trench

K --- soil hydraulic conductivity in transmission zone

K_x --- K in x-direction

K_y --- K in y-direction

K_z --- K in z-direction

n --- porosity of soil

ns --- incremental volumetric moisture content

O_{ut} --- flow rate out of trench (through infiltration)

q --- runoff at any time

Q --- vertical infiltration rate

Q_{in} --- inflow

Q_{out} --- outflow

Q_p --- peak discharge

Q_x --- horizontal flow rate

r --- factor due to air entrapment in the transmission zone

s --- net increment of the degree of saturation, $s = s_2 - s_1$

s_1 --- degree of saturation before wetting

s_2 --- degree of saturation after wetting

S --- volume of water in storage at any time

t --- time

T --- time for the wetting front to meet the surface of capillary fringe

T_c --- time of concentration

T_d --- rainfall duration

T_p --- time of incipient runoff

w --- width of trench

x --- horizontal advance of wetting front y --- vertical advance of wetting front

y_s --- mean depth of wetting front when the surface is saturated

Δt --- time increment

Δx --- horizontal length of a grid in finite difference formulation

Δy --- vertical length of a grid in finite difference formulation

θ --- water content in soil

θ_s --- saturated water content

θ_i --- initial water content

$\Delta\theta$ --- water content deficiency, $\Delta\theta = \theta_s - \theta_i$

$$\gamma = \frac{\Delta t}{(\Delta x)^2} = \frac{\Delta t}{(\Delta y)^2}$$

$$\beta = \frac{\Delta t}{2\Delta y}$$

Chapter 1 Introduction

It has been recognized that urbanization is responsible for the increase in both peak flow rate and total volume of surface runoff because of the decrease in infiltration as compared to predeveloped conditions. In many states, the primary goal of stormwater management plans is to maintain after development, as nearly as possible, the predevelopment runoff characteristics.

Partial watershed hydrology means that storm runoff originates from a portion of the watershed and that a major part of the rainfall is lost due to evaporation, evapotranspiration, temporary surface storage and infiltration. In general, the amount of runoff, location and extent of the runoff source area are related to rainfall, soil properties, watershed characteristics, and land uses and practices. The partial watershed hydrologic phenomenon occurs in agricultural land, as well as in urban areas. An understanding of the partial watershed hydrology in urban areas will assist planners and engineers in their efforts to control urban runoff volume and nonpoint source pollution, and employ best management practices.

This study will address the phenomenon in urban areas. Peak flow and runoff volume will increase as the degree of urbanization increases. To control excessive runoff due to increases in impervious area of a watershed, detention basins and infiltration facilities are commonly employed. These facilities reduce the runoff peak to the predevelopment level for a given storm frequency.

These control structures, known as urban best management practices (BMP's), have been proven to be effective in runoff and nonpoint source pollution control. It is the intent of this study to provide information on the flow attenuation of infiltration trenches, as related to urban stormwater management and urban partial watershed hydrology.

Detention, retention, and infiltration facilities include

1. Detention / Retention Basin
    a. Dry pond
    b. Wet pond
    c. Extended wet pond
2. Infiltration Structures
    a. Infiltration trench
    b. Infiltration basin
    c. Dry well
    d. Porous asphalt pavement
    e. Vegetated swale

Impacts of BMP installation on urban partial watershed hydrology include, but are not limited to,

1. reduction in peak flow due to a storm
2. reduction or elimination of surface runoff volume
3. attenuation of peak runoff
4. increase in local soil moisture and groundwater table due to infiltration and recharge
5. low flow augmentation or feeding flow into a natural stream after the storm
6. trapping of pollutants in the facility itself
7. contamination of unsaturated and saturated subsurface zones due to percolation of pollutant

Studies on hydrologic and water quality aspects of the detention / retention basin have been carried out extensively and the results have been published widely in numerous technical journals and conference proceedings. In particular, the ASCE and the Engineering Foundation have sponsored a special conference on stormwater detention facilities(1). Vast amounts of literature are available. Unfortunately, the performance of infiltration structures has not been studied in enough detail to provide information about the design and planning of this type of BMP and to understand how the facilities alter hydrologic processes and water quality.

Infiltration structures have been employed in many parts of the country. A few representative cases are cited here. Higgs(16) has designed percolation trenches to handle surface runoff from parking lots in Northern Virginia. A dry well has been designed and constructed to serve as a rain and snow melt water catchbasin for a flat building roof and parking area in Canada(2). Infiltration basins are used to hold urban storm runoff in Florida and California(15). Porous pavements are used to reduce urban runoff in Texas(5), Virginia, and Maryland. The design methods used are generally following rules-of-thumb criteria. Design Specifications and procedures are available(4, 7, 20, 24, 29, 30, 33). Most of the design manuals deal with rational approaches and empirical formulas. Simple conservation of mass principle is used in the calculation of the volume required for the infiltration structure. No rigorous analysis has been used to derive the design methodology. This type of best management practice has only been employed very recently and, in some cases, is regarded as simply an experimental means of controlling stormwater. No detail or fundamental analysis of the infiltration trenches is available in the literature.

A simple analytical model for infiltration basins was given by Li(19). This model considers the vertical infiltration only neglecting the horizontal advance of the wetting front. Two-dimensional infiltration equations for furrow irrigation expressed in explicit forms have been developed by Fok(8-11). Vertical and horizontal advances of wetting front are calculated based upon Darcy's law and the principle of continuity. The cumulative infiltration volume in his model is calculated by multiplying the porosity of soil, the net increment in the degree of saturation, and the wetted volume.

The unsteady state two-dimensional water flow equation for unsaturated soils was solved numerically with a finite difference method(FDM) using an alternating-direction implicit method by Selim and Kirkham(28). However, the groundwater table was considered as a water source in their model such that the soil above the groundwater table becomes wetted by diffusion process before it is wetted by infiltrated water from the trench. Capillary fringe zone above groundwater table was not considered in both Fok's model and finite difference model.

The primary objective of this study is to analyze the characteristics of infiltration trenches in unsaturated soil, so that design engineers may refer to the information given in this study. In an effort to meet this objective, the following sub-objectives have been set.

1. Development of a 2-D infiltration model to include capillary zone effect due to groundwater table based upon Fok's 2-D infiltration model.

2. Development of a computer program for a 2-D finite difference model.

3. Comparison of the two infiltration models developed above.

4. Extension of Fok's 2-D model to 3-D case.

5. Development of a computer program for hydrologic routing in an infiltration trench so that designers may determine the trench size based on a given runoff hydrograph and the soil properties.

6. Examination of an infiltration trench over which surcharge occurs.

7. Definition and calculation of detention time.

8. Discussion on the significance of trench shape.

9. Discussion on the effects of soil properties on the sizing of an infiltration trench installed in unsaturated soil.

Chapter 2 Model Developments

2-1. Fok's 2-D Infiltration Equations

Introduction:

The basic assumptions made in his study are that the soil is homogeneous and unsaturated with uniform initial moisture distribution, the soil structure does not change after wetting, the loci of the wetting front are semi-elliptical, and their vertical and horizontal flow components can be described by one-dimensional infiltration equations in their prospective direction. Fig.1 shows the assumed loci of the wetting front. The x represents the horizontal component of wetting from a point source to the horizontal wetting front, and the y represents the vertically downward component of wetting from the soil surface to the wetting front.

2-1-1. Vertical Infiltration

Hansen(14), Fok(8), and Bouwer(3) assumed the soil hydraulic conductivity in the transmission zone as constant, and expressed the Darcy's law in the vertical infiltration as

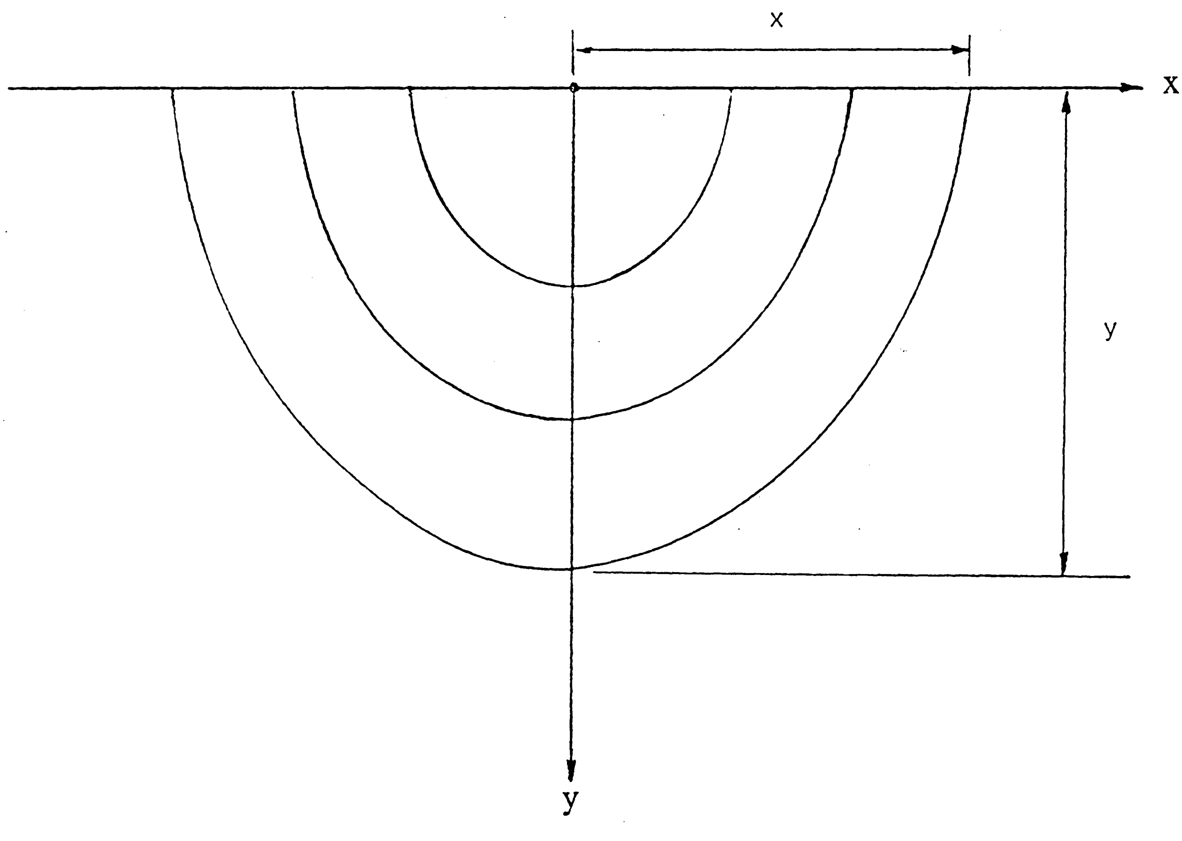


Figure 1. Assumed loci of wetting front due to a point source

$$Q = KA\frac{h + y}{y} \qquad (2-1)$$

Equating the above equation and the continuity equation

$$Q = nsA\frac{dy}{dt} \qquad (2-2)$$

and integration of the resulting equation yields an expression for the downward water movement.

$$\frac{y}{h} - \ln\left(1 + \frac{y}{h}\right) = \frac{Kt}{nsh} \qquad (2-3)$$

in which

Q = flow rate $[L^3T^{-1}]$

A = gross cross-sectional area through which flow occurs $[L^2]$

K = soil hydraulic conductivity in the transmission zone $[LT^{-1}]$

h = head loss in vertical direction in the transmission zone $[L]$

$h = h_o + h_c - h_w$

h_o = water depth on soil surface

h_c = capillary head at wetting front

h_w = pressure head loss in wetting zone

h_e = effective capillary potential, $h_e = h_c - h_w$

n = porosity of the soil [−]

s = net increment of the degree of saturation $[-]$, $s = s_2 - s_1$

s_2 = degree of saturation after wetting

s_1 = degree of saturation before wetting

Fig.2 shows the definition sketches for the vertical infiltration.

According to the principle of continuity,

$$Q = I_i A \qquad (2-4)$$

in which I_i = infiltration rate $[LT^{-1}]$.

Equating Eq. 2-4 and Eq. 2-2 and solving for I yields

$$I_i = ns\frac{dy}{dt} \qquad (2-5)$$

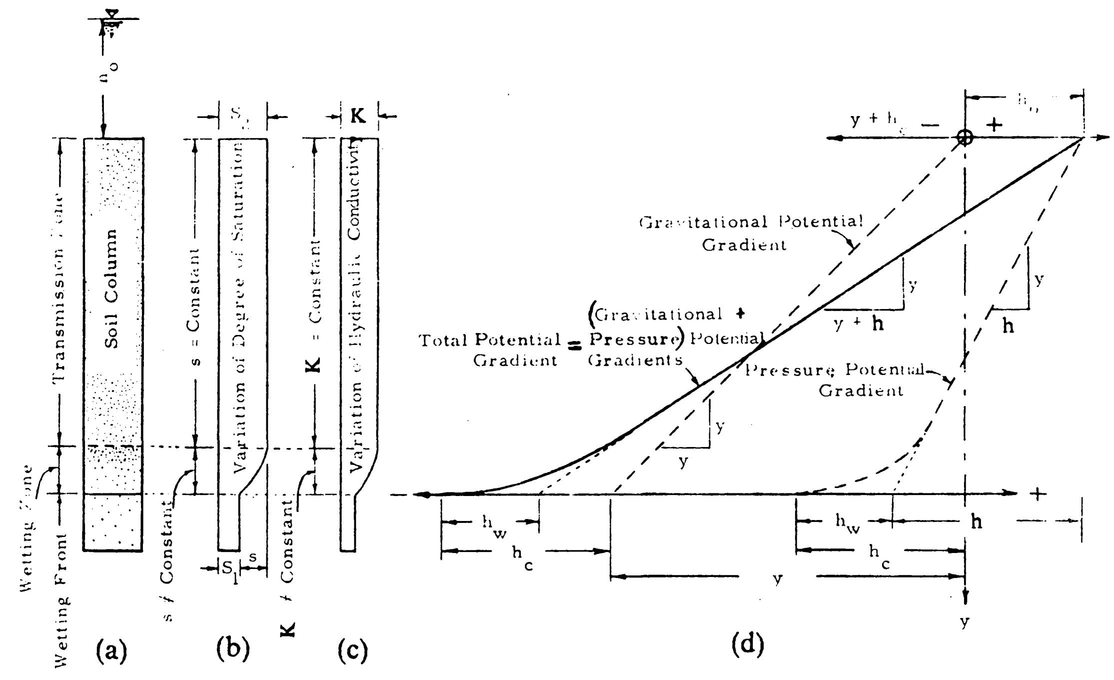
which, when integrated, yields

$$I = nsy \qquad (2-6)$$

in which I = cumulative infiltration $[L]$.

2-1-2. Graphical Approximation of Vertical Infiltration Equation

If y is an explicit function of infiltration time, t, the accumulative infiltration up to a certain time, t, could be readily known using Eq.(2-6). However, y is an implicit function of the infiltration time, t, as expressed in Eq.(2-3). An attempt was made by Fok to evaluate y as an explicit function of t by a graphical approximation.



(a) soil column with three distinct zones

(b) variation of degree of saturation

(c) variation of hydraulic conductivity

(d) relationship between potential gradients and depth of wetting

Figure 2. Definition sketches for vertical infiltration (after Ref.14)

The relationship between the two dimensionless parameters y/h and Kt/nsh of Eq.(2-3) in a log-log plot is curvilinear as shown in Fig.3. However, this curvilinear relationship can be represented approximately by several piece-wise straight lines. Four consecutive straight lines were proposed to replace the curvilinear relationship between y/h = 0.01 and y/h = 30.

Four equations showing y/h as a power function of Kt/nsh were obtained by Fok(9) from an evaluation of the four straight lines in Fig.2 for different ranges of y/h:

For $0.01 \leq \frac{y}{h} < 0.1$,

$$\frac{y}{h} = 1.45\left(\frac{Kt}{nsh}\right)^{0.5} \qquad (2-7)$$

for $0.1 \leq \frac{y}{h} < 1$,

$$\frac{y}{h} = 1.82\left(\frac{Kt}{nsh}\right)^{0.55} \qquad (2-8)$$

for $1 \leq \frac{y}{h} < 5$,

$$\frac{y}{h} = 2.19\left(\frac{Kt}{nsh}\right)^{0.68} \qquad (2-9)$$

for $5 \leq \frac{y}{h} < 30$,

$$\frac{y}{h} = 1.83\left(\frac{Kt}{nsh}\right)^{0.85} \qquad (2-10)$$

According to the ranges of y/h defined previously, the typical times, $t_1,\ t_2,\ t_3,$ *and* t_4 for the separation of different infiltration periods can be obtained by substituting the values of y/h into the corresponding Eq. (2-7), (2-8), (2-9), and (2-10). These typical times are:

For y/h = 0.1,

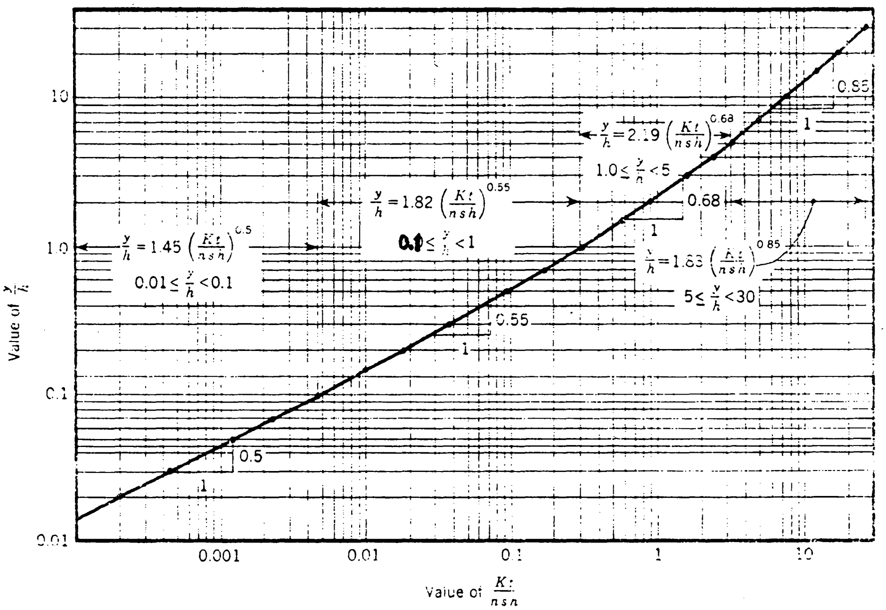


Figure 3. Relationship between y/h and Kt/nsh

$$t_1 = 0.00476\frac{nsh}{K} \qquad (2-11)$$

for y/h = 1,

$$t_2 = 0.316\frac{nsh}{K} \qquad (2-12)$$

for y/h = 5,

$$t_3 = 3.26\frac{nsh}{K} \qquad (2-13)$$

for y/h = 30,

$$t_4 = 26.86\frac{nsh}{K} \qquad (2-14)$$

It should be noted that the higher the initial soil moisture, s_1, the smaller the net increment of soil moisture, s will be. Hence, the values of t_1, t_2, t_3 *and* t_4 will also be smaller. It is also true for values of soil porosity, n, and the head loss, h. The smaller the n and h values, the smaller the t's are.

Power functions which relate the depth of wetting front, y, to time, t, can be obtained by solving y in Eqs. (2-7), (2-8), (2-9), and (2-10) for their corresponding infiltration periods:

For $t < t_1$,

$$y = 1.45\left(\frac{Kht}{ns}\right)^{0.5} \qquad (2-15)$$

for $t_1 \le t < t_2$,

$$y = 1.82\left(\frac{Kh^{0.818}t}{ns}\right)^{0.55} \qquad (2-16)$$

for $t_2 \leq t < t_3,$

$$y = 2.19\left(\frac{Kh^{0.47}t}{ns}\right)^{0.68} \qquad (2-17)$$

for $t_3 \leq t < t_4,$

$$y = 1.83\left(\frac{Kh^{0.177}t}{ns}\right)^{0.85} \qquad (2-18)$$

2-1-3. Horizontal Infiltration

Infiltration in the horizontal direction is simpler than the case of vertical infiltration because the horizontal component of gravity is zero, and water is drawn into the soil by matric suction forces only.

Darcy's law states

$$Q_x = KA\frac{h_x}{x} \qquad (2-19)$$

The continuity equation is written as

$$Q_x = nsA\frac{dx}{dt} \qquad (2-20)$$

in which

Q_x = horizontal flow rate

K = soil hydraulic conductivity

A = cross-sectional area of flow

h_x = horizontal head loss in transmission zone

x = lateral advance of the wetting front

t = infiltration time

ns = incremental volumetric moisture

Combination of Eqs.(2-19) and (2-20) gives

$$KA\frac{h_x}{x} = nsA\frac{dx}{dt} \qquad (2-21)$$

Rearranging Eq.(2-21) yields

$$xdx = \frac{Kh_x}{ns}dt \qquad (2-22)$$

By integrating Eq.(2-22) and rearranging, one obtains

$$x = \left(\frac{2Kh_x}{ns}\right)^{0.5} t^{0.5} \qquad (2-23)$$

2-1-4. 2-D Infiltration Equation

Based on the assumed wetting pattern shown in Fig.4, the two-dimensional infiltration equation can be written as

$$I = \left[2dx + wy + (\frac{\pi}{2})xy\right]bns \qquad (2-24)$$

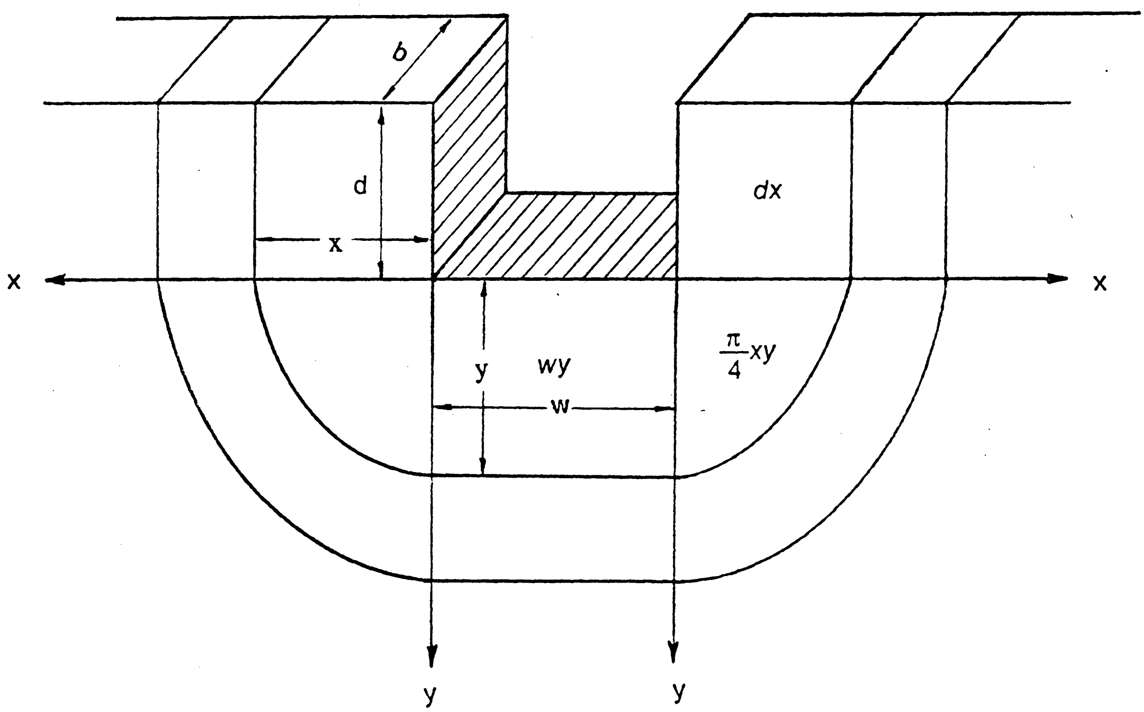


Figure 4. Wetting pattern of horizontal and vertical infiltration for a rectangular trench

in which I = cumulative infiltration; d = depth of trench; w = width of trench; b = sectional length of trench; n and s have been defined previously; the horizontal advance of wetting front x is given by Eq.(2-23) and the vertical advance of wetting front y is calculated by one of the Eqs. (2-15), (2-16), (2-17), and (2-18).

Fok's 2-D cumulative infiltration equation has been derived. The soil hydraulic conductivity used in Fok's model is assumed to be constant, whereas that used in the finite difference model of this study is a function of water content in the soil.

2-2. Finite Difference Formulation

2-2-1. Unsteady 2-D Water Flow Equation for Unsaturated Soils

To solve groundwater seepage problems where the flow is not rectilinear, it is desirable to have a general governing differential equation such as the Lapalace's equation. Laplace's equation is derived from Darcy's law and the equation of continuity.

Referring to Fig.5, the net change of water volume per unit time in the element due to flow in the x direction is

$$\begin{aligned}(inflow) - (outflow) &= v_x \Delta y \Delta z - \left(v_x + \frac{\partial v_x}{\partial x}\Delta x\right)\Delta y \Delta z \\ &= -\left(\frac{\partial v_x}{\partial x}\right)\Delta x \Delta y \Delta z\end{aligned} \qquad (2-25)$$

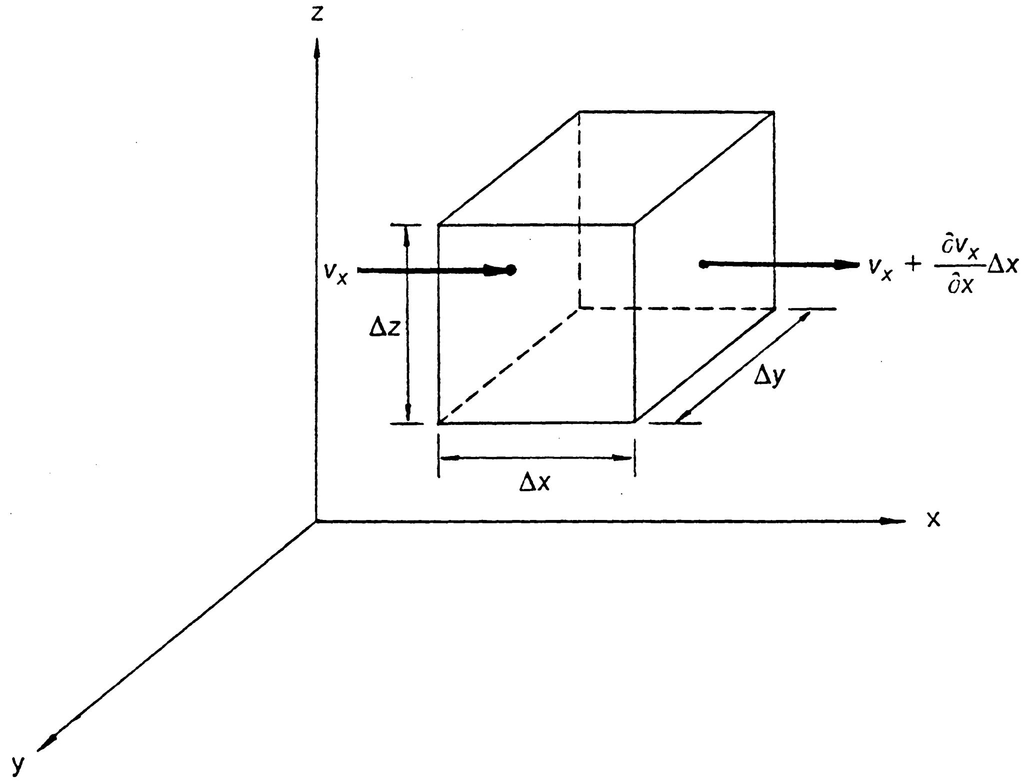


Figure 5. Infinitesimal element in which seepage occurs

Similarly, the net change of water volume per unit time in the y direction is $-(\partial v_y/\partial y)\Delta x\Delta y\Delta z$, and in the z direction is $-(\partial v_z/\partial z)\Delta x\Delta y\Delta z$, The rate $\Delta w/\Delta t$, for example, at which water volume is changed in the volume element is

$$\frac{\Delta w}{\Delta t} = -\left(\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}\right)\Delta x\Delta y\Delta z \qquad (2-26)$$

The rate of change of water volume in the element can be expressed in another way. Let $\theta(x, y, z, t)$ be the volume of water per unit volume of bulk soil at a point x, y, z, and at time t and let $\Delta\theta$ be an increase per unit volume in θ that occurs in time Δt in the neighborhood of the point (x, y, z). Then the volume of water in the element $\Delta x\Delta y\Delta z$ will be $\theta\Delta x\Delta y\Delta z$, and the rate of change of water volume $\Delta w/\Delta t$ will be, in the limit, as Δt approaches zero and $\Delta\theta/\Delta t$ approaches $\partial\theta/\partial t$, given by

$$\frac{\Delta w}{\Delta t} = \frac{\partial(\theta\Delta x\Delta y\Delta z)}{\partial t} = \frac{\partial\theta}{\partial t}(\Delta x\Delta y\Delta z) \qquad (2-27)$$

Equating Eqs. (2-26) and (2-27) yields

$$\frac{\partial\theta}{\partial t}(\Delta x\Delta y\Delta z) = -\left(\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}\right)\Delta x\Delta y\Delta z$$

or

$$\frac{\partial\theta}{\partial t} = -\left(\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}\right) \qquad (2-28)$$

which is called the equation of continuity.

Darcy's law, though originally conceived for saturated flow only, was extended by Richards(27) to unsaturated flow, with the provision that the hydraulic conductivity in an unsaturated soil is a variable. Therefore, it can be written as

$$v_x = -K_x\frac{\partial h}{\partial x}, \quad v_y = -K_y\frac{\partial h}{\partial y}, \quad v_z = -K_z\frac{\partial h}{\partial z} \qquad (2-29)$$

in which

$$h = h_t + z \qquad (2-30)$$

where h is the total hydraulic head, h_t is the tension head due to capillary effect, and z is the gravitational head. Substituting Eq. (2-29) into Eq. (2-28) gives

$$\frac{\partial\theta}{\partial t} = \left[\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)\right] \qquad (2-31)$$

If the soil can be assumed to be isotropic, then K_x, K_y, and K_z can be given by $K_x = K_y = K_z = K$. Eq. (2-31) can now be simplified to

$$\frac{\partial\theta}{\partial t} = \left[\frac{\partial}{\partial x}\left(K\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z}\right)\right] \qquad (2-32)$$

which is a basic form of the unsaturated flow equation where K is considered as a variable and therefore is not factored outside.

Substituting h given by Eq. (2-30) into Eq. (2-32) and performing the required differentiation yield

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left(K\frac{\partial h_t}{\partial x}\right) + \frac{\partial}{\partial y}\left(K\frac{\partial h_t}{\partial y}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial h_t}{\partial z}\right) + \frac{\partial K}{\partial z} \qquad (2-33)$$

Richards(27) proposed that h_t and K are single valued functions of the moisture content θ. h_t is a function of θ and θ is in turn a function of x, y, z, and time t. Therefore,

$$h_t = \text{fct}[\theta(x, y, z, t)]$$

where fct[$\theta(x, y, z, t)$] means some function of x, y, z, and t. Using the chain rule, the following relations can be written;

$$
\begin{aligned}
K\frac{\partial h_t}{\partial x} &= K\frac{\partial h_t}{\partial \theta}\frac{\partial \theta}{\partial x} \\
K\frac{\partial h_t}{\partial y} &= K\frac{\partial h_t}{\partial \theta}\frac{\partial \theta}{\partial y} \\
K\frac{\partial h_t}{\partial z} &= K\frac{\partial h_t}{\partial \theta}\frac{\partial \theta}{\partial z}
\end{aligned}
\qquad (2-34)
$$

A new term D called the diffusivity is defined as

$$
D = K\frac{dh_t}{d\theta} \qquad (2-35)
$$

where K and $dh_t/d\theta$ are both functions of θ . Substituting Eq. (2-35) into Eq. (2-34), and then into Eq.(2-33), it gives another form of the unsaturated flow equation, which is

$$
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial \theta}{\partial x}\right) + \frac{\partial}{\partial y}\left(D\frac{\partial \theta}{\partial y}\right) + \frac{\partial}{\partial z}\left(D\frac{\partial \theta}{\partial z}\right) + \frac{\partial K}{\partial z} \qquad (2-36)
$$

in which D is a function of moisture content, $D = D(\theta)$.

If two-dimensional(taking x as horizontal and y as vertical direction) water flow in unsaturated soils is considered, the governing differential equation is

$$
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta)\frac{\partial \theta}{\partial x}\right] + \frac{\partial}{\partial y}\left[D(\theta)\frac{\partial \theta}{\partial y}\right] - \frac{\partial K(\theta)}{\partial y} \qquad (2-37)
$$

which shall be used for the finite difference formulation.

2-2-2. Numerical Method

The finite difference method adopted in this study is the alternating-direction implicit (ADI) technique for parabolic partial differential equations such as Eq. (2-37). The ADI technique is described by Douglas(6) and Varga(31). The Eq. (2-37) is first approximated by two simultaneous systems of difference equations. The ADI technique calls for alternate solutions of the two systems of difference equations until the desired time is reached.

A discrete set of points in the (x, y, t) plane given by a grid with spacings Δx, Δy, and Δt is considered. Referring to Fig.6, grid or mesh points are denoted by (i, j, m) where $x = i\Delta x$, $y = j\Delta y$, $t = m\Delta t$ and i = 1, 2, 3, ... , I; j = 1, 2, 3, ... , J; m = 0, 1, 2, ... The value of the dependent variable θ at any point $(i\Delta x, j\Delta y, m\Delta t)$ in the flow region is denoted by $\theta^m_{i,j}$.

The two systems of finite difference equations for Eq. (2-37) are

$$\frac{\theta^{m+1}_{i,j} - \theta^m_{i,j}}{\Delta t} = \frac{D\left(\theta^{m+1/2}_{i+1/2,j}\right)\left[\theta^{m+1}_{i+1,j} - \theta^{m+1}_{i,j}\right] - D\left(\theta^{m+1/2}_{i-1/2,j}\right)\left[\theta^{m+1}_{i,j} - \theta^{m+1}_{i-1,j}\right]}{(\Delta x)^2} + \frac{D\left(\theta^{m+1/2}_{i,j+1/2}\right)\left[\theta^{m}_{i,j+1} - \theta^{m}_{i,j}\right] - D\left(\theta^{m+1/2}_{i,j-1/2}\right)\left[\theta^{m}_{i,j} - \theta^{m}_{i,j-1}\right]}{(\Delta y)^2} - \frac{K\left(\theta^{m+1/2}_{i,j+1}\right) - K\left(\theta^{m+1/2}_{i,j-1}\right)}{2\Delta y} \qquad (2-38)$$

and

$$\frac{\theta^{m+2}_{i,j} - \theta^{m+1}_{i,j}}{\Delta t} = \frac{D\left(\theta^{m+3/2}_{i+1/2,j}\right)\left[\theta^{m+1}_{i+1,j} - \theta^{m+1}_{i,j}\right] - D\left(\theta^{m+3/2}_{i-1/2,j}\right)\left[\theta^{m+1}_{i,j} - \theta^{m+1}_{i-1,j}\right]}{(\Delta x)^2} + \frac{D\left(\theta^{m+3/2}_{i,j+1/2}\right)\left[\theta^{m+2}_{i,j+1} - \theta^{m+2}_{i,j}\right] - D\left(\theta^{m+3/2}_{i,j-1/2}\right)\left[\theta^{m+2}_{i,j} - \theta^{m+2}_{i,j-1}\right]}{(\Delta y)^2} - \frac{K\left(\theta^{m+3/2}_{i,j+1}\right) - K\left(\theta^{m+3/2}_{i,j-1}\right)}{2\Delta y} \qquad (2-39)$$

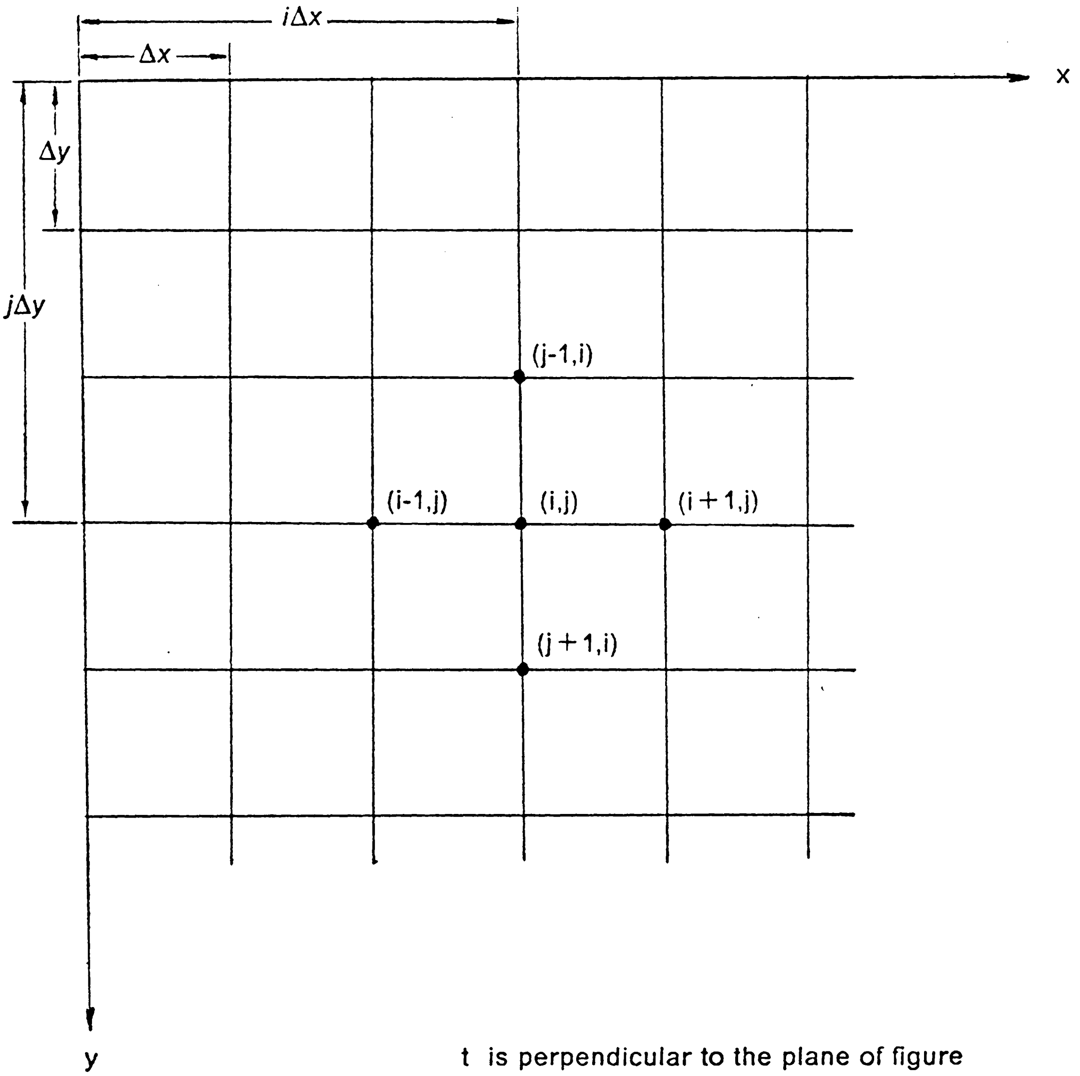


Figure 6. Grid points on (x,y) plane

Eq. (2-38) is at an incremental time step m + 1, and Eq. (2-39) is at an incremental time step m + 2. Eqs. (2-38) and (2-39) are non-linear since the values of

$$D\left(\theta^{m+1/2}_{i\pm 1/2,j\pm 1/2}\right) \quad \text{and} \quad K\left(\theta^{m+1/2}_{i,j\pm 1}\right)$$

are dependent on the values of

$$\theta^{m+1}_{i,j} \quad \text{and} \quad \theta^{m+1}_{i\pm 1,j\pm 1}$$

for which solutions are being sought. Remson(26) and Selim(28) found that D and K may be approximated satisfactorily using θ^m as

$$D\left(\theta^{m+1/2}_{i\pm 1/2,j\pm 1/2}\right) = D\left(\theta^{m}_{i\pm 1/2,j\pm 1/2}\right) \qquad (2-40)$$

$$K\left(\theta^{m+1/2}_{i,j\pm 1}\right) = K\left(\theta^{m}_{i,j\pm 1}\right) \qquad (2-41)$$

The use of θ^m simplifies the computations since the system of equations becomes linear.

Taking $\Delta x = \Delta y$ and using the abbreviations $\gamma = \frac{\Delta t}{(\Delta x)^2} = \frac{\Delta t}{(\Delta y)^2}$ and $\beta = \frac{\Delta t}{2\Delta y}$, Eq. (2-38) reduces to

$$- \left[\gamma D\left(\theta^{m}_{i-1/2,j}\right)\right] \theta^{m+1}_{i-1,j} - \left[\gamma D\left(\theta^{m}_{i+1/2,j}\right)\right] \theta^{m+1}_{i+1,j}$$

$$+ \left[1 + \gamma D\left(\theta^{m}_{i+1/2,j}\right) + \gamma D\left(\theta^{m}_{i-1/2,j}\right)\right] \theta^{m+1}_{i,j} = e^{m}_{i,j} \qquad (2-42)$$

where

$$\begin{aligned} e^{m}_{i,j} = {} & \left[\gamma D\left(\theta^{m}_{i,j-1/2}\right)\right] \theta^{m}_{i,j-1} \\ & + \left[1 - \gamma D\left(\theta^{m}_{i,j+1/2}\right) - \gamma D\left(\theta^{m}_{i,j-1/2}\right)\right] \theta^{m}_{i,j} \\ & + \left[\gamma D\left(\theta^{m}_{i,j+1/2}\right)\right] \theta^{m}_{i,j+1} - \beta\left[K\left(\theta^{m}_{i,j+1}\right) - K\left(\theta^{m}_{i,j-1}\right)\right] \end{aligned} \qquad (2-43)$$

In Eq. (2-42), $\theta^{m}_{i,j}$ and the coefficients $\theta^{m+1}_{i-1,j}$, $\theta^{m+1}_{i,j}$, and $\theta^{m+1}_{i+1,j}$ are known from time step n. Therefore, including the initial and boundary condition, Eq. (2-42) represents a linear system of equations which is convenient since the coefficient matrix is tridiagonal. A tridiagonal system of equations can be easily solved by Gaussian elimination(17). Eq. (2-39), at incremental time step m + 2, can be treated in the same manner.

Eq.(2-39) reduces to

$$
\begin{aligned}
& - \left[\gamma D\left(\theta^{m+1}_{i-1/2,j}\right)\right] \theta^{m+2}_{i-1,j} - \left[\gamma D\left(\theta^{m+1}_{i+1/2,j}\right)\right] \theta^{m+2}_{i+1,j} \\
& + \left[1 + \gamma D\left(\theta^{m+1}_{i+1/2,j}\right) + \gamma D\left(\theta^{m+1}_{i-1/2,j}\right)\right] \theta^{m+2}_{i,j} = e^{m+1}_{i,j}
\end{aligned}
\qquad (2-44)
$$

where

$$
\begin{aligned}
e^{m+1}_{i,j} = & \left[\gamma D\left(\theta^{m+1}_{i,j-1/2}\right)\right] \theta^{m+1}_{i,j-1} \\
& + \left[1 - \gamma D\left(\theta^{m+1}_{i,j+1/2}\right) - \gamma D\left(\theta^{m+1}_{i,j-1/2}\right)\right] \theta^{m+1}_{i,j} \\
& + \left[\gamma D\left(\theta^{m+1}_{i,j+1/2}\right)\right] \theta^{m+1}_{i,j+1} - \beta\left[K\left(\theta^{m+1}_{i,j+1}\right) - K\left(\theta^{m+1}_{i,j-1}\right)\right]
\end{aligned}
\qquad (2-45)
$$

2-3. Application of Capillary Zone to Both Models

2-3-1. Capillary Fringe

Capillary stress is one of the so-called active forces controlling the movement of water. It acts at every point where the three phases constituting a soil particle, water, and air meet one another.

The results of its effect is the development of a capillary fringe bordering the phreatic water body of free surface.

The capillary fringe extends from the water table up to the limit of capillary rise of water. Its thickness depends on the soil properties and on the homogeneity of the soil, mainly on the pore size distribution. The capillary rise ranges from practically nothing in coarse material, to as much as to 2 m to 3 m and more in fine materials(e.g., clay). Within the capillary fringe there is a gradual decrease in moisture content with height above the water table. Just above the water table, the pores are practically saturated. Moving higher, only the smaller connected pores contain water.

In this study, the Ida silt loam soil and the Webster clay loam soil were examined due to the data availability in the literature. According to Bouwer(3), the capillary rise of loam soil is approximately 2 m. Porosity of 0.47 and 0.49 were selected for the Ida silt loam soil and the Webster clay loam soil, respectively, according to Israelson and Hansen(18). The water content above the capillary fringe, called field capacity, was assumed to be 0.1. A finite difference program was coded to calculate the capillary fringe. The program listing is included in the Appendix. Table 1, Fig.7, and Fig.8 show the calculated capillary fringes which shall be applied to both the finite difference model and the Fok's model for the calculation of the infiltration volume from a trench.

2-3-2. Finite Difference Model

The geometry of the flow region is shown in Fig.9. The region is a homogeneous unsaturated soil having a trench to which water is supplied. For this example, the depth of trench is 50cm and the width is 100cm. There is a 200cm thick capillary fringe 30cm below the bottom of the trench.

Only one section of the region, section ODFG, is considered because of symmetry. A cartesian coordinates system is used with origin O at the upper left-hand corner of the flow region; x is hor-

Table 1. Capillary fringe obtained by finite difference model

Distance from Water Table	Water Content	
	Ida silt loam soil	Webster clay loam soil
200	0.1000	0.1000
180	0.3290	0.3317
160	0.3615	0.3717
140	0.3785	0.3934
120	0.3905	0.4088
100	0.4001	0.4212
80	0.4083	0.4320
60	0.4159	0.4421
40	0.4234	0.4522
20	0.4312	0.4630
0	0.4700	0.4900

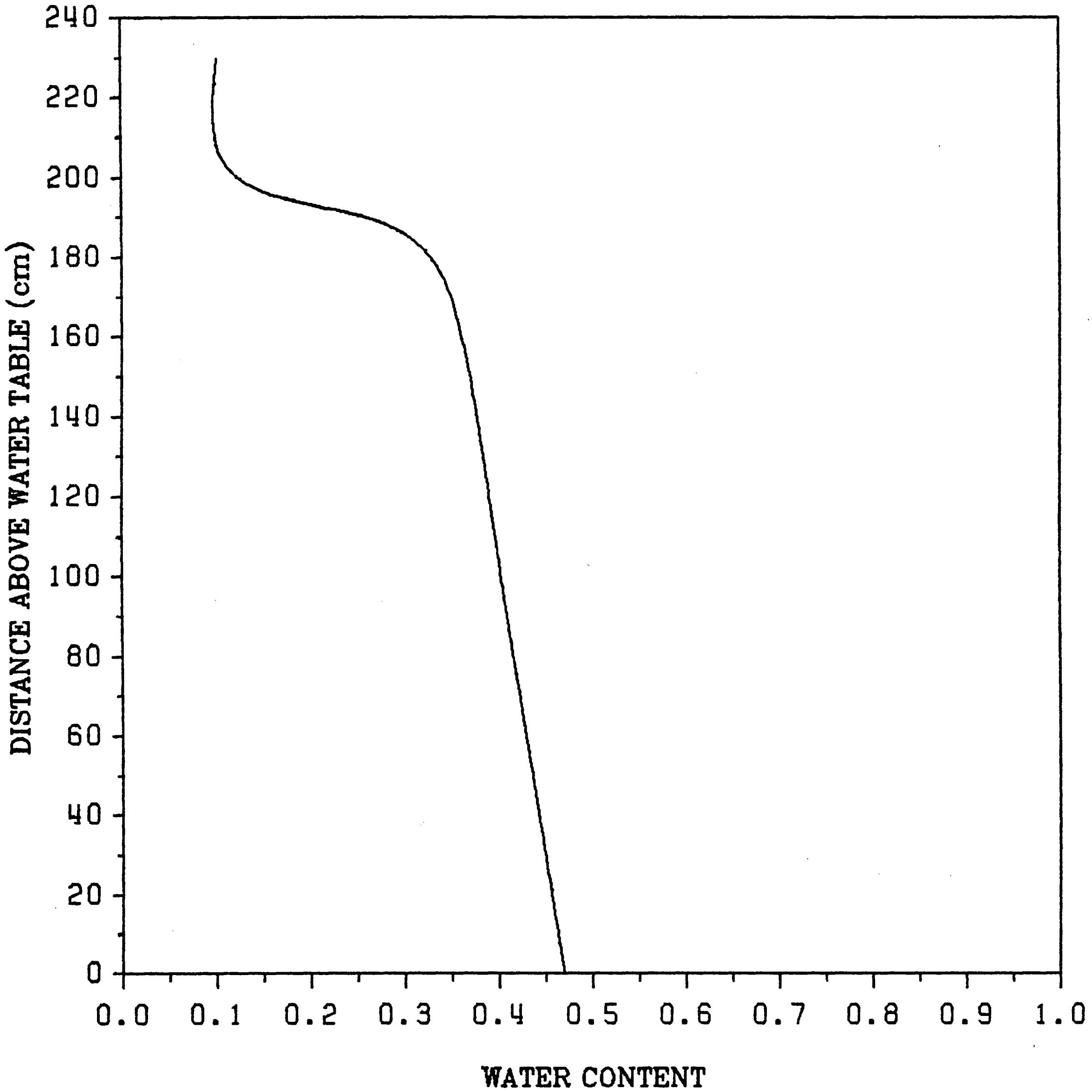


Figure 7. Capillary fringe obtained by F.D.M. for Ida silt loam soil

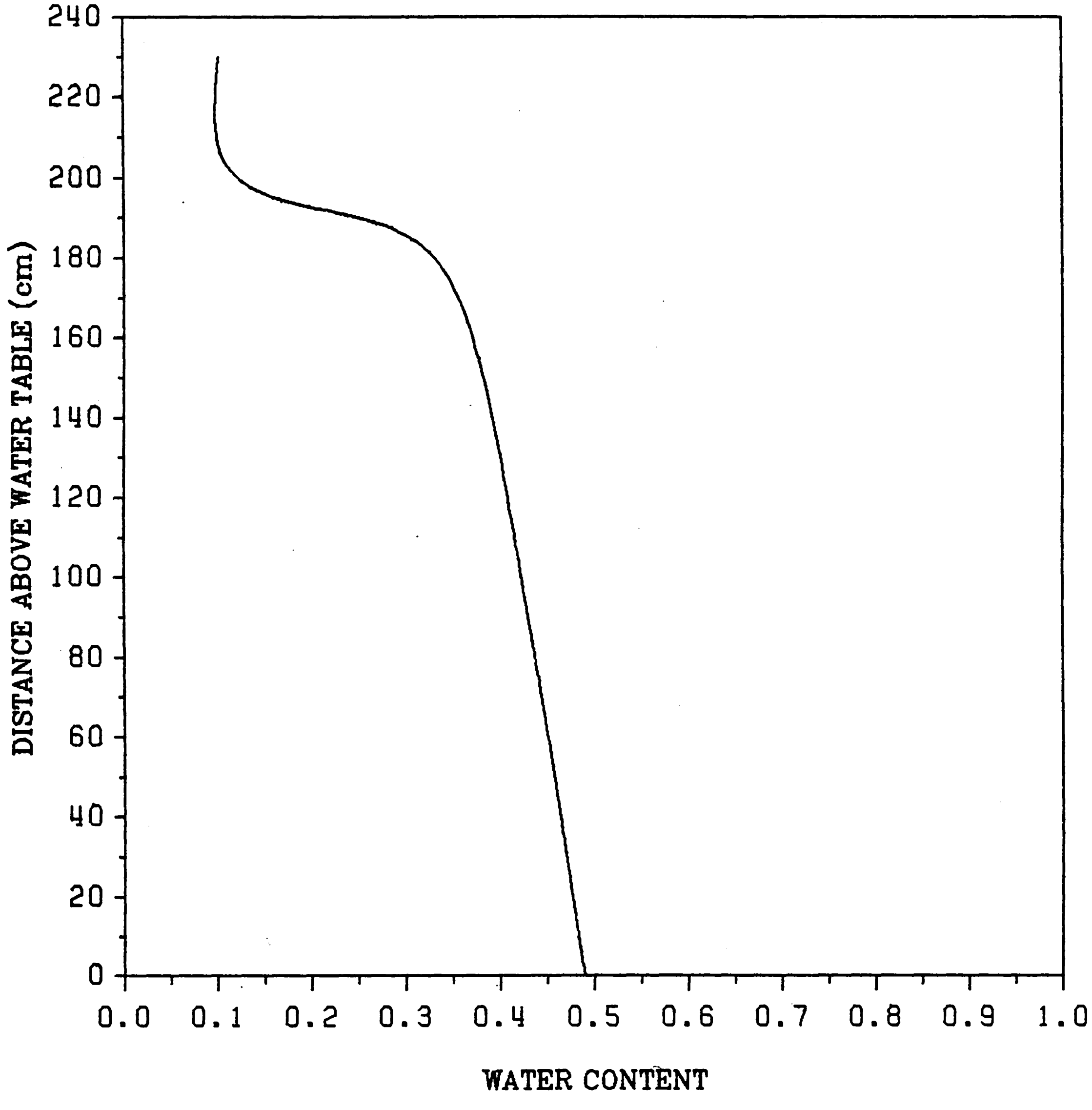


Figure 8. Capillary fringe obtained by F.D.M. for Webster clay loam soil

izontally to the right, y vertically downward, and z inward perpendicular to the plane of the figure. It is assumed that the flow region extends to infinity in the z-direction.

The initial water content θ_d for the region above the surface of capillary fringe HE is assumed to be constant throughout the flow medium. A value of 0.1 is specified for θ_i in this study for illustration purpose.

$$\theta = \theta_i \quad \text{at } t = 0$$

The initial distribution of water content in the capillary region HEFG is given in Table 1.

The boundary conditions are:

1. Along the soil surface OA a zero vertical flux boundary condition is maintained at all times:

$$- D(\theta)\frac{\partial\theta}{\partial z} + K(\theta) = 0, \qquad t \geq 0 \text{ along OA}$$

   It is assumed that a negligible amount of water is lost by evaporation from the surface OA. Also, there is no flux across the surface associated with infiltration due to overland flow. The conditions described here are common for the paved urban areas where the infiltration trenches are installed. A case which considers infiltration due to overland flow will be discussed later in this study.

2. Along the side wall AB and the bottom BC of the trench, there is a water source in the trench to maintain a constant water content θ_s, which is considered to be close to saturation at all times $t > 0$:

$$\theta = \theta_s, \quad t > 0 \text{ along AB and BC}$$

3. Along the vertical line CF, the rate of water flow in the horizontal direction, because of symmetry, is zero:

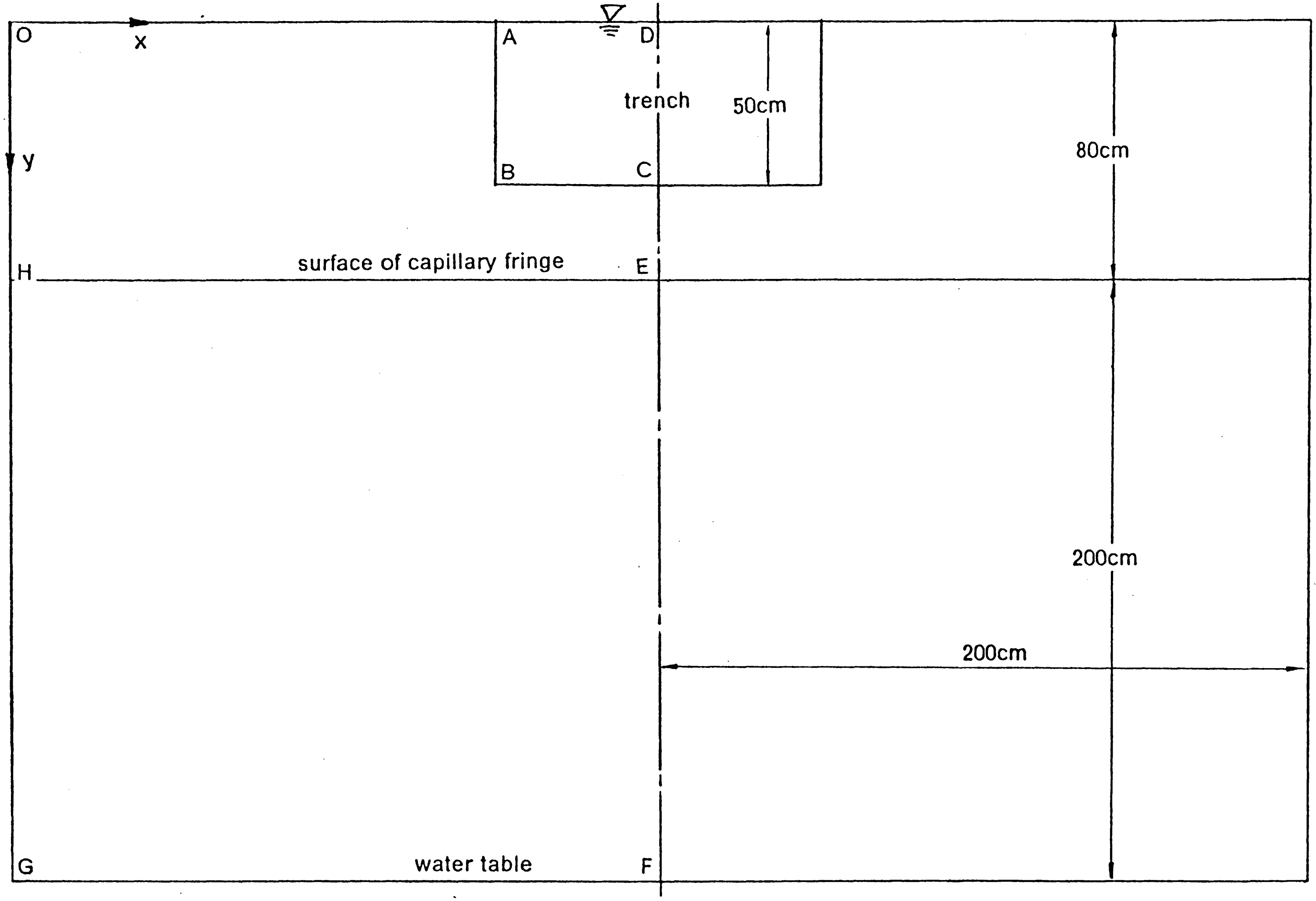


Figure 9. Schematic diagram of the flow region

$$\frac{\partial\theta}{\partial x} = 0, \quad t \geq 0 \quad \text{along CF}$$

4. Along the vertical line OG, it is assumed that zero flux in the horizontal direction is maintained to a certain time, t_{ct} :

$$\frac{\partial\theta}{\partial x} = 0, \quad 0 \leq t \leq t_{ct} \quad \text{along OG}$$

   This assumption will be further discussed later in this study.

5. Along GF, there is a groundwater table that maintains the water content at saturation:

$$\theta = \theta_s, \quad t \geq 0 \quad \text{along GF}$$

Two finite difference programs were coded to find the wetting front and the infiltration rate from the trench, respectively, and are included in Appendix.

2-3-3. Fok's Model

Fok's 2-D model does not take the ground water table into consideration. His model has been refined to reflect the ground water table effect by considering the capillary fringe. A typical result of the refined model is shown in Fig.10 (a). Until the wetting front meets the surface of the capillary fringe, the total infiltration volume is calculated in the same manner as described in section 2-1. After the wetting front meets the surface of the capillary fringe, it is calculated as follows:

1. The horizontal advance of the wetting front, x, is the same as that without the capillary fringe.

2. Find the time for the wetting front to meet the surface of the capillary fringe, say T, using one of Eqs.(2-15)-(2-18) depending on which time interval it is in.

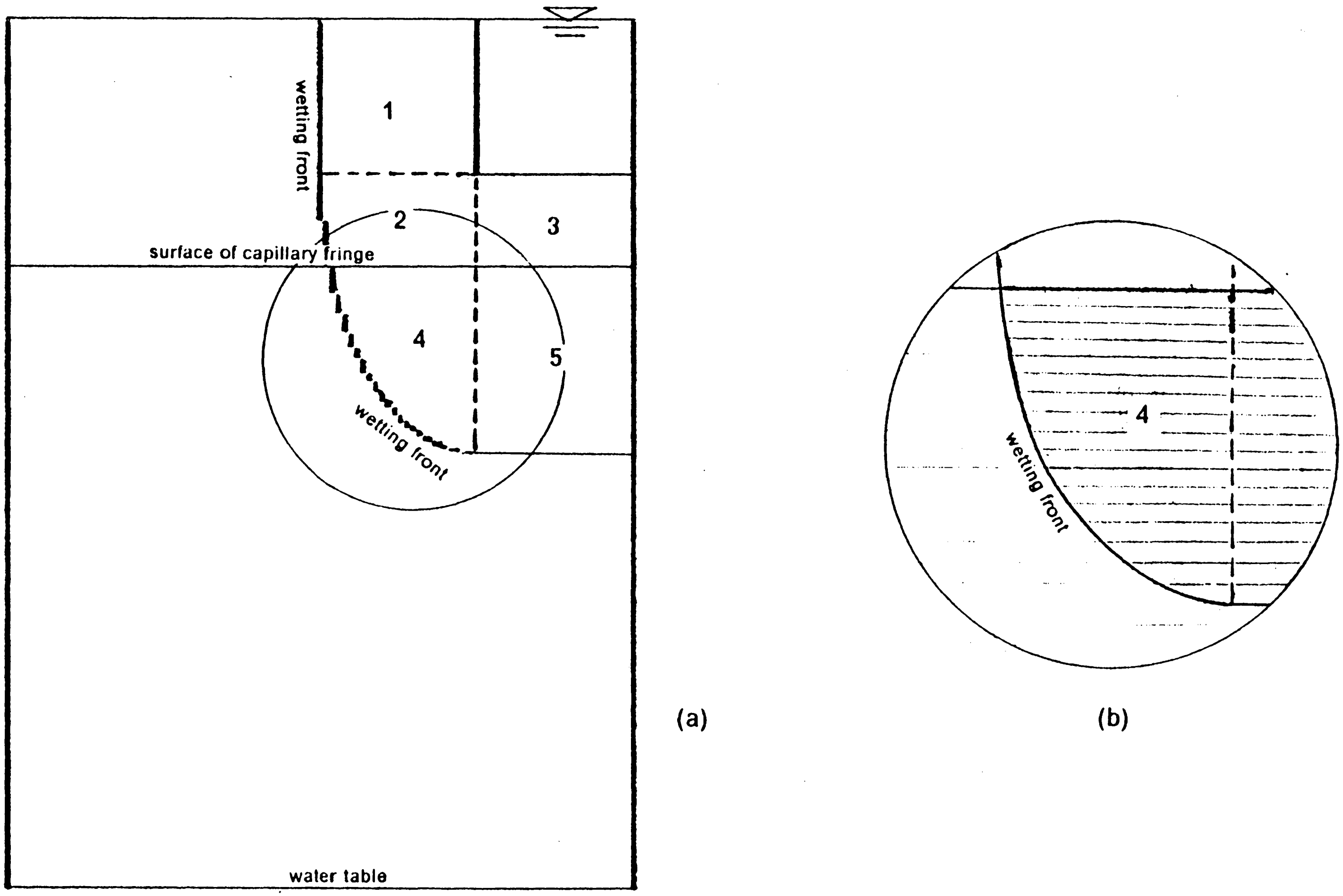


Figure 10. Fok's 2-D model with capillary fringe

3. The capillary zone is devided into many horizontal layers(100 layers in this study) so that the time for the wetting front to pass through each layer can be calculated.

4. Calculate the net increment of the degree of saturation, s, for each layer using $s = r(\theta_s - \theta_j)/\theta_s$ in which θ_j is the initial water content in the layer of interest, and θ_s is the saturated water content behind the wetting front. r = 0.8 is used in this study because the soil is not fully saturated due to air entrapment in the transmission zone. Hansen(14) and Chong et al(4) give the detail information about r.

5. Calculate the time for the wetting front to pass through each layer. Add up these infiltration times for each layer until the sum of T and the infiltration times becomes equal to or greater than a specified seepage time, t, at which the infiltration flux is found.

6. Find the exact point of the wetting front by interpolation between the top and the bottom of the current layer. Add up the thickness of all the layers through which the wetting front has passed to find y, the vertical advance of the wetting front.

7. Find the area of sections 1, 2, 3, 4, 5 as shown in Fig.10 (a) and multiply by the porosity, n, and the net increment of the degree of saturation, s for the respective section.

8. Sum up all those values obtained in step 7 to find the total infiltration volume per unit length of trench $[L^3/L]$ for the seepage time, t of interest.

Chapter 3 Comparison of the two Infiltration Models

3-1. Comparison

A comparison was made between Fok's model and the finite difference model for two kinds of soil, that is, an Ida silt loam soil and a Webster clay loam soil. The comparison is both for the advance of the wetting front and for the infiltration flux out of a trench.

The functional relationships between $D(\theta)$, $K(\theta)$ and θ used in the finite difference model were obtained by Selim(28) using the physical data given by Green et al.(13) and Fritton et al.(12).

For the Ida silt loam soil, the data used are of Green et al., which are approximately fit by the expressions:

$$D(\theta) = 3.33\exp(29.34\theta)\ 10^{-5}\ \text{cm}^2/\text{min} \qquad (3-1)$$

$$K(\theta) = 3.33\exp(54.11\theta)\ 10^{-13}\ \text{cm/min} \qquad (3-2)$$

For the Webster clay loam soil, the data used are of Fritton et al., which are approximately fit by the expressions:

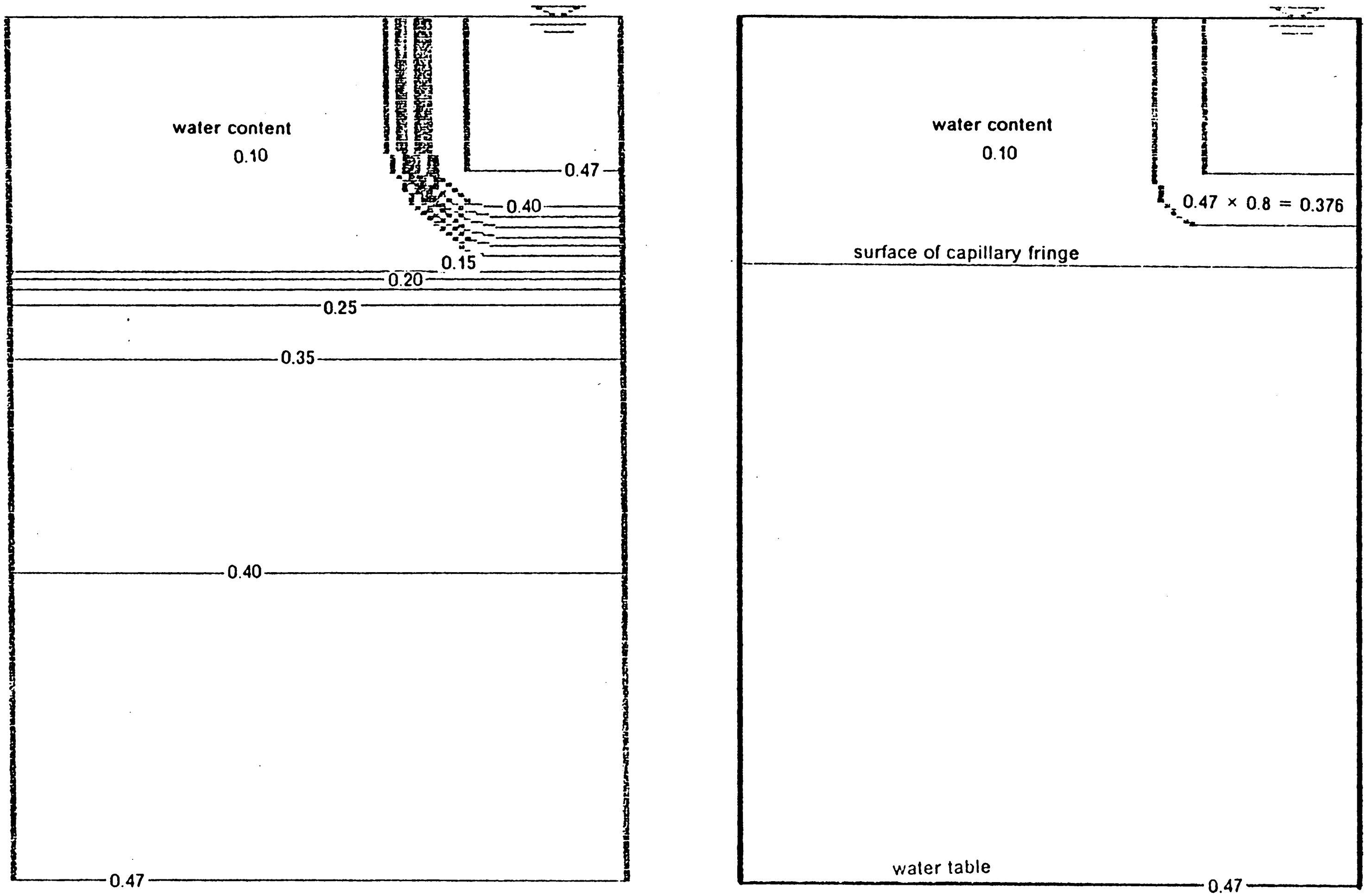
$$D(\theta) = 4.01\exp(22.10\theta)\ 10^{-4}\ \ cm^2/min \qquad (3-3)$$

$$K(\theta) = 3.98\exp(46.11\theta)\ 10^{-12}\ \ cm/min \qquad (3-4)$$

Mein(21) and Panikar(25) have suggested the effective capillary potential head, $(h_c - h_w)$, for various types of soils. In this study 10cm was selected for the Ida silt loam soil and 25cm for the Webster clay loam soil, respectively, to be applied to Fok's model.

According to Israelson and Hansen(18), the porosities for a silt loam soil and a clay loam soil are 0.47 and 0.49, and the hydraulic conductivities in the transmission zone are 0.020 cm/min. for a silt loam soil and 0.012 cm/min. for a clay loam soil, respectively.

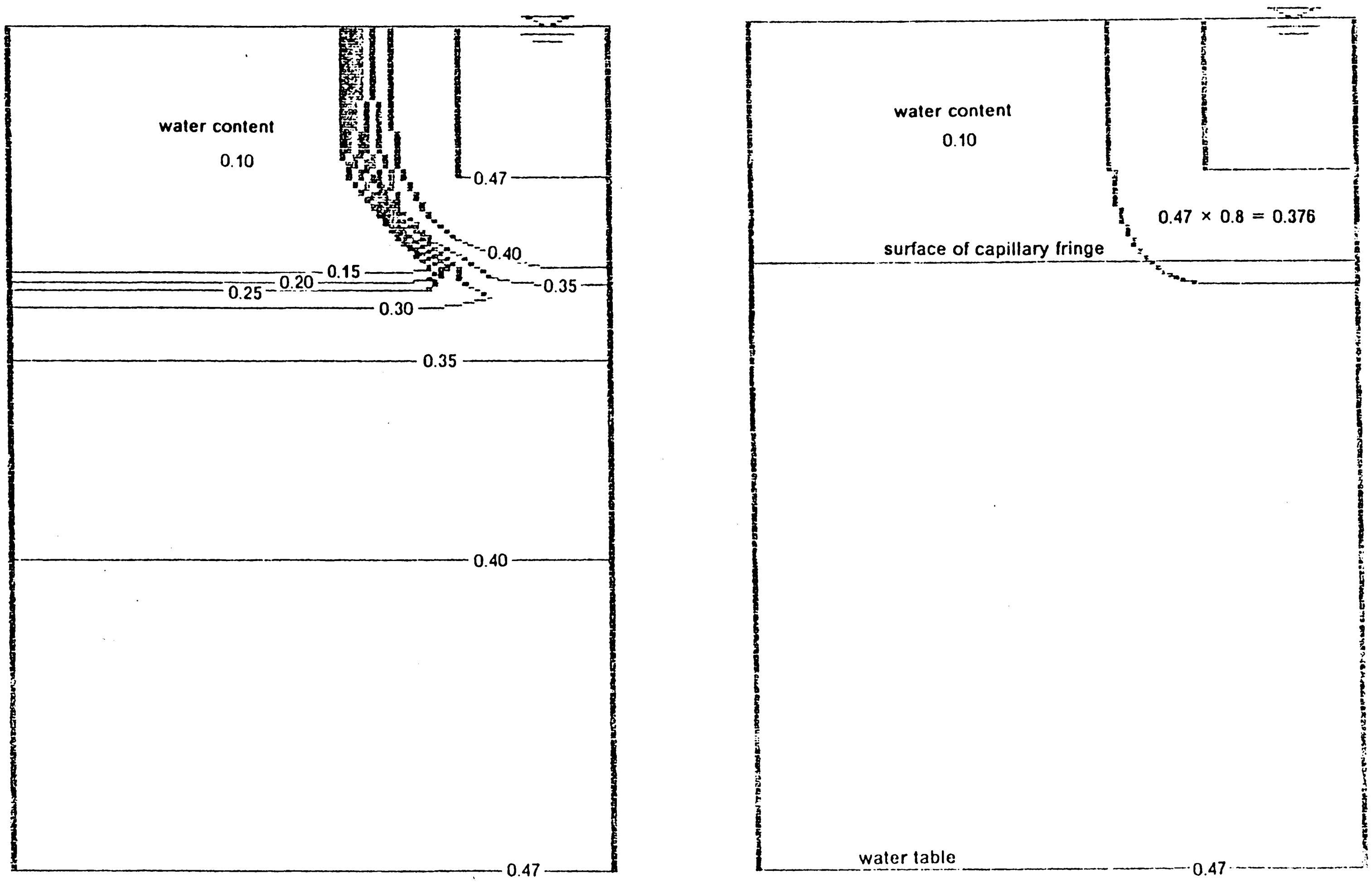
Fig.11 - Fig.16 show very good comparison of the advances of the wetting front by both the finite difference model and the Fok's model. Fig.11 - fig.13 are for the Ida silt loam soil for infiltration times 30min., 120min., and 360min., and Fig.14 - Fig.16 are for the Webster clay loam soil for infiltration times 60min., 240min., and 360min., respectively. Fig.17 and Fig.18 show good comparison of the infiltration rate between the two models for the two soils. A time of 480 minutes seems long enough for the design of an infiltration trench since the detention time for an infiltration facility in urbanized area is usually not more than 2 hours(20).



(a) Finite Difference Model

(b) Fok's Model

Figure 11. Comparison of the advance of wetting front for Ida silt loam soil (30 minutes later)



(a) Finite Difference Model *(b) Fok's Model*

Figure 12. Comparison of the advance of wetting front for Ida silt loam soil (120 minutes later)

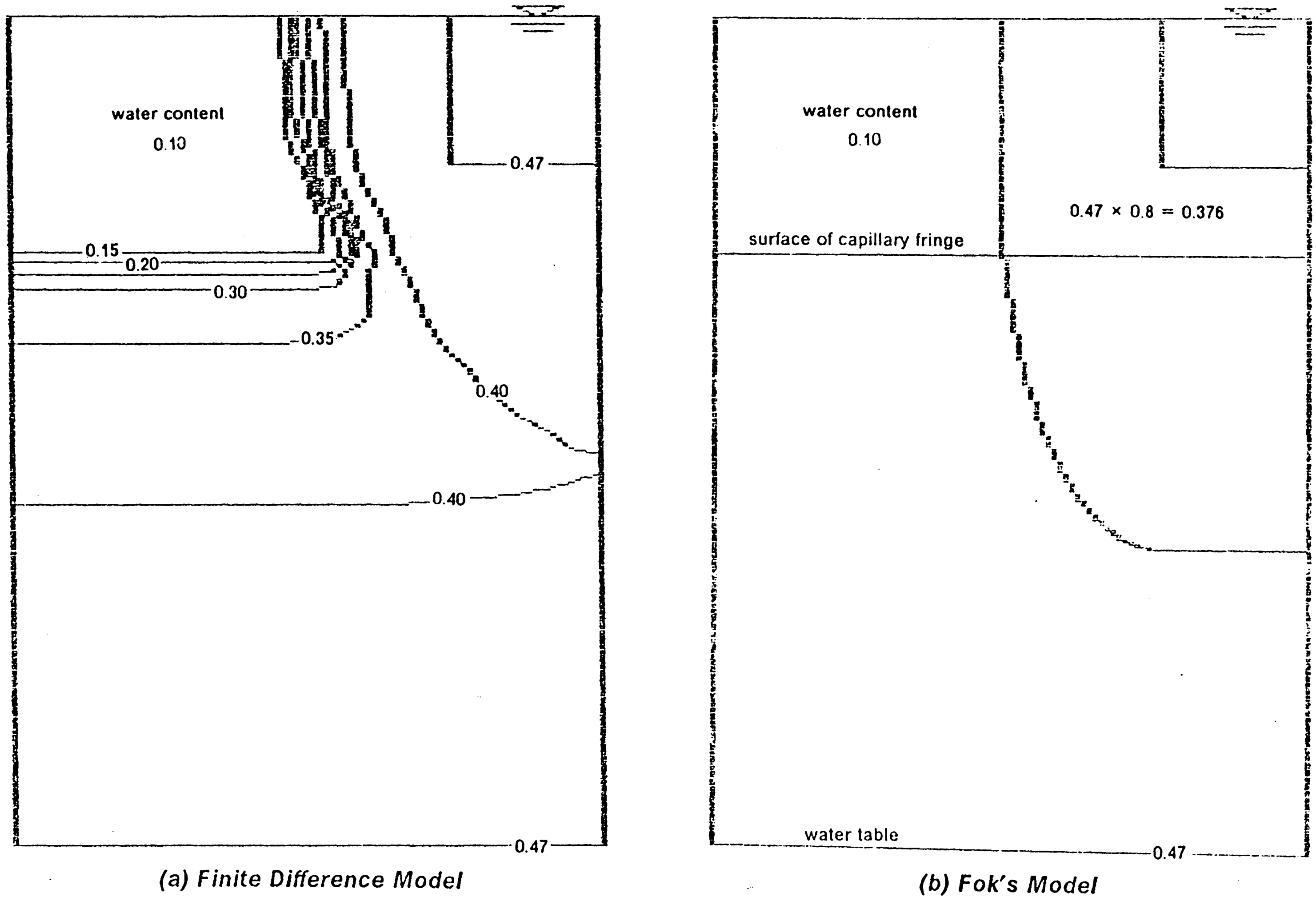
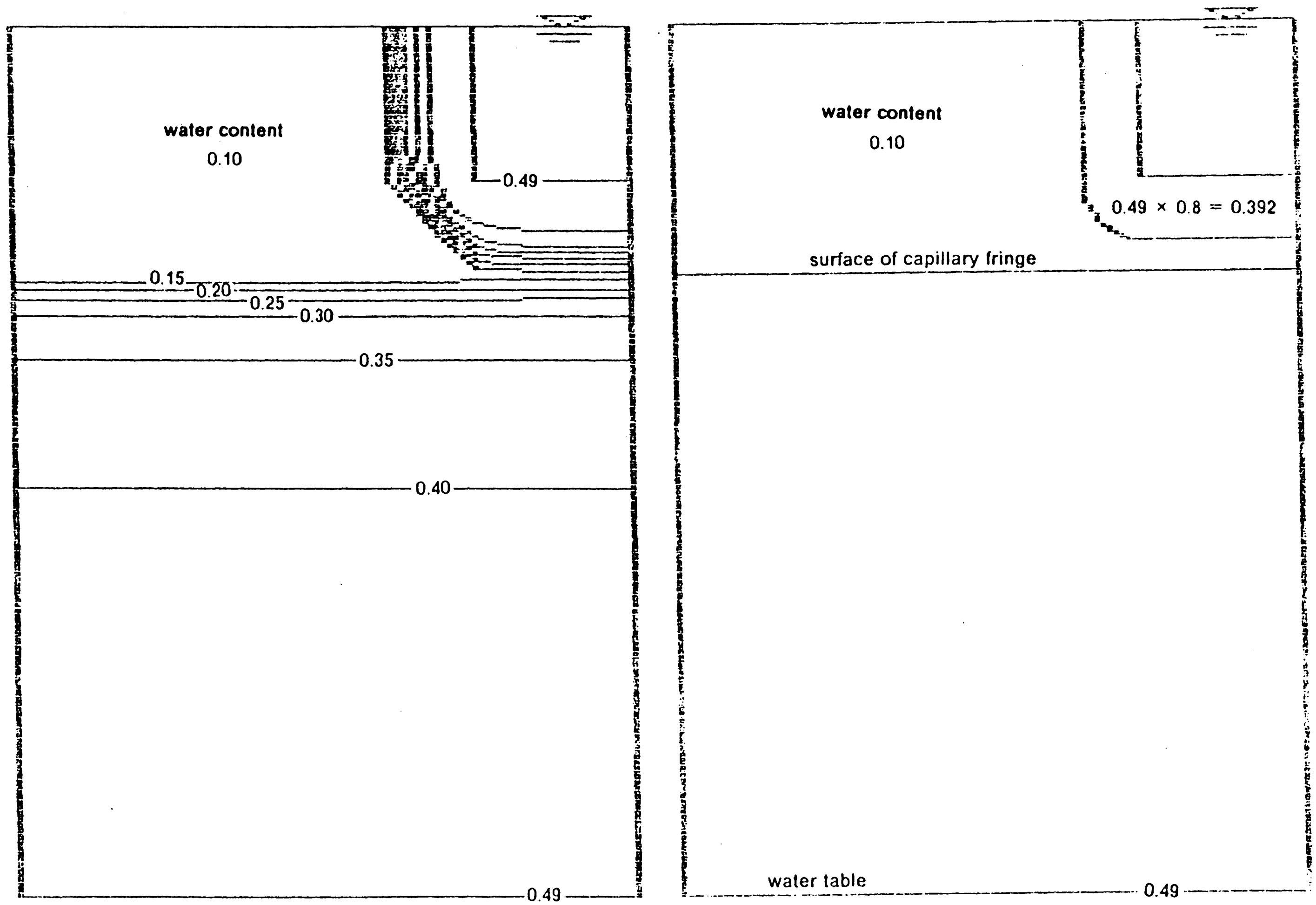


Figure 13. Comparison of the advance of wetting front for Ida silt loam soil (360 minutes later)



(a) Finite Difference Model *(b) Fok's Model*

Figure 14. Comparison of the advance of wetting front for Webster clay loam soil (60 minutes later)

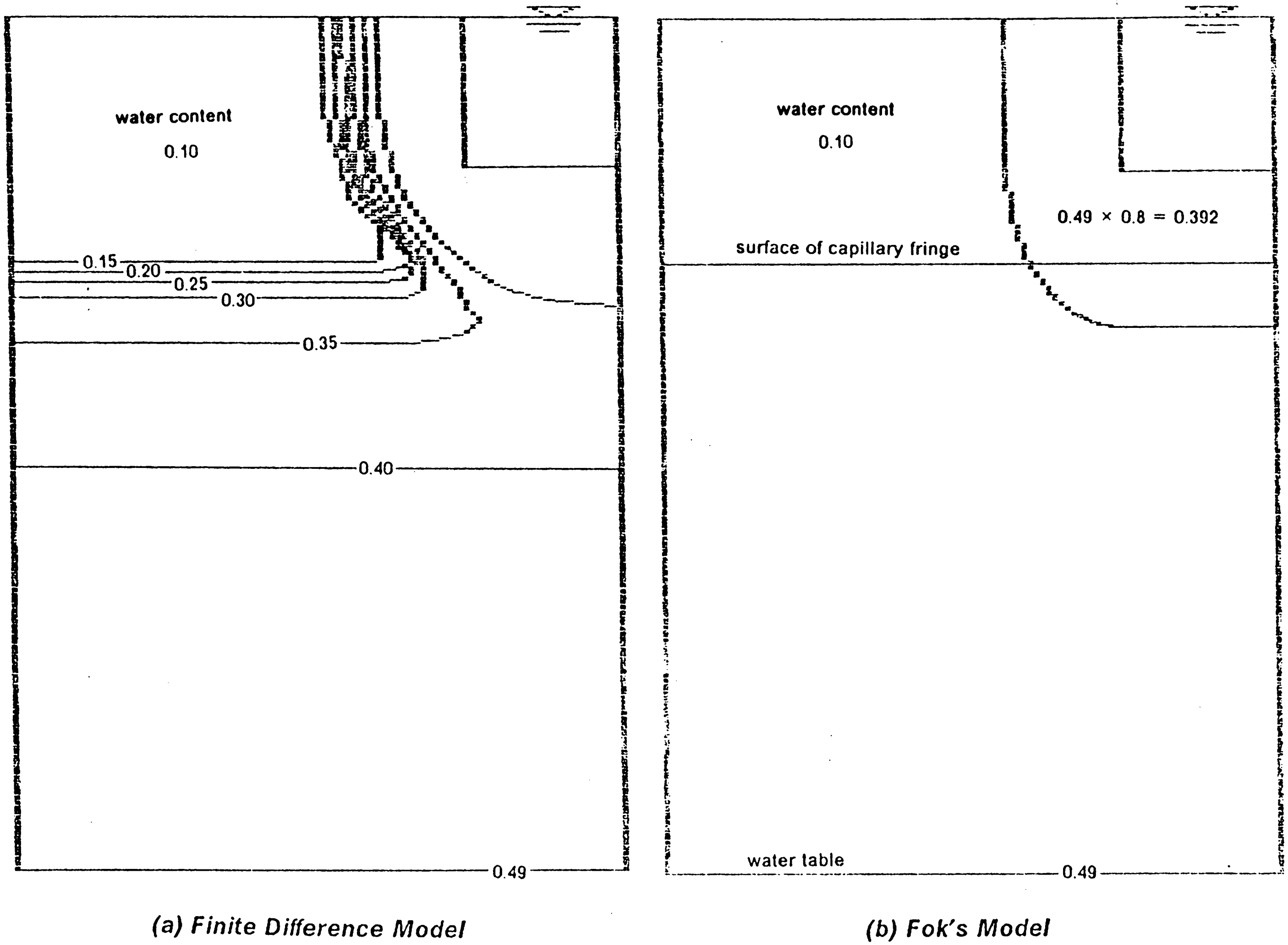
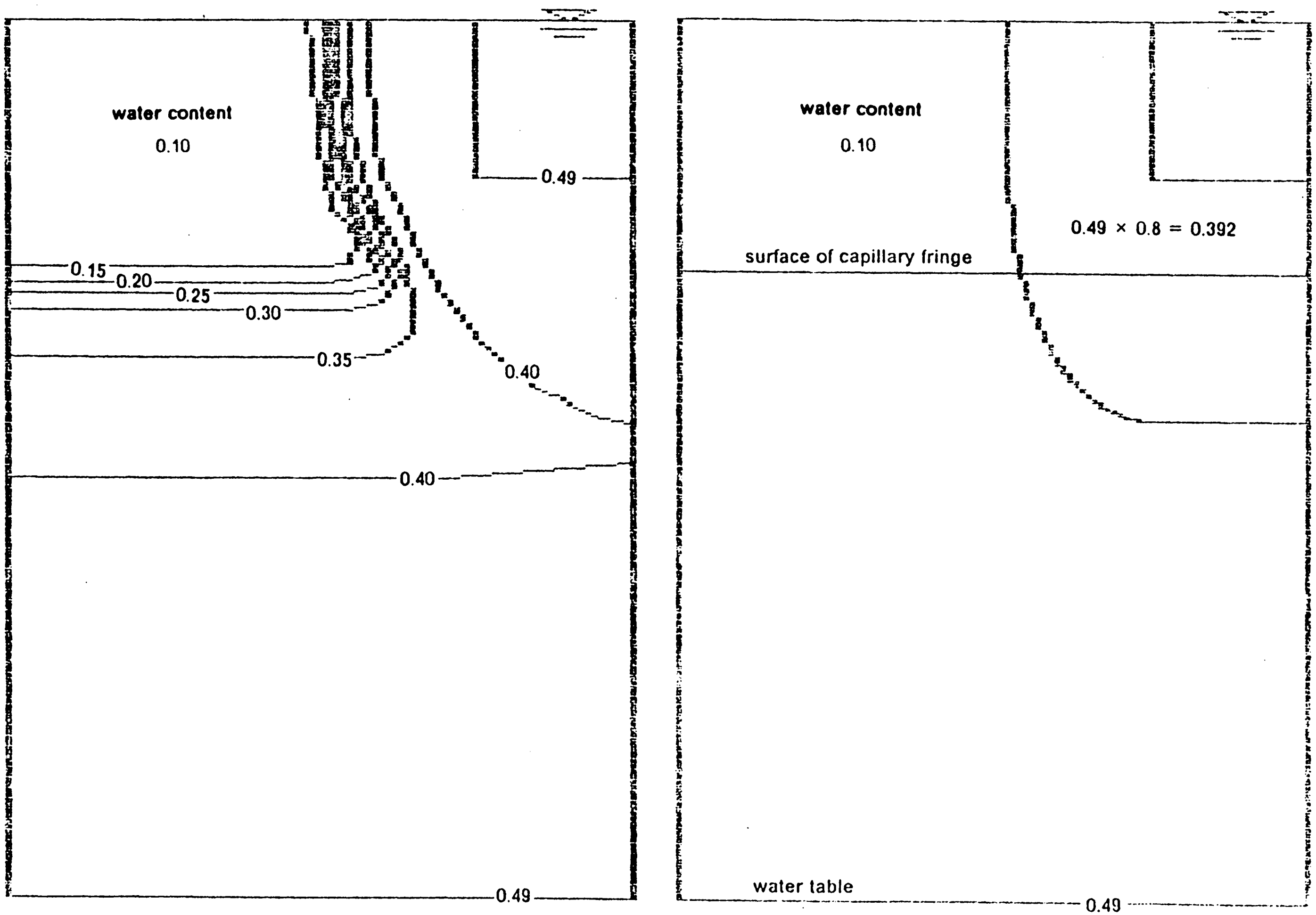


Figure 15. Comparison of the advance of wetting front for Webster clay loam soil (240 minutes later)



(a) Finite Difference Model *(b) FoK's Model*

Figure 16. Comparison of the advance of wetting front for Webster clay loam soil (360 minutes later)

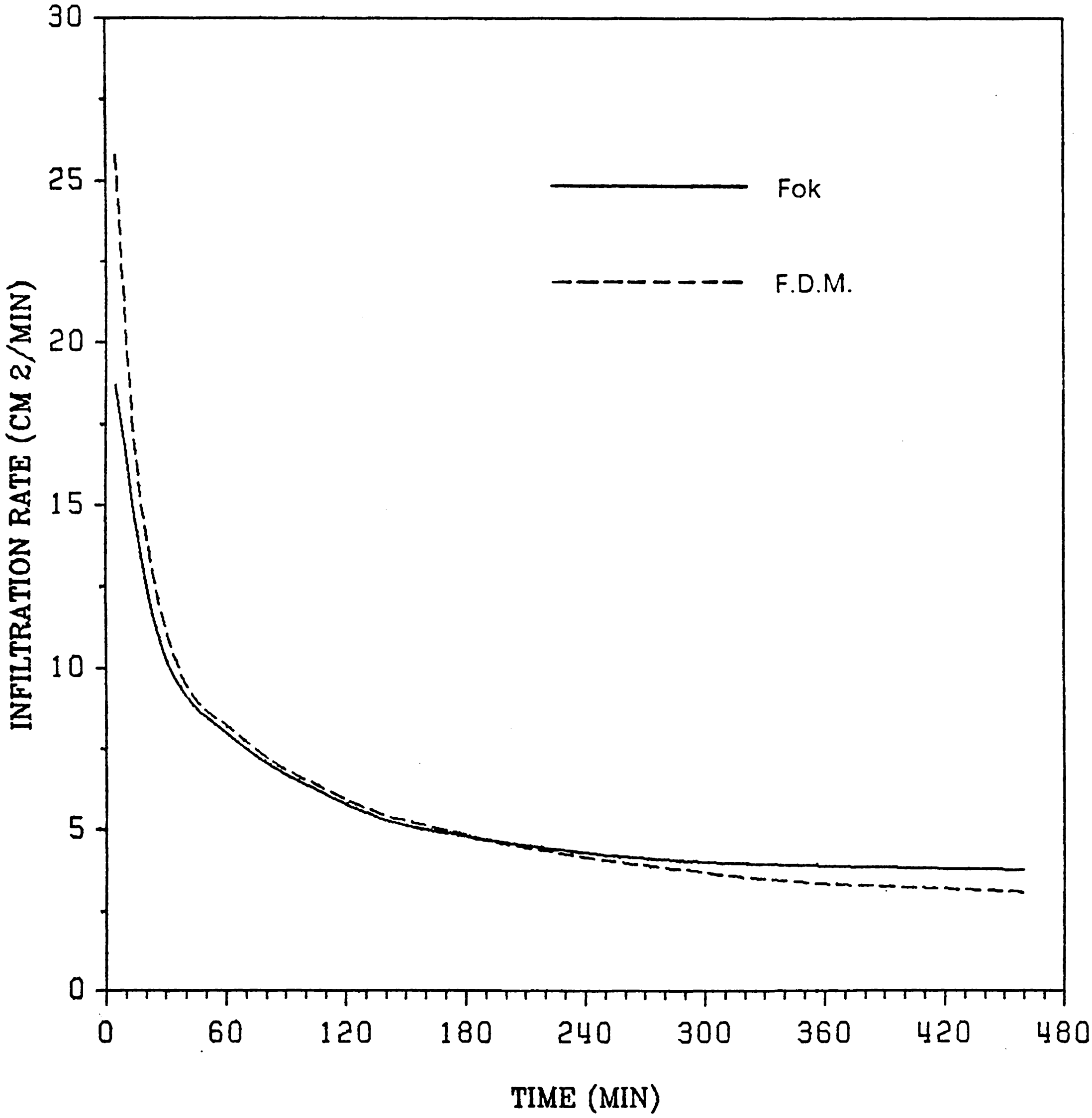


Figure 17. Comparison of the infiltration rate from trench (for Ida silt loam soil)

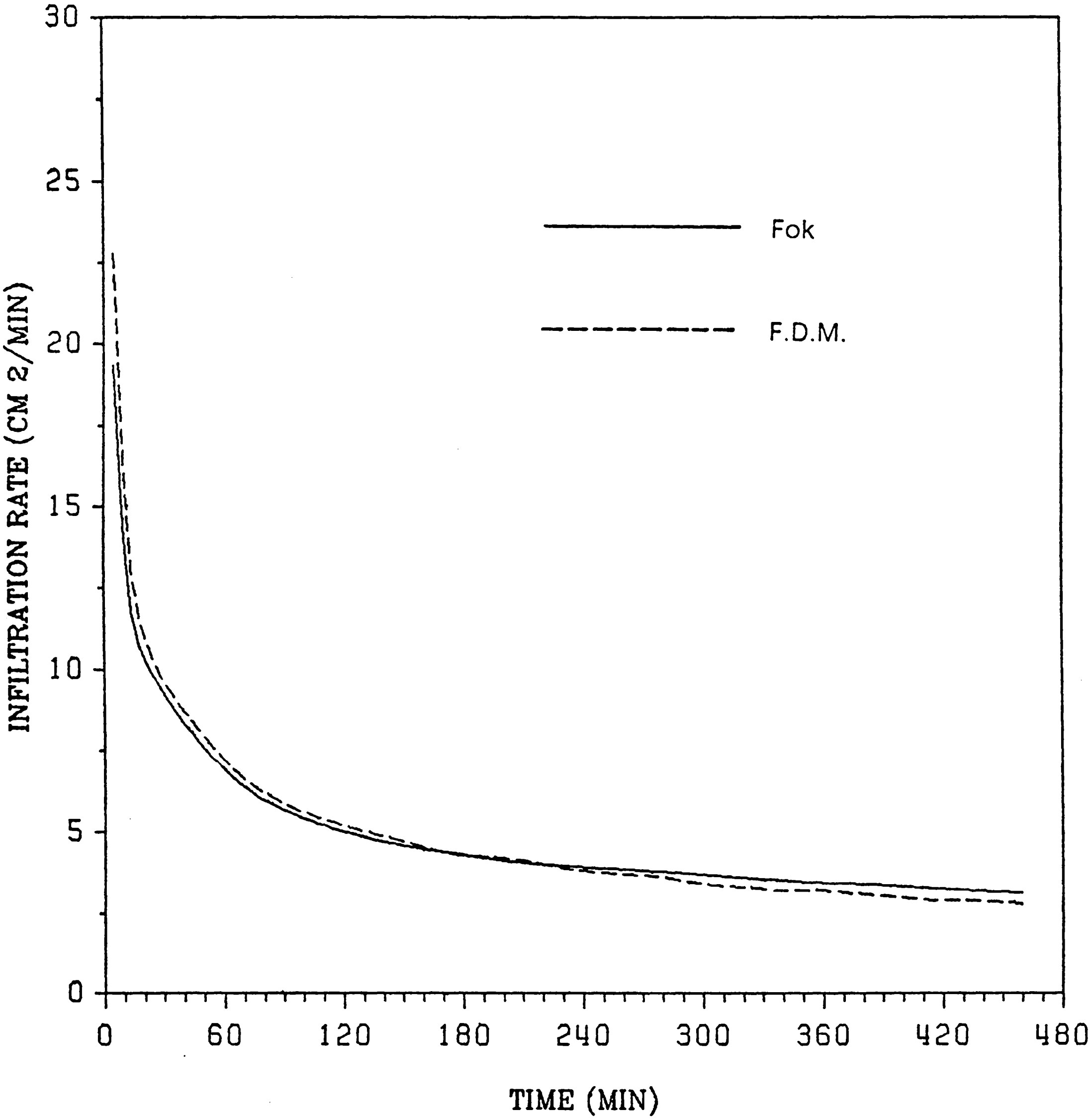


Figure 18. Comparison of the infiltration rate from trench (for Webster clay loam soil)

Chapter 4 Application to an Infiltration Trench

Introduction:

An infiltration trench is defined as a subsurface trench that is used to temporarily store runoff in a stone filled reservoir. The water infiltrates slowly into the surrounding soil media. A three-dimensional cumulative infiltration equation has been derived based upon Fok's two-dimensional equation. Hydrologic routing is performed for the infiltration trench by considering stormwater runoff as inflow and the infiltration flux as outflow. The result of a routing example is presented. An infiltration trenches with overflow is also examined.

4-1. Infiltration Trench

4-1-1. Description

An infiltration trench consists of a shallow excavated trench, generally 2 to 10 feet in depth backfilled with a coarse stone aggregate, allowing for temporary storage of storm runoff in the voids between the aggregate material. Stored runoff then gradually infiltrates into the surrounding soil.

Fig.19 provides a typical section of infiltration trenches. The surface of the trench will consist of stone, gabion, or a grassed covered area with a surface inlet.

An infiltration trench will generally be used on relatively small drainage areas. This practice can be used on residential lots, commercial areas, parking lots, and open space areas. A trench may also be installed under a swale to increase the storage of the infiltration system.

4-1-2. Considerations in Design

The depth of an infiltration trench ranges from 2 to 10 feet. A trench with a grassed covered surface will consist of at least one foot of overlying soil above the aggregate reservoir. A 3 feet depth of aggregate is felt to represent the shallowest infiltration trench likely to be built. In general, the design engineer will seek to make the trench as deep as possible to minimize the surface area of the trench.

The permeability or infiltration rate of various soil textural classifications will be a limiting factor in the selection of infiltration trenches by itself. The infiltration rate becomes a major factor when combined with other considerations such as minimum construction depth, maximum allowable storage time, and surface area requirements for a specified level of runoff control. According to Maryland Standards and Specifications for Infiltration Practices(Ref.20), soil textural classes with infiltration rates greater or equal to 0.27 inch/hour (0.011 cm/min.) can be considered for the use of infiltration trenches.

The seasonally high groundwater table should be located at least 2 to 4 feet below the bottom of the trench at all times. Also infiltration trenches shall be located at least 100 feet horizontally away from any water supply well.

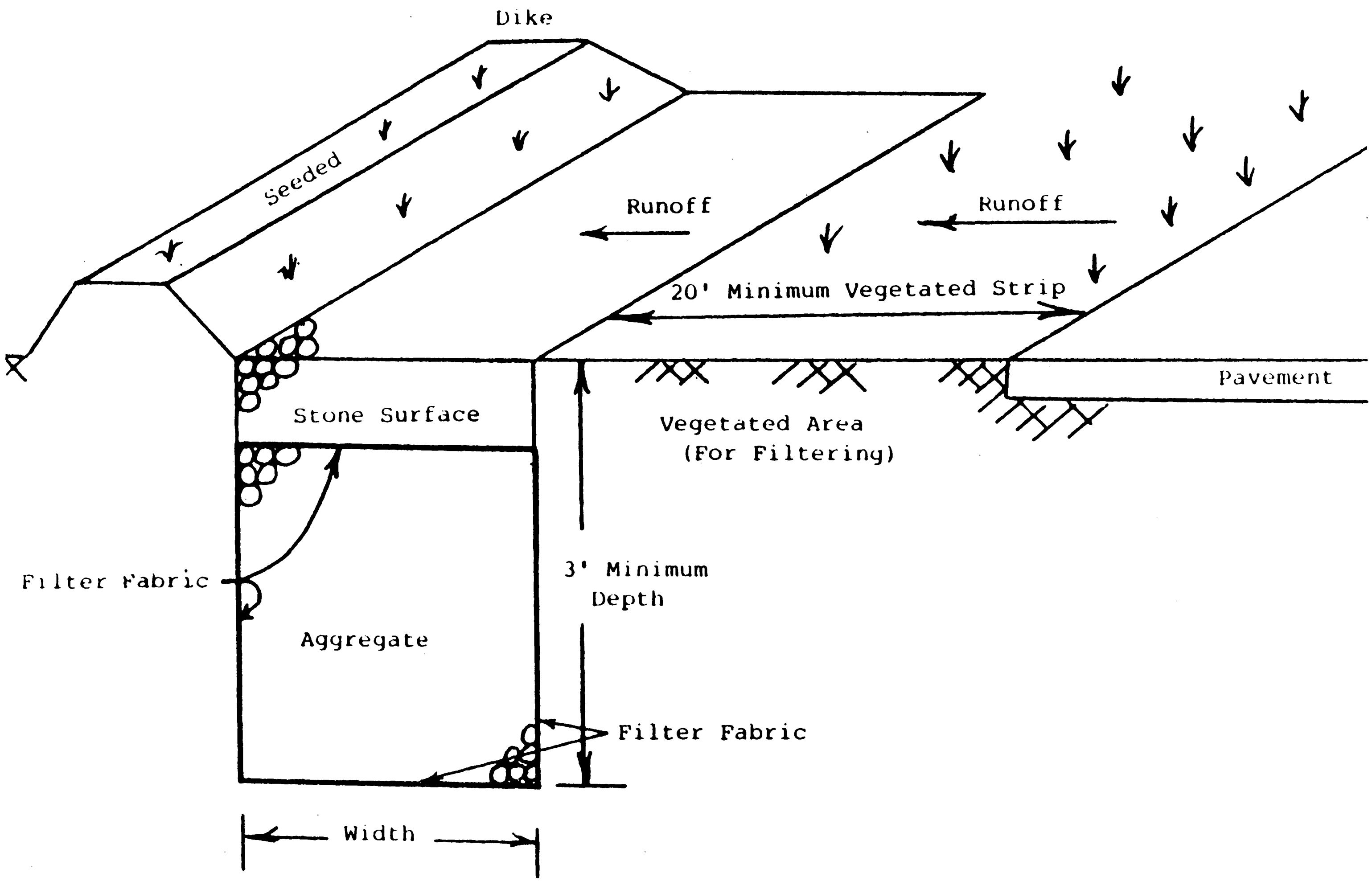


Figure 19. Typical section of infiltration trenches (after Ref.20)

The aggregate material for the infiltration trenches shall consist of a clean aggregate with a maximum diameter of 3 inches and a minimum diameter of 1.5 inches. The aggregate should be graded such that there will be few aggregates smaller than the selected size. Void space for these aggregates are assumed to be between the range of 30 to 40 percent.

The aggregate fill material shall be completely surrounded as shown in Fig.19 with filter fabric. In the case of an aggregate surface, filter fabric should surround all of the aggregate fill material except for the top one foot.

4-2. Extension of Fok's Model to 3-D Case

Fok's two-dimensional cumulative infiltration equation derived in chapter 2 can be applied to long trenches. However, this equation is not applicable to the trenches which are not long enough. A three-dimensional cumulative infiltration equation has been derived so that the hydrologic routing can be performed for the trench.

The geometry involved in the derivation of the 3-D equation is shown in Fig.20, which can easily be understood when compared with Fig.4 in chapter 2.

The three-dimensional cumulative infiltration equation is

$$I = \left(\pi x^2 d + 2xbd + 2xwd + \frac{\pi}{2}xyw + \frac{\pi}{2}xyb + \frac{2}{3}\pi x^2 y + wby\right)ns$$

which can be rearranged as

$$I = \left[\pi x^2(d + \frac{2}{3}y) + x(b + w)(2d + \frac{\pi}{2}y) + wby\right]ns \qquad (4-1)$$

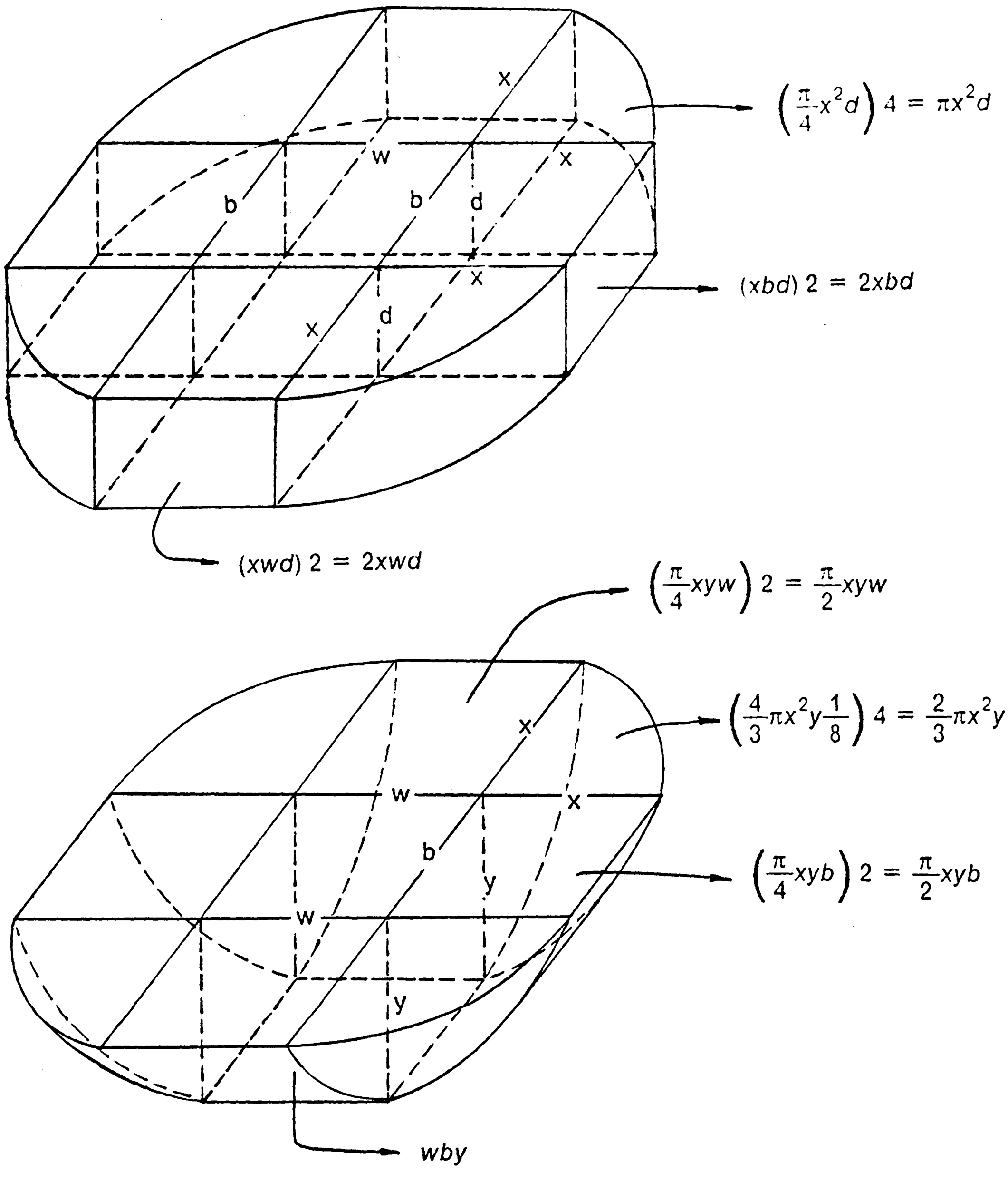


Figure 20. Geometry for the derivation of 3-D infiltration equation

in which

b = length of the trench

d = depth of the trench

w = width of the trench

x = horizontal advance of the wetting front

y = vertical advance of the wetting front

n = porosity of the soil

s = net increment of the degree of saturation

4-3. Hydrologic Routing

4-3-1. Description

The hydrologic routing for this study is the storage routing in which storage effects are dominant. This involves solving the continuity equation to ascertain the rate of storage of water in a trench.

The main task in the routing is the balancing of inflow, outflow, and volume of water in the trench. Over a time interval Δt, inflow volume − outflow volume = change in storage

i.e.

$$\frac{1}{2}(I_{n1} + I_{n2})\Delta t - \frac{1}{2}(O_{ut1} + O_{ut2})\Delta t = S_2 - S_1 \qquad (4-2)$$

in which

I_n = flow into the trench

O_{ut} = flow out of the trench (through infiltration)

S = volume of water in storage at any instant

subscripts 1 and 2 indicate the beginning and the end of a time interval respectively

The above equation may be rearranged such that the unknowns (S_2 and O_{ut2}) are on the right hand side of the equation.

$$(I_{n1} + I_{n2}) + \left(\frac{2S_1}{\Delta t} - O_{ut1}\right) = \left(\frac{2S_2}{\Delta t} + O_{ut2}\right) \qquad (4-3)$$

The inflow quantities are generally known and provided in the form of a hydrograph. Thus if the storage and the outflow at the beginning of a time interval are known, the right hand side of the Eq.(4-3) can be determined. However, no predetermined relationships of ($2S/\Delta t + O_{ut}$) and O_{ut} against H is available, because the flow out of the trench through infiltration, O_{ut}, is not only a function of the water depth in the trench, H, but also a function of time, t. Therefore, the value of outflow at the end of a time interval Δt is calculated by trial and error method. S and O_{ut} can be expressed in terms of H, i.e., $S = f(H)$ and $O_{ut} = f(H, t)$. A H is assumed to check if Eq.(4-3) is satisfied. If not, a new H is assumed based on the half interval search method. Once the exact value of H is found, O_{ut} is calculated using the cumulative infiltration equation derived in section 4-2.

4-3-2. Inputs and Outputs

The input for the hydrologic routing in a trench is provided in the form of a hydrograph. The inflow hydrograph will be the design hydrograph and will always be given, for example, using the unit hydrograph procedures. The inflow hydrograph for a small urbanized area is adopted in this study according to the Drainage Manual published by the Virginia Department of Highways and Transportation(32). Fig.21 shows the hydrograph.

Rational Formula:

The Rational Formula which represents the relation between rainfall intensity and peak runoff is

$$Q_p = Cia \qquad (4-4)$$

where

Q_p = peak discharge (cfs)

C = runoff coefficient representing the fraction of rainfall which becomes surface runoff

i = rainfall intensity (inches/hour)

a = drainage area (acre)

The following assumptions are made for the Rational Formula:

1. The rate of runoff resulting from any rainfall intensity reaches the maximum when this rainfall lasts as long as or longer than the time of concentration.

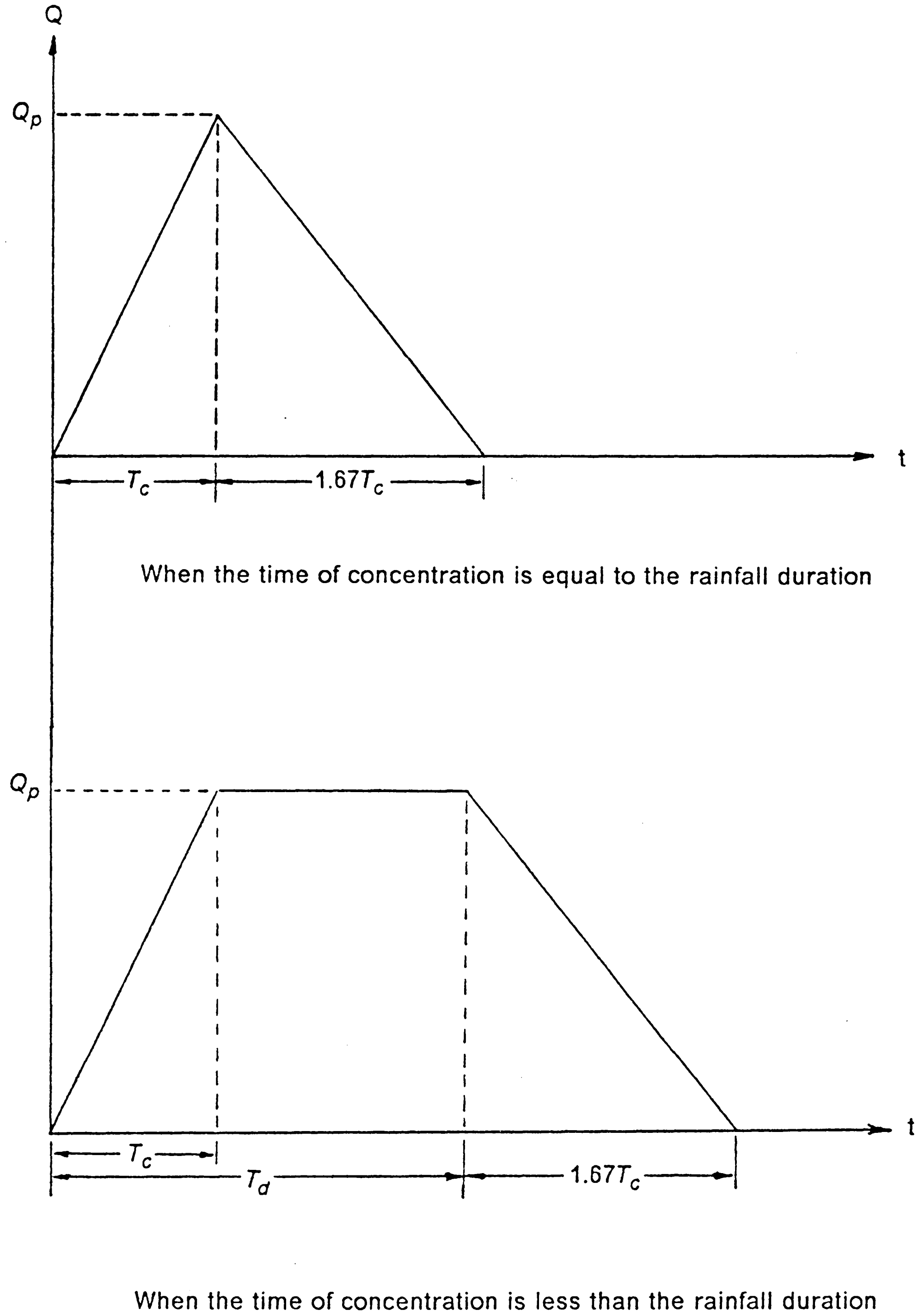


Figure 21. Hydrograph for a small drainage area

2. The frequency of the peak discharges are the same as that of the rainfall.

3. The runoff coefficient is the same for storms of various frequencies.

Hydrograph:

A hydrograph represents the variation of discharge with respect to time and reflects the physiographic and climatic characteristics that govern the relations between rainfall and runoff of a particular drainage area. Time of concentration is a very important parameter in the calculation of hydrograph using the Rational Formula. It depends on the shape of the drainage area and is a basic input data in this study.

The procedure to generate a hydrograph is outlined as follows:

1. The Rational Formula is used to calculate the peak discharge.

2. If the time of concentration, T_c, is equal to the rainfall duration, the equation to describe the rising limb is expressed by

$$q = \frac{Q_p}{T_c} t \qquad 0 \leq t \leq T_c \tag{4 - 5}$$

and the recession limb by

$$q = Q_p - \frac{Q_p}{1.67T_c}(t - T_c) \qquad T_c \leq t \leq (T_c + 1.67T_c) \tag{4 - 6}$$

in which

q = runoff discharge at any time (cfs)

Q_p = peak discharge (cfs)

T_c = time of concentration (min.)

t = time (min.)

3. If the time of concentration is less than the rainfall duration, three equations are required to describe the three parts of the hydrograph.

$$q = \frac{Q_p}{T_c} t \qquad 0 \le t \le T_c \tag{4-7}$$

$$q = Q_p \qquad T_c \le t \le T_d \tag{4-8}$$

$$q = Q_p - \frac{Q_p}{1.67T_c}(t - T_c) \qquad T_d \le t \le (T_d + 1.67T_c) \tag{4-9}$$

in which T_d is the rainfall duration.

4. When the rainfall duration is less than the time of concentration, the peak time of the hydrograph is set equal to the time of concentration and the peak discharge is calculated based on the Rational Formula with rainfall intensity chosen based on the time of concentration in the intensity-duration-frequency curve.

4-3-3. An Example Run of Hydrologic Routing Program

A computer program for hydrologic routing has been coded to calculate the change of water depth in an infiltration trench, and is listed in the Appendix. The result of an example run of the computer program is shown in Table 2. The outputs include time, inflow, outflow, water depth in the trench, horizontal and vertical advance of the wetting front.

The data used in this example run are as follows:

routing period = 1 min.

runoff coefficient, C = 0.9

rainfall intensity = 2.3 inches/hour

time of duration = 60 min.

time of concentration = 10 min.

drainage area = 2 acres

hydraulic conductivity of Soil = 0.0007 ft/min. (0.02 cm/min.)

porosity of soil = 0.47

effective capillary potential (h_e) = 0.33 ft

initial soil water content = 0.1

porosity of aggregate = 0.40

distance of capillary fringe surface from soil surface = 10 ft.

trench depth = 8 ft.

trench width = 8 ft.

trench length = 500 ft.

Fig.22 shows the results of the hydrologic routing in an infiltration trench. At the early stages of the routing(1 min. in this example), the volume of the inflow is entirely infiltrated because the incipient infiltration capacity of the soil is bigger than the inflow discharge. Fig.23 shows the time history of the wetting front from the infiltration trench.

How the soil properties such as hydraulic conductivity, porosity, effective capillary potential, and location of the groundwater table affect the routing in infiltration trenches will be discussed in the next chapter.

Designers are recommended to run this hydrologic routing program with various types and sizes of trenches for a given hydrograph and the soil properties at the construction site. In this way, they can choose the dimensions of the trench by considering other design aspects such as the economic, social, and environmental factors.

Table 2. Output of an example run of hydrologic routing program

TIME (MIN)	QIN (CFS)	QOUT (CFS)	H (FT)	X (FT)	Y (FT)
0.0	0.00	0.00	0.00	0.00	0.00
1.0	0.41	0.41	0.01	0.04	0.04
2.0	0.83	0.30	0.02	0.05	0.06
3.0	1.24	0.27	0.05	0.07	0.07
4.0	1.66	0.26	0.09	0.08	0.08
5.0	2.07	0.26	0.15	0.08	0.09
6.0	2.48	0.28	0.23	0.09	0.10
7.0	2.90	0.30	0.32	0.10	0.12
8.0	3.31	0.32	0.42	0.11	0.13
9.0	3.73	0.34	0.54	0.12	0.14
10.0	4.14	0.36	0.68	0.13	0.15
11.0	4.14	0.38	0.82	0.15	0.16
12.0	4.14	0.40	0.96	0.16	0.18
13.0	4.14	0.42	1.10	0.17	0.19
14.0	4.14	0.43	1.24	0.18	0.20
15.0	4.14	0.45	1.38	0.19	0.22
16.0	4.14	0.47	1.52	0.20	0.23
17.0	4.14	0.48	1.66	0.21	0.24
18.0	4.14	0.50	1.80	0.23	0.26
19.0	4.14	0.51	1.93	0.24	0.27
20.0	4.14	0.53	2.07	0.25	0.29
21.0	4.14	0.54	2.21	0.26	0.30
22.0	4.14	0.56	2.34	0.27	0.31
23.0	4.14	0.57	2.48	0.28	0.33
24.0	4.14	0.59	2.61	0.30	0.34
25.0	4.14	0.60	2.74	0.31	0.35
26.0	4.14	0.61	2.88	0.32	0.37
27.0	4.14	0.63	3.01	0.33	0.38
28.0	4.14	0.64	3.14	0.35	0.40
29.0	4.14	0.65	3.27	0.36	0.41
30.0	4.14	0.67	3.40	0.37	0.42
31.0	4.14	0.68	3.53	0.38	0.44
32.0	4.14	0.69	3.66	0.39	0.45
33.0	4.14	0.71	3.79	0.41	0.47
34.0	4.14	0.72	3.92	0.42	0.48
35.0	4.14	0.73	4.05	0.43	0.49
36.0	4.14	0.75	4.18	0.44	0.51
37.0	4.14	0.76	4.31	0.45	0.52
38.0	4.14	0.77	4.43	0.47	0.54
39.0	4.14	0.79	4.56	0.48	0.55
40.0	4.14	0.80	4.68	0.49	0.57
41.0	4.14	0.81	4.81	0.50	0.58
42.0	4.14	0.82	4.94	0.51	0.59
43.0	4.14	0.84	5.06	0.53	0.61
44.0	4.14	0.85	5.18	0.54	0.62
45.0	4.14	0.86	5.31	0.55	0.64
46.0	4.14	0.87	5.43	0.56	0.65
47.0	4.14	0.88	5.55	0.58	0.66

Table 2 continued

48.0	4.14	0.90	5.68	0.59	0.68
49.0	4.14	0.91	5.80	0.60	0.69
50.0	4.14	0.92	5.92	0.61	0.71
51.0	4.14	0.93	6.04	0.62	0.72
52.0	4.14	0.94	6.16	0.64	0.73
53.0	4.14	0.95	6.28	0.65	0.75
54.0	4.14	0.97	6.40	0.66	0.76
55.0	4.14	0.98	6.52	0.67	0.78
56.0	4.14	0.99	6.64	0.68	0.79
57.0	4.14	1.00	6.76	0.70	0.80
58.0	4.14	1.01	6.87	0.71	0.82
59.0	4.14	1.02	6.99	0.72	0.83
60.0	4.14	1.02	7.11	0.73	0.85
61.0	3.89	1.03	7.22	0.74	0.86
62.0	3.64	1.04	7.32	0.76	0.87
63.0	3.40	1.02	7.42	0.77	0.89
64.0	3.15	1.00	7.50	0.78	0.90
65.0	2.90	0.99	7.58	0.79	0.92
66.0	2.65	0.97	7.64	0.80	0.93
67.0	2.40	0.94	7.70	0.82	0.94
68.0	2.16	0.92	7.75	0.83	0.96
69.0	1.91	0.90	7.79	0.84	0.97
70.0	1.66	0.87	7.83	0.85	0.98
71.0	1.41	0.84	7.85	0.86	1.00
72.0	1.17	0.81	7.87	0.87	1.01
73.0	0.92	0.79	7.87	0.89	1.03
74.0	0.67	0.75	7.87	0.90	1.04
75.0	0.42	0.72	7.86	0.91	1.05
76.0	0.17	0.69	7.85	0.92	1.06
77.0	0.00	0.68	7.82	0.93	1.08
78.0	0.00	0.67	7.80	0.94	1.09
79.0	0.00	0.67	7.77	0.95	1.10
80.0	0.00	0.66	7.75	0.97	1.12
81.0	0.00	0.66	7.73	0.97	1.13
82.0	0.00	0.65	7.70	0.99	1.14
83.0	0.00	0.65	7.68	1.00	1.15
84.0	0.00	0.64	7.65	1.01	1.17
85.0	0.00	0.64	7.63	1.02	1.18
86.0	0.00	0.64	7.60	1.03	1.19
87.0	0.00	0.63	7.58	1.04	1.20
88.0	0.00	0.63	7.56	1.05	1.21
89.0	0.00	0.62	7.53	1.06	1.23
90.0	0.00	0.62	7.51	1.07	1.24
91.0	0.00	0.61	7.49	1.08	1.25
92.0	0.00	0.61	7.46	1.09	1.26
93.0	0.00	0.61	7.44	1.10	1.27
94.0	0.00	0.61	7.42	1.11	1.29
95.0	0.00	0.60	7.39	1.12	1.30
96.0	0.00	0.60	7.37	1.13	1.31
97.0	0.00	0.59	7.35	1.14	1.32
98.0	0.00	0.59	7.33	1.15	1.33
99.0	0.00	0.59	7.30	1.16	1.35

Table 2 continued

100.0	0.00	0.58	7.28	1.16	1.35
101.0	0.00	0.58	7.26	1.17	1.36
102.0	0.00	0.58	7.24	1.18	1.38
103.0	0.00	0.57	7.22	1.19	1.39
104.0	0.00	0.57	7.19	1.20	1.40
105.0	0.00	0.57	7.17	1.21	1.41
106.0	0.00	0.56	7.15	1.22	1.42
107.0	0.00	0.56	7.13	1.23	1.43
108.0	0.00	0.56	7.11	1.24	1.44
109.0	0.00	0.55	7.09	1.25	1.45
110.0	0.00	0.55	7.07	1.26	1.46
111.0	0.00	0.55	7.04	1.27	1.47
112.0	0.00	0.55	7.02	1.27	1.49
113.0	0.00	0.54	7.00	1.28	1.50
114.0	0.00	0.54	6.98	1.29	1.51
115.0	0.00	0.54	6.96	1.30	1.52
116.0	0.00	0.54	6.94	1.31	1.53
117.0	0.00	0.53	6.92	1.32	1.54
118.0	0.00	0.53	6.90	1.33	1.55
119.0	0.00	0.53	6.88	1.33	1.56
120.0	0.00	0.53	6.86	1.34	1.57
121.0	0.00	0.52	6.84	1.35	1.58
122.0	0.00	0.52	6.82	1.36	1.59
123.0	0.00	0.52	6.80	1.37	1.60
124.0	0.00	0.51	6.78	1.38	1.61
125.0	0.00	0.51	6.77	1.38	1.62
126.0	0.00	0.51	6.75	1.39	1.63
127.0	0.00	0.51	6.73	1.40	1.64
128.0	0.00	0.50	6.71	1.41	1.65
129.0	0.00	0.50	6.69	1.42	1.66
130.0	0.00	0.50	6.67	1.42	1.66
131.0	0.00	0.50	6.65	1.43	1.67
132.0	0.00	0.50	6.63	1.44	1.68
133.0	0.00	0.49	6.61	1.45	1.69
134.0	0.00	0.49	6.60	1.45	1.70
135.0	0.00	0.49	6.58	1.46	1.71
136.0	0.00	0.49	6.56	1.47	1.72
137.0	0.00	0.48	6.54	1.48	1.73
138.0	0.00	0.48	6.52	1.49	1.74
139.0	0.00	0.48	6.50	1.49	1.75
140.0	0.00	0.48	6.49	1.50	1.76
141.0	0.00	0.48	6.47	1.51	1.77
142.0	0.00	0.47	6.45	1.52	1.78
143.0	0.00	0.47	6.43	1.52	1.79
144.0	0.00	0.47	6.42	1.53	1.79
145.0	0.00	0.47	6.40	1.54	1.80
146.0	0.00	0.46	6.38	1.54	1.81
147.0	0.00	0.46	6.36	1.55	1.82
148.0	0.00	0.46	6.35	1.56	1.83
149.0	0.00	0.46	6.33	1.57	1.84
150.0	0.00	0.46	6.31	1.57	1.85

****

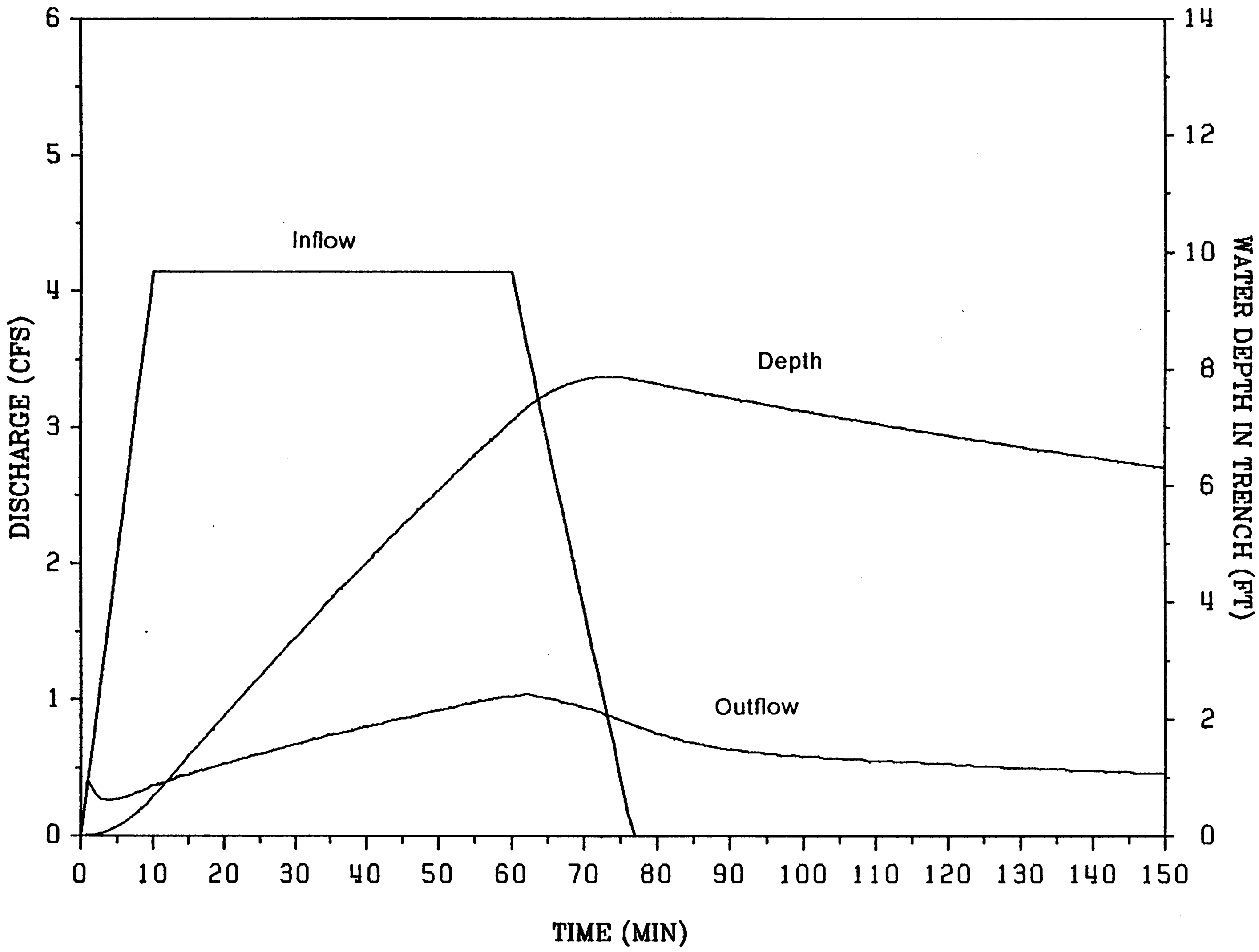


Figure 22. Results of hydrologic routing in an infiltration trench

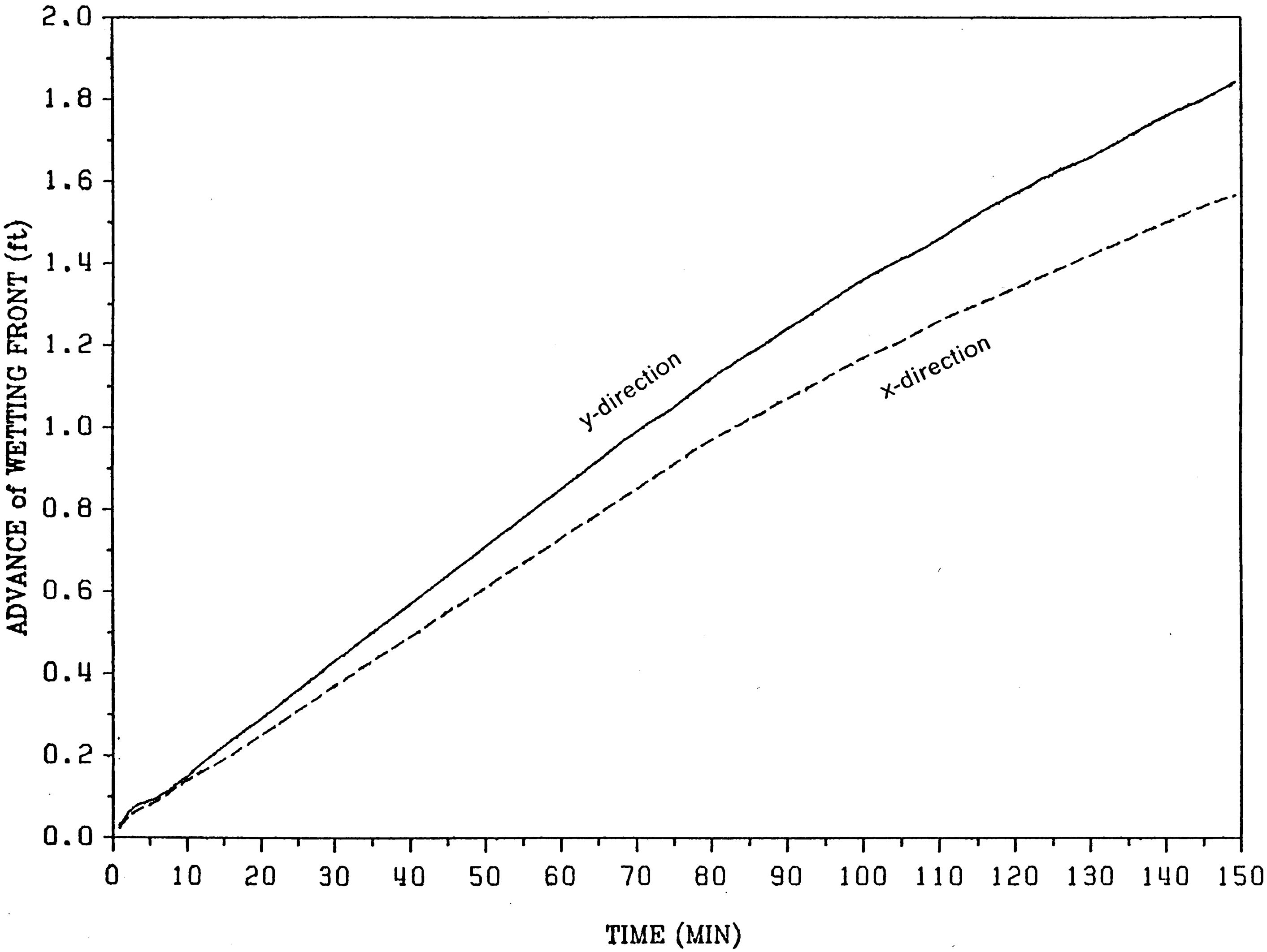


Figure 23. Time history of the wetting front

4-3-4. *Infiltration Trench with Overflow and Detention Time*

If the trench volume is not big enough to contain all the runoff, the excessive runoff would flow over the trench. The excessive runoff which is called 'overflow' in this study flows downstream as surface runoff. However, since the primary goal of stormwater management plans is to maintain the pre-development runoff characteristics after development, it is desirable that the overflow does not exceed the peak discharge for the pre-development condition.

The hydrograph representing the difference of inflow and outflow and the overflow hydrograph of the example run are shown in Fig.24 (a) and (b).
A discharge of 3 cfs is taken as the allowable discharge (i.e. peak discharge for the pre-development condition). The volume of the trench is sized such that the overflow from the trench doesn't exceed the allowable discharge. The detention time is defined as the time required to store this volume. The minimum required trench volume in this example is 28,400 ft^3 (trench width = 8 ft, length = 500 ft, depth = 7.1 ft), whereas the volume of trench without overflow requires 31,600 ft^3 (trench width = 8 ft, length = 500 ft, depth = 7.9 ft). The detention time has been found to be 60 minutes.

4-3-5. *Results of Hydrologic Routing in Nondimensional Form*

The following dimensionless terms are found by dimensional analysis(19).

$$\Gamma = \frac{Q_{in}}{A_t K}, \quad \Omega = \frac{Q_{out}}{A_t K}, \quad \eta = \frac{H}{KT_d}, \quad \lambda = \frac{x}{KT_d}, \quad \mu = \frac{y}{KT_d}, \quad \tau = \frac{t}{T_d} \qquad (4-10)$$

where

Q_{in} = inflow

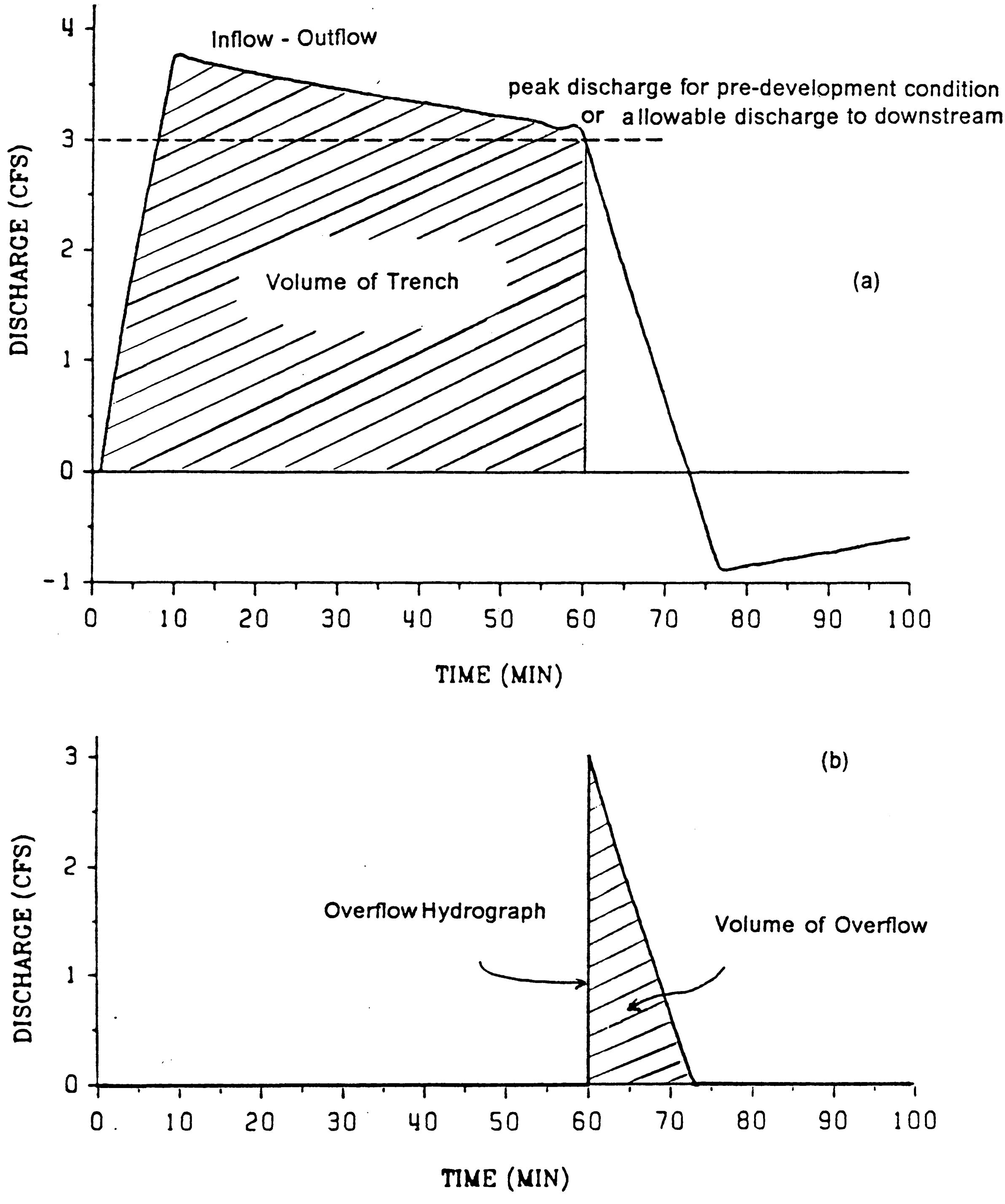


Figure 24. An examination of an infiltration trench with overflow

Q_{out} = outflow

A_t = area of the trench bottom

K = soil hydraulic conductivity

H = water depth in the trench

T_d = rainfall duration

x = horizontal advance of the wetting front

y = vertical advance of the wetting front

t = time

A nondimensional graph for the results of the hydrologic routing is given in Fig.25.

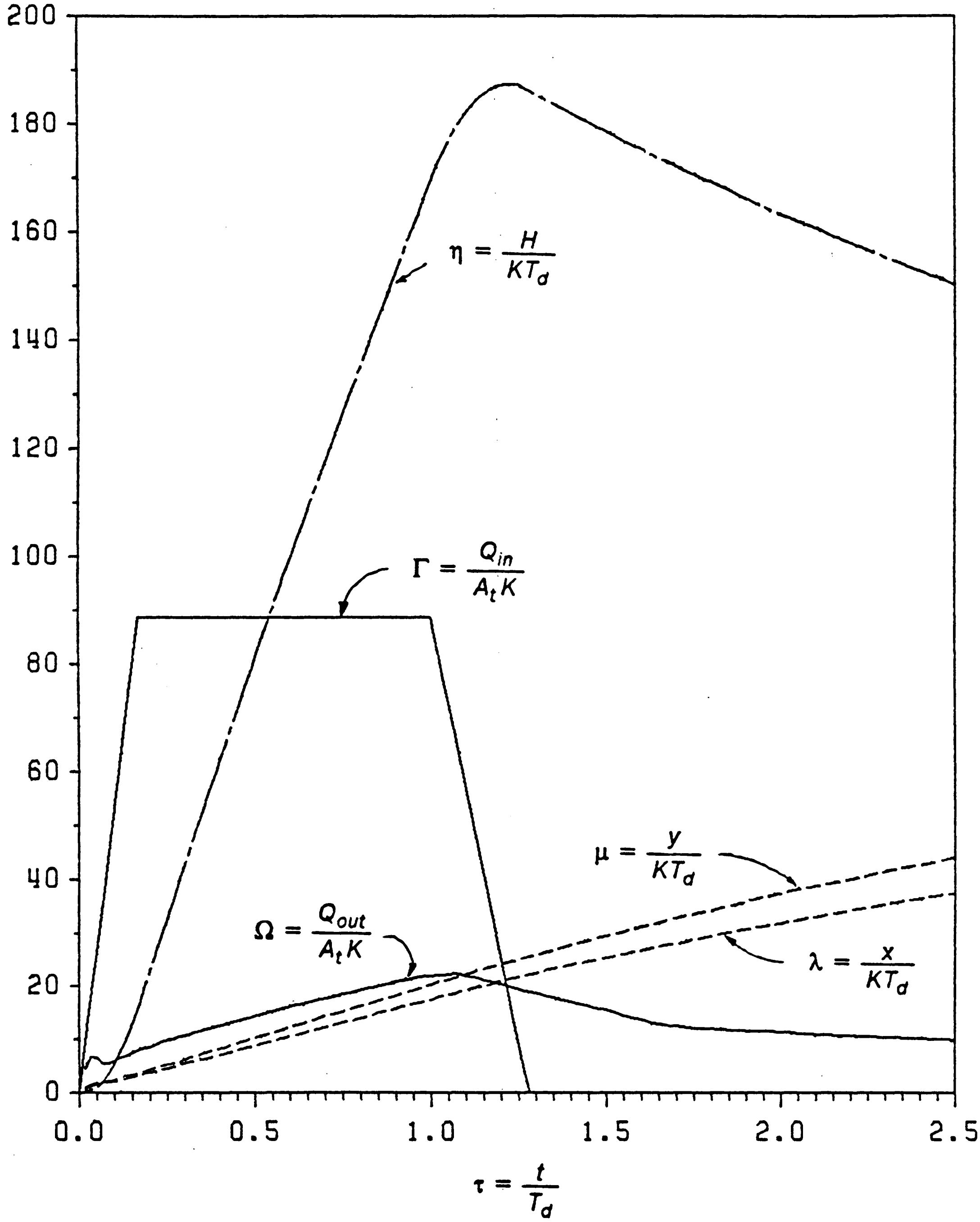


Figure 25. Nondimensional graph for the results of hydrologic routing

Chapter 5 Discussion

5-1. General

In the prescription of boundary condition No.4 on page 32, zero flux in the horizontal direction is assumed along the vertical line OG of Fig.9. A flow region which has the same length in the vertical direction and twice the length in the horizontal direction with the same trench size was chosen to be compared with the original one. Comparison shows that the infiltration volume in the wider flow region is greater than that in the original flow region by a difference of less than 1 %, which is considered to be insignificant.

The finite difference model adopted in this study is based upon an unsteady water flow equation which can be applied to the unsaturated soil only. The calculation of the infiltration volume in Fok's model is based on the wetting front concept and the difference in the degree of saturation before and after the wetting. Since there wouldn't be any difference in the degree of saturation below the groundwater table, Fok's model is considered to be invalid after the wetting front meets the groundwater table. Therefore, this study is limited to unsaturated soils only. However, since it is generally recommended that the groundwater table at the facility site should be low enough, the saturated flow is not likely to happen during the time period under consideration.

5-2. Sensitivity Analysis of Parameters

A narrow and long trench is more effective for water to infiltrate into the soil than a wide and short trench for the same trench area (width × length). Comparison between the two trench shapes is shown in Fig.26. The minimum depth required for a trench area $500ft \times 8ft$ is 7.9 ft, whereas that for $80ft \times 50ft$ is 8.7 ft.

Fig.27, 28, 29, 30 show how the changes of hydraulic conductivity, porosity, effective capillary potential, and location of the groundwater table affect the storage in a trench and the infiltration rate which is related to the outflow. Fig.27 shows that the hydraulic conductivity of the soil is a very important factor in the design of an infiltration trench. Fig.28 shows that the porosity of the soil has a minor effect. Fig.29 shows some difference in outflow(infiltration) at an early stage of routing. But, as time passes and the depth in the trench increases, the effect of the effective capillary potential becomes negligible. Fig.30 shows a small difference between the two cases, a 2-ft clearance and a zero clearance. Examination of Fig.30 reveals that the outflow for the zero clearance case is greater than the other case up to the infiltration time of 95 minutes. Beyond this time, the trend is reversed. It seems that infiltration rate in a soil media having a partial saturation is greater than that in a drier soil media. Since the net increment in the degree of saturation, s, in a soil having a partial saturation is smaller than that in a drier soil, referring to Eq.(2-15, 16, 17, 18, 23), the vertical and horizontal advances of the wetting front in a soil having a partial saturation are greater than those in a drier soil. However, as the degree of saturation approaches the full saturation, the infiltration rate decreases.

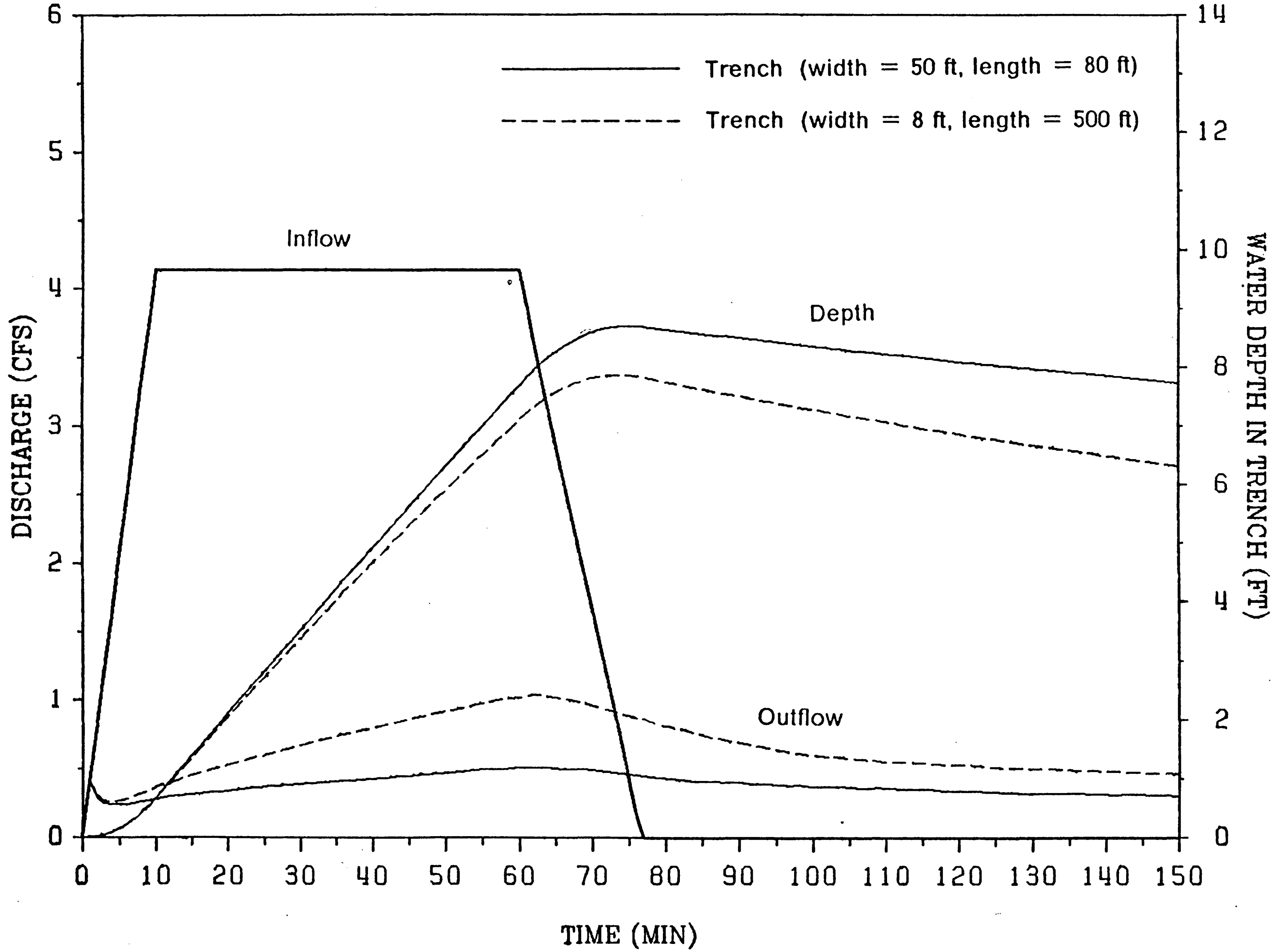


Figure 26. Effect of trench shape on hydrologic routing in trench

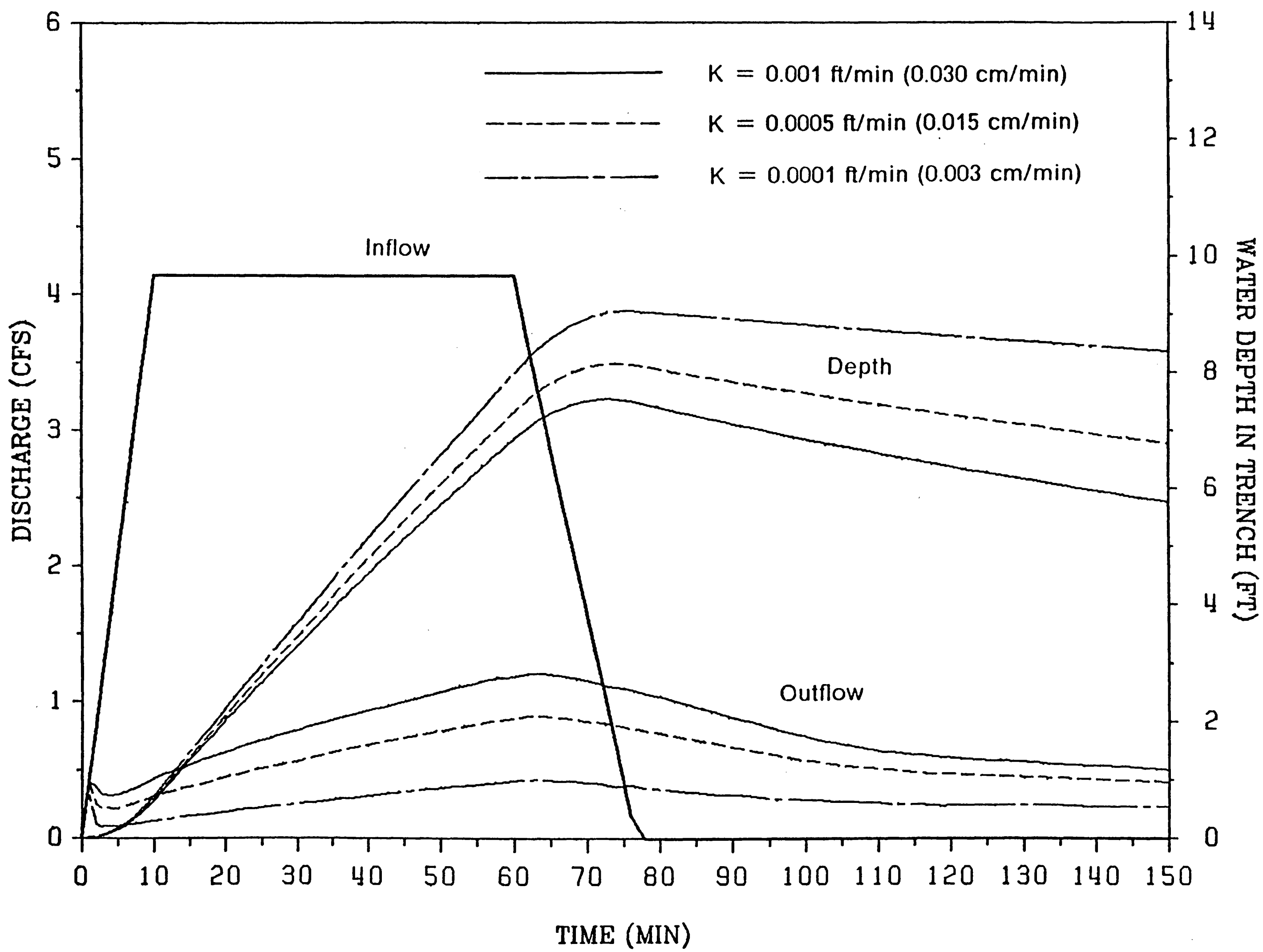


Figure 27. Effect of soil hydraulic conductivity on hydologic routing in trench

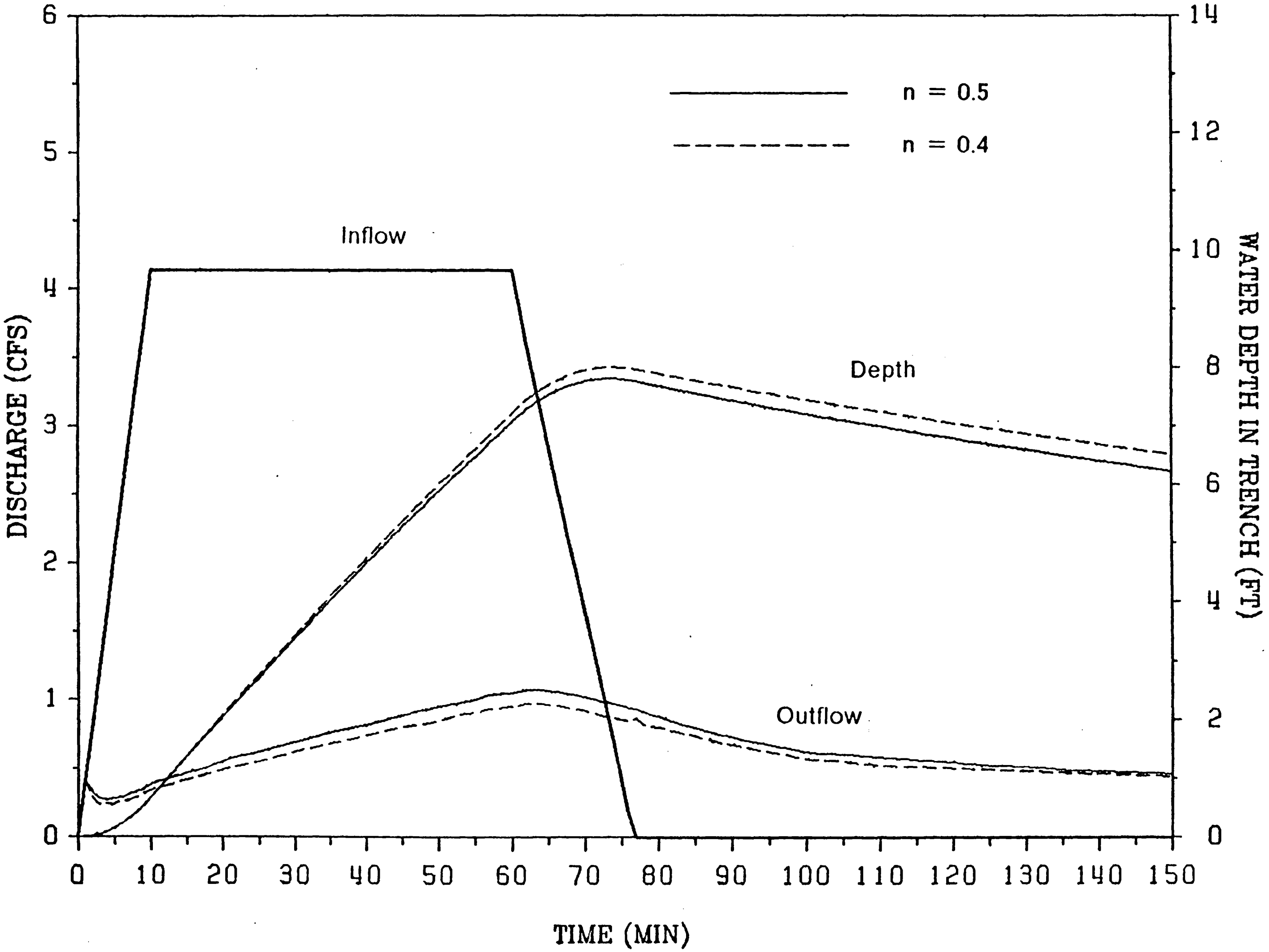


Figure 28. Effect of soil porosity on hydrologic routing in trench

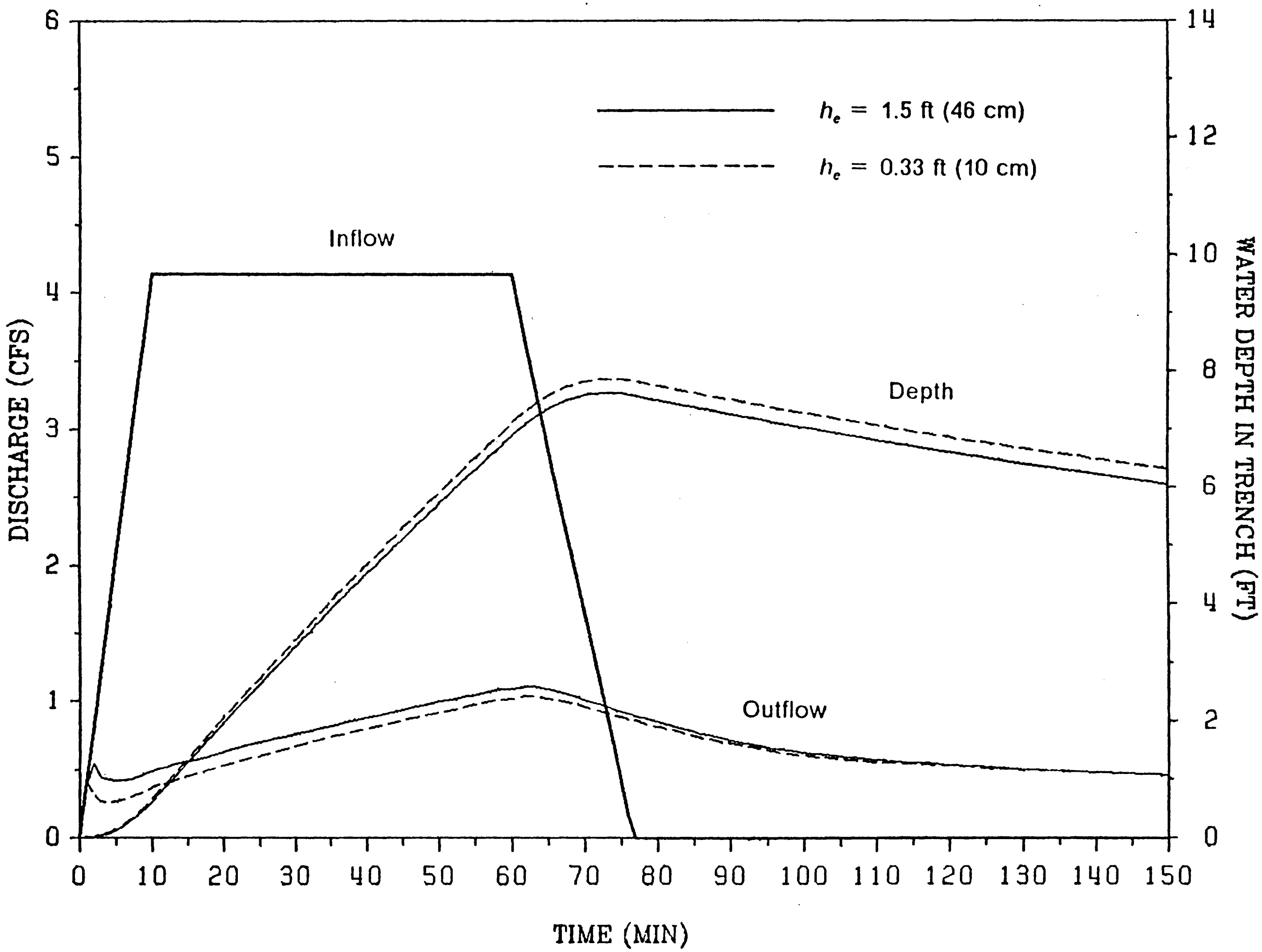


Figure 29. Effect of effective capillary potential on hydrologic routing in trench

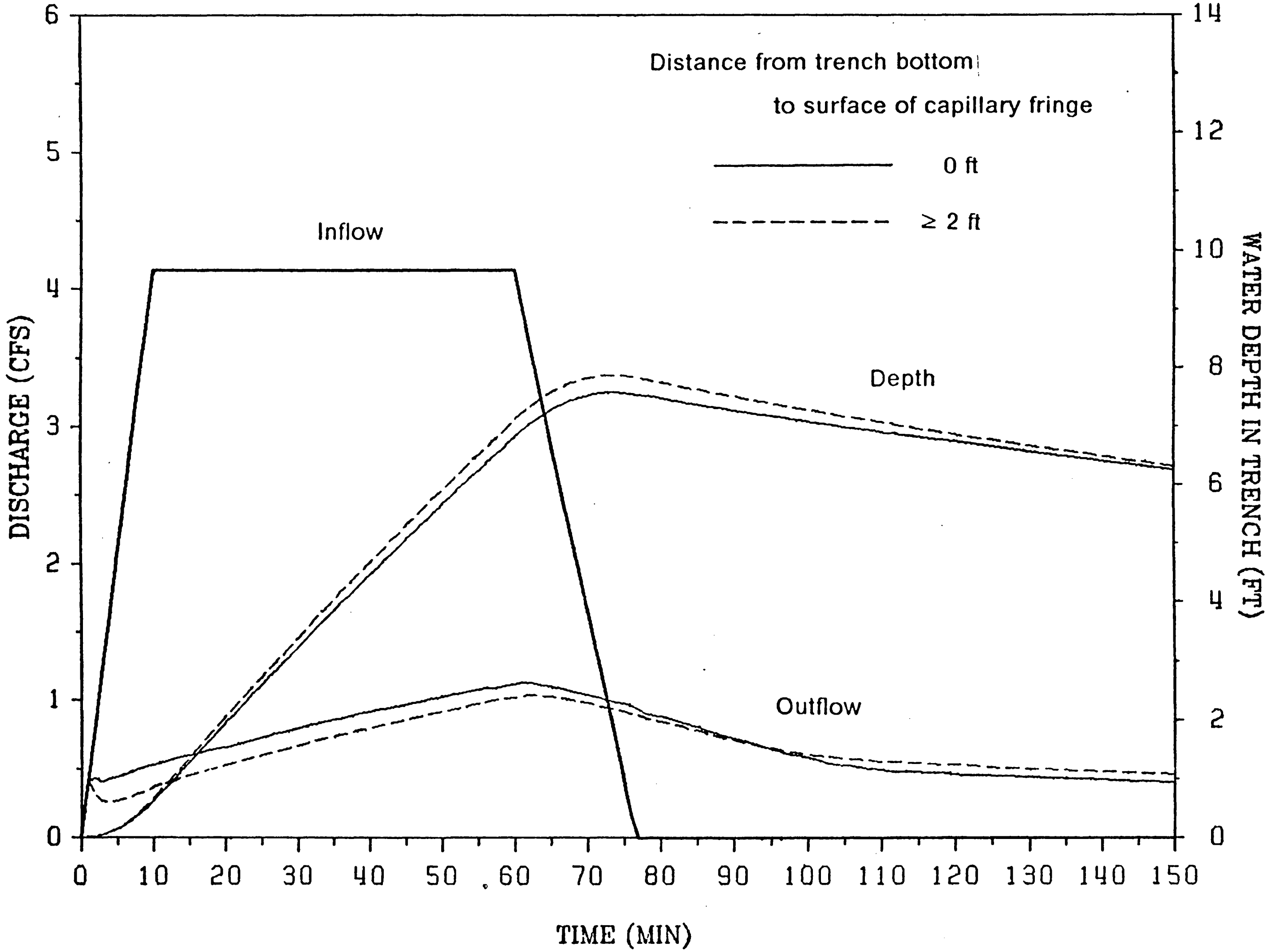


Figure 30. Effect of location of groundwater table on hydrologic routing in trench

5-3. *Infiltration of Rainfall*

If the rainfall intensity i is less than the infiltration capacity f_p of the soil, all rain will infiltrate into the ground. If $i > f_p$, runoff will be generated at the rate of $i - f_p$. f_p may initially be greater than a certain constant rainfall intensity i. As the rain continues, f_p decreases with time and may become equal to i and then less than i, as illustrated in Fig.31.

5-3-1. *Case of*

Before runoff begins, the water content at the soil surface increases until saturation is reached. The approximate vertical profile of the water content at the moment of saturation in the soil surface layer is shown in Fig.32 (a). The area bounded by the profile, the constant θ_i line, and the θ axis represents the amount of infiltration up to this point in time. The shaded area A_s is drawn equal to this area which is given by

$$A_s = \Delta\theta\, y_s \qquad (5-1)$$

where $\Delta\theta(= \theta_s - \theta_i)$ is the water content defficiency and y_s is the mean depth of the wetted zone. At this stage of surface saturation, the infiltration rate Q is still equal to the rainfall intensity, i. Therefore, Darcy's law can be written as (22, 23)

$$Q = i = K\frac{y_s + h_e}{y_s} \qquad (5-2)$$

in which

Q = infiltration rate

i = rainfall intensity

K = hydraulic conductivity

y_s = depth of the wetting front

h_e = effective capillary potential ($h_c - h_w$)

Combining Eqs.(5-1) and (5-2) yields

$$A_s = \frac{h_e \Delta\theta K}{(i - K)} \quad \text{for } i \geq K \qquad (5-3)$$

And the time T_p for incipient ponding or runoff to occur can be calculated by

$$T_p = \frac{A_s}{i} = \frac{h_e \Delta\theta K}{i(i - K)} \qquad (5-4)$$

5-3-2. Case of

After runoff begins, i.e. after the soil surface has become saturated, the water content profile can be represented by Fig.32 (b). Darcy's law can be applied again with the infiltration rate now being equal to the infiltration capacity f_p (22, 23).

$$f_p = K\frac{h_e + y_s + L}{y_s + L} \qquad (5-5)$$

where ($y_s + L$) is the depth of the wetting front. If F is the cumulative infiltration at any time, then $y_s + L = F/\Delta\theta$. Substituting this into Eq.(5-5) gives

$$f_p = K\left(1 + \frac{h_e \Delta\theta}{F}\right) \qquad (5-6)$$

Defining f_p = dF/dt and separating the variables yield

$$\int_{A_s}^{F} \frac{F\,dF}{F + h_e \Delta\theta} = \int_{T_p}^{t} K\,dt \qquad (5-7)$$

which is

$$\begin{aligned} K(t - T_p) + A_s - h_e \Delta\theta \, \ln(A_s + h_e \Delta\theta) \\ = F - h_e \Delta\theta \, \ln(F + h_e \Delta\theta) \end{aligned} \qquad (5-8)$$

Eq.(5-8) can be solved for F by iteration.

The following data are used for illustration.

rainfall intensity = 2.3 inches/hour

drainage area = 2 acres

time of concentration = 10 min.

rainfall duration = 60 min.

hydraulic conductivity of soil = 0.0007 ft/min.

saturated water content = 0.47

initial water content = 0.1

effective capillary potential = 0.33 ft

The time for incipient runoff to occur can be calculated by Eq.(5-4). For the data given above it is found to be 10.7 minutes. Fig.33 (a) shows the inflow hydrograph without infiltration from the soil surface and the infiltration rate from the soil surface as calculated by Eq.(5-8) and (5-6).

The net inflow hydrograph into the trench in pervious areas which is shown in Fig.33 (b) is obtained by subtracting the infiltration rate from the inflow.

With the same reason explained in Section 5-1, Fok's model is not applicable to an infiltration trench surrounded by saturated soil. A solution based on Fok's model is valid only before the wetting front meets the saturated soil in the layer near the ground surface. Referring to Fig.9, the flow region near the corner of OAB exhibits a saturated flow soon after the overland flow infiltrates into the ground. Therefore, Fok's model is not applicable in this case. In order to investigate the effect of surface infiltration due to overland flow on the distribution of the water content in the soil media, the finite difference method developed in this study can be used as an alternative solution technique. However, there are some weak features in this method. The finite difference program requires many iterations for solving systems of linear equations. Besides, as it was explained in Section 4-3-1, the hydrologic routing in an infiltration trench requires trial and error procedures. Therefore, the finite difference method is too expensive to carry out the hydrologic routing in the trench. A typical computer run to obtain a complete set of solution without surface infiltration requires an estimate of CPU time of more than 200 minutes for an infiltration time of 120 minutes. However, in order to just show the effect of the surface infiltration on the θ distribution, the finite difference method is used for the Ida silt loam soil with the boundary condition on the soil surface layer prescribed based on Eqs.(5-4) and (5-8). Realizing the wetting process in the surface layer is time dependent, the boundary condition is a function of time. Eqs.(5-4) and (5-8) are used for $t = T_p$ and $t > T_p$ respectively. For the case of $t < T_p$, linear interpolation to calculate θ at the soil surface and the average depth of wetting front, y_s, is adapted for each time interval Δt. For example, $\theta = 0$ at $t = 0$, and $\theta = \theta_s$ at $t = T_p$ at the soil surface are used. Fig.34 and 35 show the comparisons of the advances of the wetting front for the cases with and without surface infiltration for infiltration time of 60min. and 240min. respectively. The difference in the distribution of the soil water content is not significant except in the surface layer. It is not anticipated that the surface infiltration will significantly affect the infiltration from the trench as can be seen in Fig.36 in which the infiltration rates are compared for the cases with and without surface infiltration.

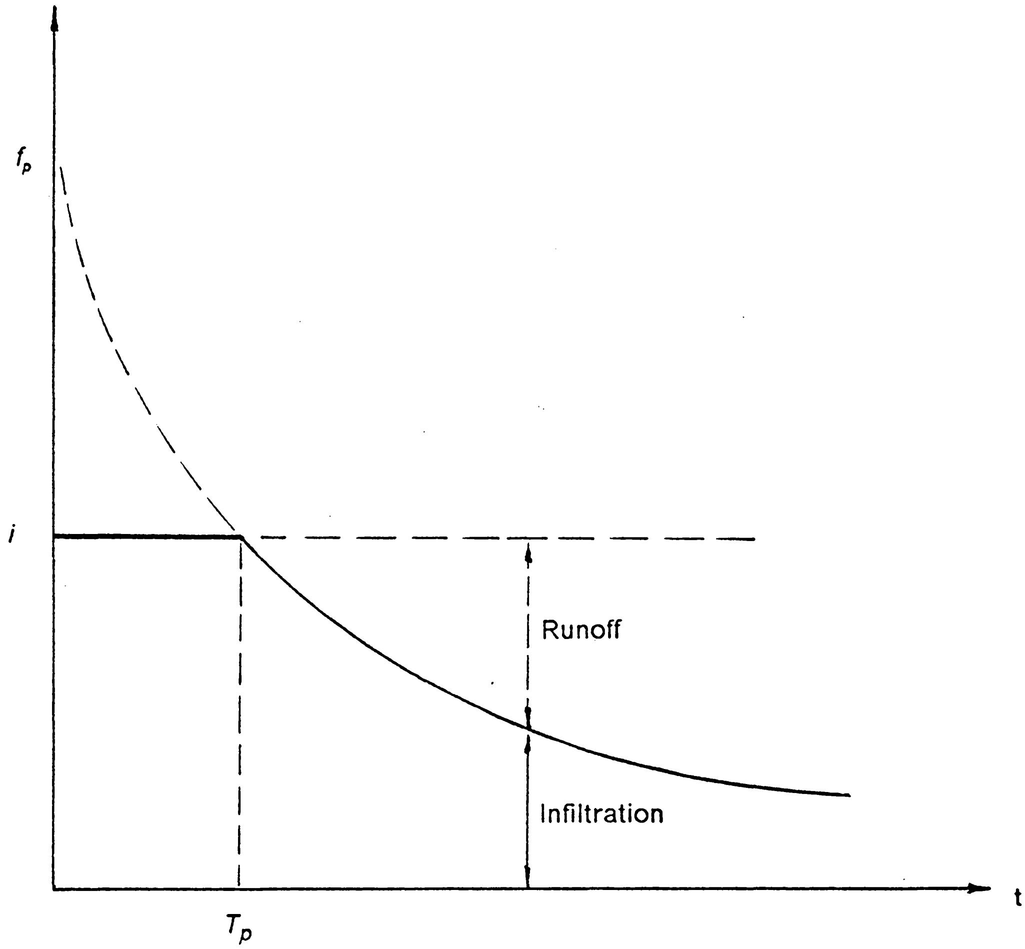


Figure 31. Infiltration and runoff for rainfall of uniform intensity

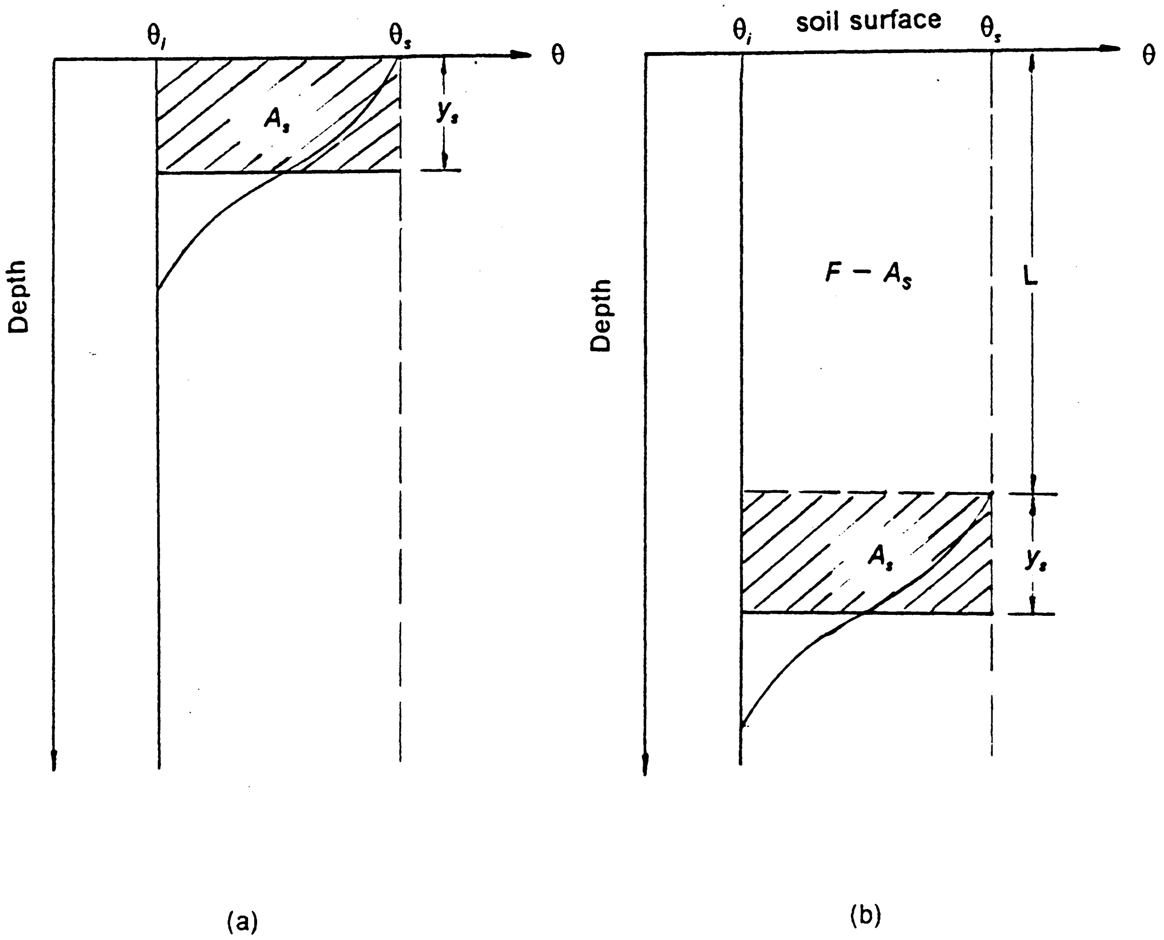


Figure 32. **Soil moisture profiles due to rainfall infiltration:** (a) at the moment of surface saturation and (b) at a later time (24, 25)

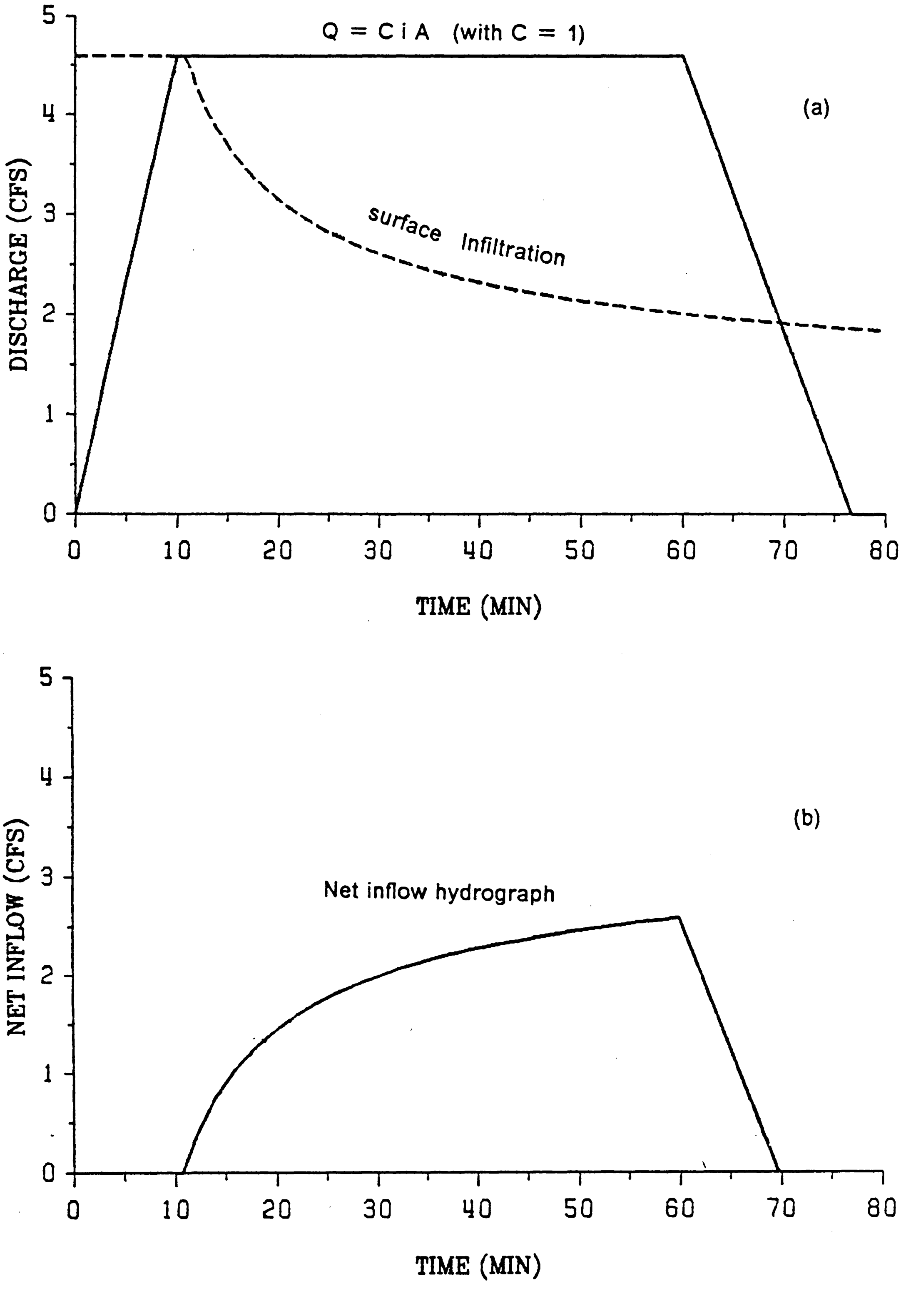
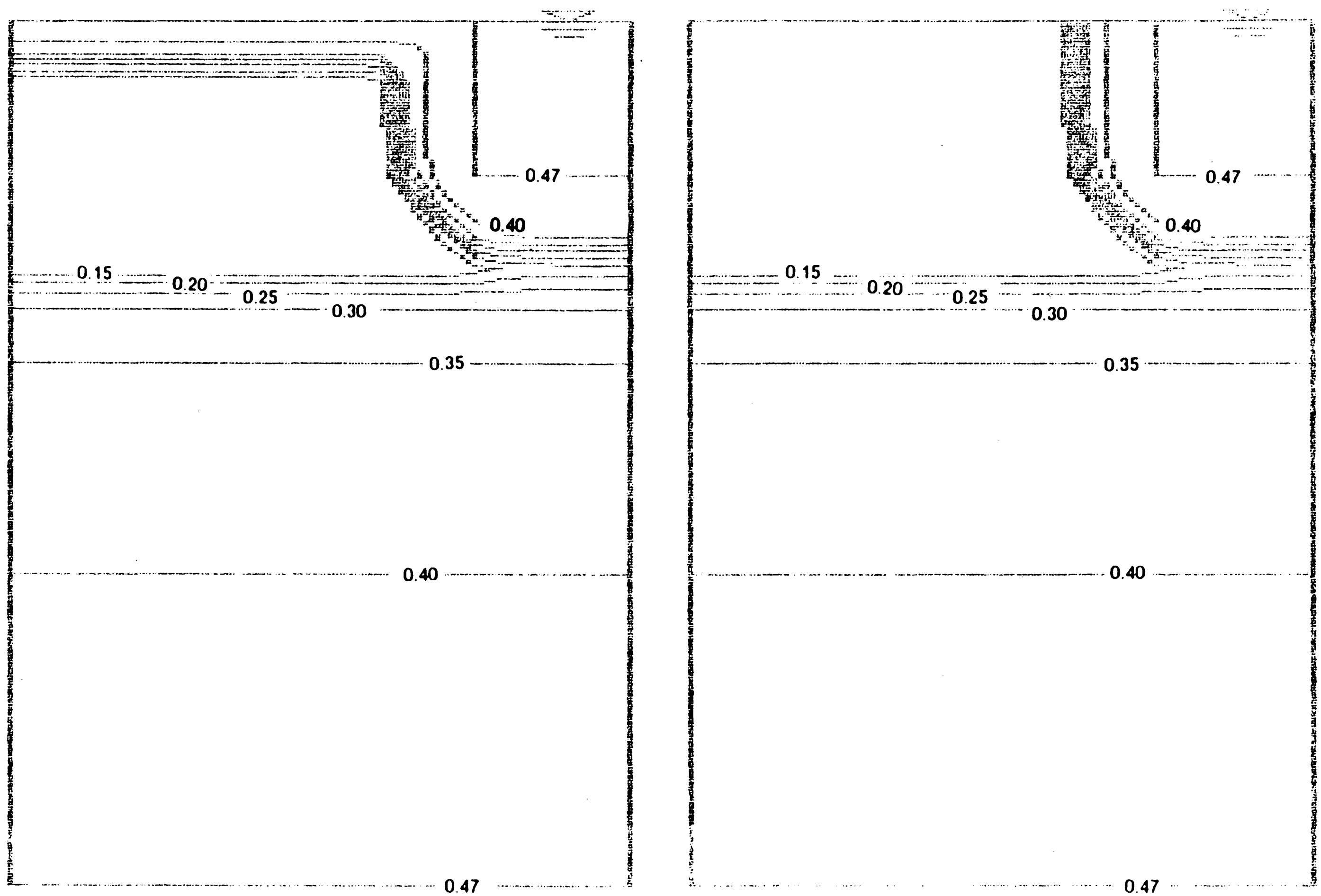


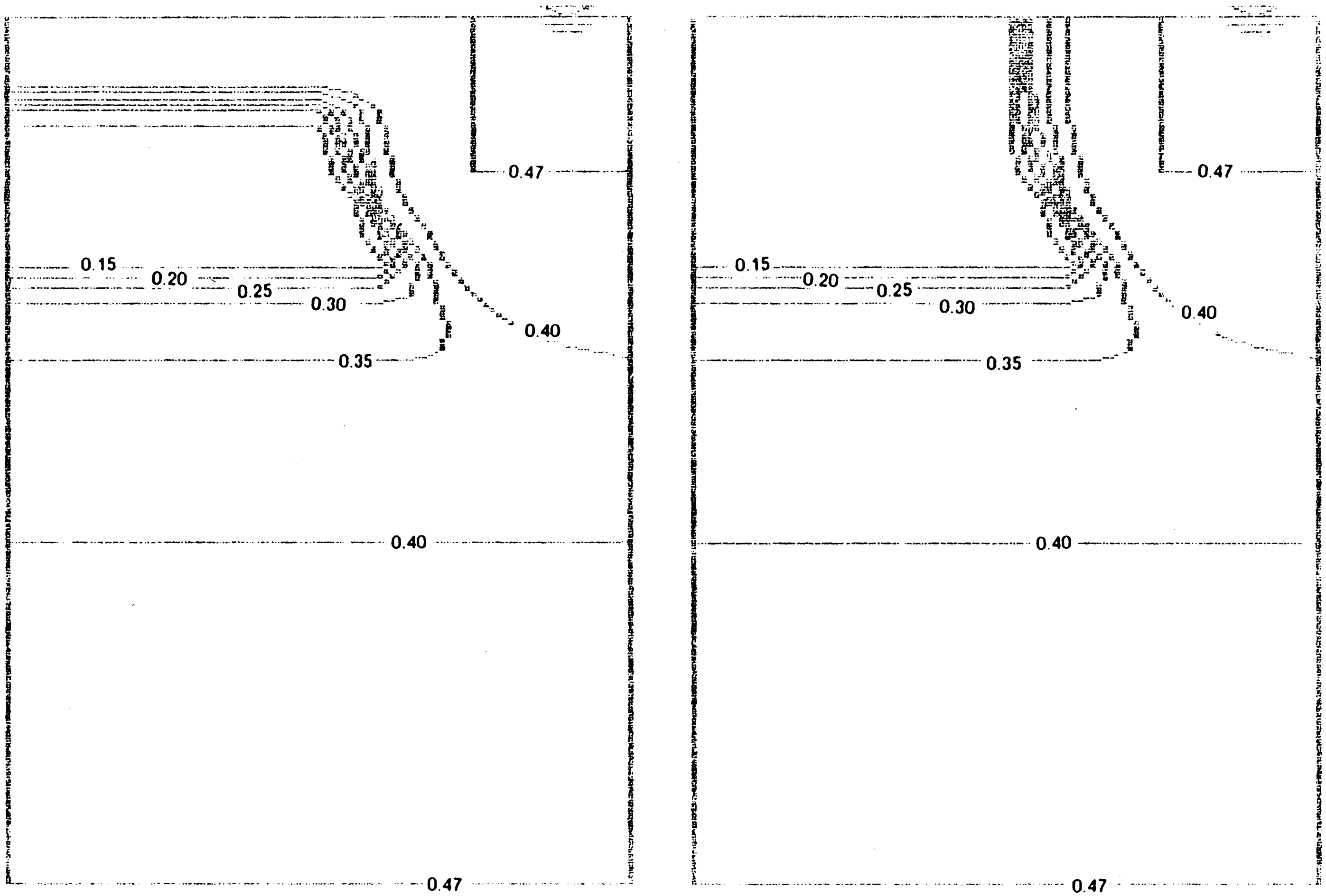
Figure 33. Net inflow hydrograph from pervious areas



(a) with surface infiltration

(b) without surface infiltration

Figure 34. Comparison of the advances of wetting front from trench with rainfall infiltration being considered (60 minutes later)



(a) with surface infiltration

(b) without surface infiltration

Figure 35. Comparison of the advances of wetting front from trench with rainfall infiltration being considered (240 minutes later)

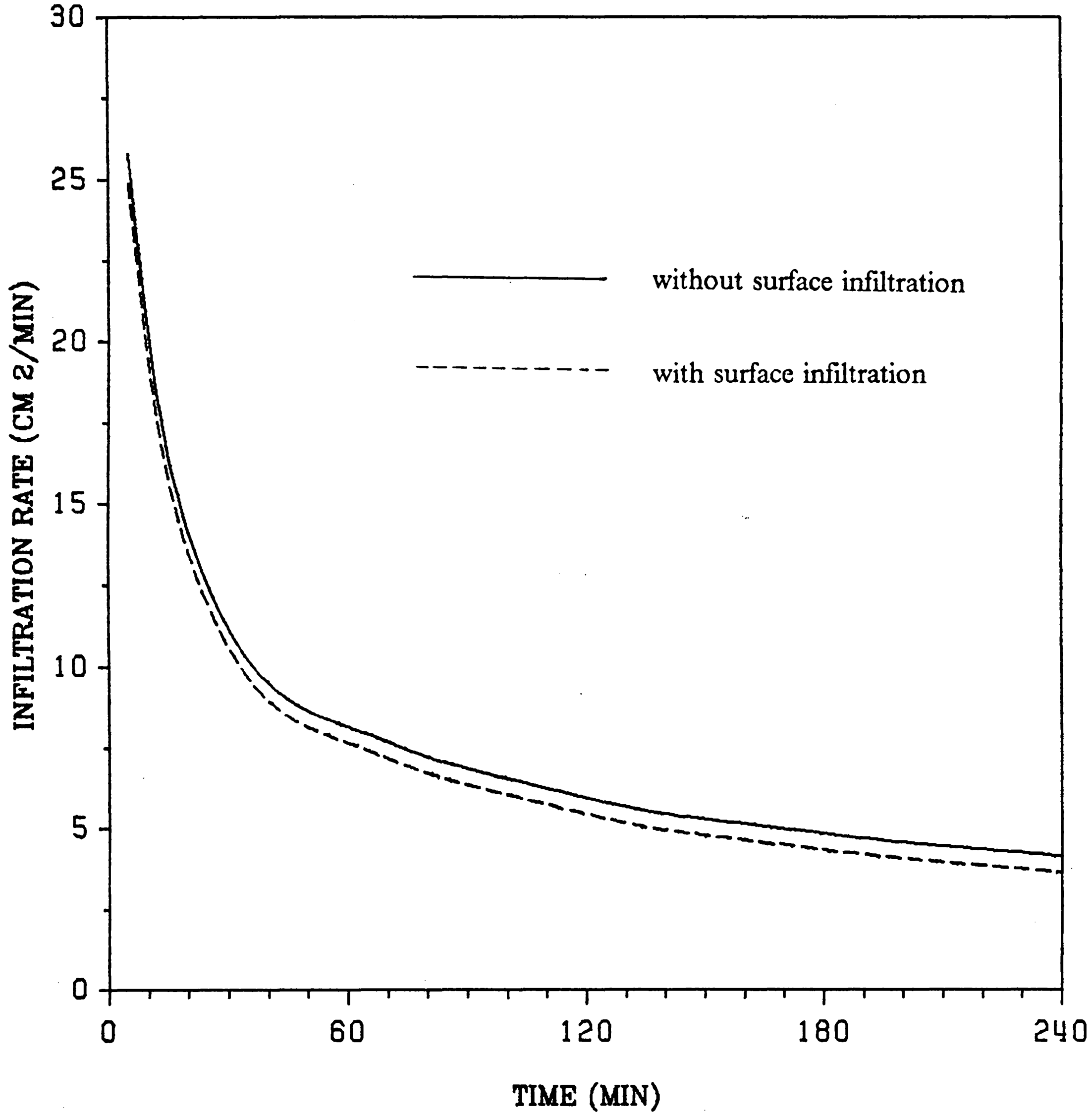


Figure 36. Comparison of infiltration rates for the cases with and without surface infiltration

Chapter 6 Summary and Conclusion

Summary:

The hydrologic and hydraulic characteristics of infiltration trenches in unsaturated soil have been studied. The following specific work tasks have been completed.

1. A computer program for the finite difference method has been coded. The water content profiles in the capillary fringe zone above the groundwater table for both the Ida silt loam soil and the Webster clay loam soil have been calculated using this program and have been applied to both the Fok's model and the finite difference model in the calculation of the water content distribution in unsaturated soil under the influence of an infiltration trench.

2. The water content distributions in the soil calculated by the Fok's model and the finite difference model have been compared with each other for both the Ida silt loam soil and the Webster clay loam soil. The infiltration rates from the trench have also been compared.

3. A 3-dimensional cumulative infiltration equation has been derived based upon the Fok's 2-D equation.

4. An inflow hydrograph to the infiltration trench has been generated based on the Rational Formula.

5. A computer program for hydrologic routing in an infiltration trench has been developed, and the results of an example run have been presented.

6. An infiltration trench which permits overflow has been examined. The detention time has been defined and calculated.

7. The effects of the trench shape and the soil properties on the storage in the trench and the infiltration rate have been discussed.

8. The surface recharge effects on the inflow hydrograph in pervious areas, the water distribution in the soil, and the infiltration rates have been discussed.

Conclusions

1. The main objective of installing an infiltration trench is to control peak runoff. It has been demonstrated in this study that an infiltration trench, if designed properly, can be an effective practice in urban stormwater management.

2. Infiltration trenches with overflow can be designed such that the maximum overflow does not exceed the allowable discharge which is normally equal to the peak discharge for pre-development land use condition.

3. A long narrow trench is more effective for water to infiltrate into soil than a short wide trench of the same trench area(length × width). The hydraulic conductivity of soil is a main factor in the design of an infiltration trench, whereas the porosity and the effective capillary potential have minor effects. At the early stage of infiltration, the trench which has a higher groundwater table underneath infiltrates more water. However, since this trend is reversed as time passes,

it is recommended that an infiltration trench be installed where the groundwater table is low. The inflow hydrograph from a pervious drainage area can be found by subtracting the surface infiltration rate from the surface runoff with C = 1 in the Rational Formula. It has been found that the surface infiltration due to overland flow does not significantly alter the infiltration rate from the trench.

4. Fok's model is easier to apply to the practical design of the infiltration trenches since infiltration rate and cumulative infiltration can be calculated by relatively simple equations as compared with the finite difference model which requires extensive computation time. Fok's original 2-D model is valid only for infiltration calculations in unsaturated soil and without the presence of the capillary fringe due to the groundwater table. The latter deficiency has been rectified in the present study and the 2-D model has been extended to the 3-D case. Fok's model, when compared with the finite difference model, favorably predicts the distribution of the soil water content and the infiltration rate from the trench. Therefore, it is recommended that the 3-D infiltration equation developed in this study be used for the analysis and design of infiltration trenches.

Bibliography

1. American Society of Civil Engineers ***Stormwater Detention Facilities*** Proceedings of Conference, Henniker, New Hampshire, August, 1982.

2. Beukeboom,Th.J. "A Dry-Well System for Excess Rainwater Discharge" Proceedings of the International Symposium on Urban Hydrology, Hydraulics and Sediment Control, Lexington, Kentucky, July, 1982.

3. Bouwer,Herman ***Groundwater Hydrology*** McGraw-Hill, 1978.

4. Chong,S.K., Green,R.E. and Ahuja,L.R. "Simple Insitu Determination of Hydraulic Conductivity by Power Function Descriptions of Drainage" Water Resources Research, Vol.17, pp.1108-1114, 1981.

5. Diniz,E.V. "Quantifying the Effects of Porous Pavements on Urban Runoff" Proceedings of the National Symposium on Urban Hydrology, Hydraulics, and Sediment Control, Lexington, Kentucky, July, 1976.

6. Douglas Jr.,J. "A Survey of Numerical Methods of Parabolic Differential Equations" Adv. Comput., Vol.2, pp.1-54, 1961.

7. Ericsson,L.O. and Gustafson,G. "Design of Stormwater Recharge Basins" Proceedings of the Conference on Stormwater Detention Facilities, Henniker, New Hampshire, August, 1982.

8. Fok,Yu-Si and Hansen,Voughn E. "One-dimensional Infiltration Into Homogeneous Soil" Journal of Irrigation and Drainage Division, ASCE, Vol.92, No.IR3, pp.35-48, Sept. 1966.

9. Fok,Yu-Si "Infiltration Equation in Exponential Forms" Journal of Irrigation and Drainage Division, ASCE, Vol.93, No.IR4, pp.125-135, Dec. 1969.

10. Fok,Yu-Si, Chung,Sang-Ok and Liu,Clark C.K. "Two-dimensional Exponential Infiltration Equations" Journal of Irrigation and Drainage Division, ASCE, Vol.108, No.IR4, pp.231-241, Dec. 1982.

11. Fok,Yu-Si and Chiang,Shan-Hsin "2-D Infiltration Equations for Furrow Irrigation" Journal of Irrigation and Drainage Division, ASCE, Vol.110, No.2, pp.208-217, June 1984.

12. Fritton,D.D., Kirkham,D. and Shaw,R.H. "Soil Water Evaporation, Isothermal Diffusion, and Heat and Mass Transfer" Soil Science Society of America, proc., Vol.34, pp.183-189, 1970.

13. Green,R.E., HanksR.J. and Larson,W.E. "Estimates of Field Infiltrations by Numerical Solutions of the Moisture Flow Equation" Soil Science Society of America, proc., Vol.28, pp.15-19, 1964.

14. Hansen,Vaughn E. "Infiltration and Soil Water Movement during Irrigation" Soil Science, Vol.79, No.2 , pp.93-105, Feb. 1955.

15. Hantzsche,N.N. and Franzini,J.B. "Utilization of Infiltration Basins for Urban Stormwater Management" Proceedings of the International Symposium on Urban Runoff, Lexington, Kentucky, July, 1980.

16. Higgs,G.E. "A Case Study of Percolation Storage" Proceedings of the International Symposium on Urban Stormwater Management, Lexington, Kentucky, July, 1978.

17. Hilderbrand,F.B. ***Introduction to Numerical Analysis*** McGraw-Hill, New York, 1956.

18. Israelson and Hansen,Vaughn E. ***Irrigation Principles and Practices*** John Wiley & Sons, 1962.

19. Li,Wen-hsiung ***Fluid Mechanics in Water Resources Engineering*** pp.421-424, Allyn and Bacon Inc., 1983.

20. Maryland Department of Natural Resources. ***Standards and Specifications for Infiltration Practices*** Stormwater Management Division, Water Resources Administration, Feb. 1984.

21. Mein,R.G. and Farrell,D.A. "Determination of Wetting Front Suction in the Green-Ampt Equation" Soil Science Society of America Proc., Vol.38, pp.872-876, 1974.

22. Mein,R.G. and Larson,C.L. "Modeling the Infiltration Component of the Rainfall-Runoff Process" Bull.43, pp.15-20, Water Resources Research Center, Univ. of Minn., Minneapolis, 1971.

23. Mein,R.G. and Larson,C.L. "Modeling Infiltration during a Steady Rain" Water Rsources Research, Vol.9, No.2, pp.384-394, April, 1973.

24. Northern Virginia Planning District Commission ***Guidebook for Screening Urban Nonpoint Pollution Management Strategies*** 1978.

25. Panikar,J.T. and Nanjappa,G. "Suction Head at Wet Front in Unsaturated-flow Problems-A new definition" Journal of Hydrology, Vol.33, pp.1-14, 1977.

26. Remson,I., Hornberger,G.M. and Molz,F.J. ***Numerical Methods in Subsurface Hydrology*** Wiley-Interscience, New York, 1971.

27. Richards,L.A. "Capillary Conduction of Liquids through Porous Mediums" Physics, Vol.1, pp.318-333, 1931.

28. Selim,H.M. and Kirkham,Don "Unsteady State Two-dimensional Water Content Distribution and Wetting Fronts in Soils" Geoderma, Vol.11, pp.259-274, 1974.

29. Sieker,F. "Stormwater Infiltration in Urban Areas" Proceedings of the Third International Conference on Urban Storm Drainage, Goteborg, Sweden, June, 1984.

30. South Florida Water Management District ***Permitting Information Manual*** Vol.4, Management and Storage of Surface Waters, Jan. 1983.

31. Varga,R.S. ***Matrix Iterative Analysis*** Prentice-Hall, 1962.

32. Virginia Department of Highways & Transportation. ***Drainage Manual***

33. Virginia State Water Control Board. ***Best Management Practices Handbook*** Chapter on Urban, Nov. 1978.

Appendix A. Listing of Computer Programs

```
C
C  THIS PROGRAM IS TO CALCULATE THE INFILTRATION RATE
C      VS. TIME  USING FOK'S INFILTRATION MODEL
C           WITH CAPILLARY FRINGE
C
C  IDA SILT LOAM,   IW=.1,  SW=.47
C
      DIMENSION WC(21), S(101), SS(100)
C
      READ(5,100) POR, H, P, W, D, GAP
  100 FORMAT(6F10.0)
C
      WC(1) = 0.1
      WC(2) = 0.2868
      WC(3) = 0.3290
      WC(4) = 0.3487
      WC(5) = 0.3615
      WC(6) = 0.3709
      WC(7) = 0.3785
      WC(8) = 0.3849
      WC(9) = 0.3905
      WC(10) = 0.3955
      WC(11) = 0.4001
      WC(12) = 0.4043
      WC(13) = 0.4083
      WC(14) = 0.4122
      WC(15) = 0.4159
      WC(16) = 0.4197
```

```
      WC(17) = 0.4234
      WC(18) = 0.4272
      WC(19) = 0.4312
      WC(20) = 0.4343
      WC(21) = 0.47
C
      DO 200 I = 0, 19
       DIFF = (WC(I+2)-WC(I+1))/5.
       SS(5*I+1) = WC(I+1) + DIFF/2.
       SS(5*I+2) = SS(5*I+1) + DIFF
       SS(5*I+3) = SS(5*I+2) + DIFF
       SS(5*I+4) = SS(5*I+3) + DIFF
       SS(5*I+5) = SS(5*I+4) + DIFF
  200 CONTINUE
      S(101) = (POR-0.1)/POR * 0.8
      DO 300 I = 1, 100
       S(I) = (POR-SS(I))/POR * 0.8
  300 CONTINUE
C
      COM = POR*S(101)*H/P
      T1 = 0.00476 * COM
      T2 = 0.316 * COM
      T3 = 3.26 * COM
      T4 = 26.86 * COM
      TTT = (GAP/1.82)**(1./0.55)*POR*S(101)/P/H**0.818
C
C
      FLUX2 = 0.
```

```
      DO 1500 IT = 1, 480
        X = SQRT(2.*P*H/POR/S(101)*IT)
        IF (IT.GT.TTT) GO TO 500
        IF (IT.GT.T1) GO TO 400
        Y = 1.45*SQRT(P*H*IT/POR/S(101))
        GO TO 1100
  400   Y = 1.82*(P*H**0.818*IT/POR/S(101))**0.55
        GO TO 1100
C
  500   TT4 = 0.
        DO 800 J = 1, 100
          IF ((TTT+TT4).GT.T2) GO TO 600
          TT1 = ((GAP+2.*(J-1))/1.82)**(1./0.55)
     %              *POR*S(J)/P/H**0.818
          TT2 = ((GAP+2.*J)/1.82)**(1./0.55)
     %              *POR*S(J)/P/H**0.818
          GO TO 700
  600     TT1 = ((GAP+2.*(J-1))/2.19)**(1./0.68)
     %              *POR*S(J)/P/H**0.47
          TT2 = ((GAP+2.*J)/2.19)**(1./0.68)
     %              *POR*S(J)/P/H**0.47
  700     TT3 = TT2 - TT1
          TT4 = TT4 + TT3
          IF ((TTT+TT4).GE.IT) GO TO 900
  800   CONTINUE
        YYY = 2.19*(P*H**0.47*(TTT+TT4)/POR/S(100))**0.68
        YY = 2.19*(P*H**0.47*IT/POR/S(100))**0.68
        Y = GAP + 200. + (YY-YYY)
```

```
      GO TO 910
C
  900 Y = GAP+2.*(J-1)+2.*(TT3-TTT-TT4+IT)/TT3
  910 SUB1 = 0.
      IF (Y.GE.(GAP+2.)) GO TO 950
      SUB1 = AREA(GAP, Y, X, Y)*S(1)
      GO TO 1050
  950 DO 1000 I = 1, J-1
        DIS1 = GAP+2.*(I-1)
        DIS2 = GAP+2.*I
        SSUB = AREA(DIS1, DIS2, X, Y)*S(I)
        SUB1 = SUB1 + SSUB
 1000 CONTINUE
      SUB1 = SUB1 + AREA(DIS2, Y, X, Y)*S(J)
 1050 AREA1 = AREA(0, GAP, X, Y)
      SUB2 = (AREA1 + W*GAP + D*X)*S(101)
      FLUX = (SUB1+SUB2)*POR
      GO TO 1200
C
 1100 FLUX = (3.14159/4.*X*Y + W*Y + D*X)*POR*S(101)
C
C
C
 1200 FLUX1 = FLUX - FLUX2
      FLUX2 = FLUX2 + FLUX1
      WRITE(6,1300) IT, X, Y, FLUX1
 1300 FORMAT(5X, I4, ' MIN. LATER   X=', F5.1, 'CM Y=',
```

```
    %      F5.1,'CM   FLUX=', F7.2, 'CM¢3/CM')
1500 CONTINUE
    STOP
    END
C   ############################
    FUNCTION AREA(A, B, X, Y)
C   ############################
    AREAB = X/2./Y*(B*SQRT(Y**2.-B**2.)+Y**2.*ASIN(B/Y))
    AREAA = X/2./Y*(A*SQRT(Y**2.-A**2.)+Y**2.*ASIN(A/Y))
    AREA = AREAB - AREAA
    RETURN
    END
```

```
C ############################################################################
C
C THIS PROGRAM IS TO CALCULATE THE WATER CONTENT AT NODAL
C    POINTS IN FLOW REGION  BY  FINITE DIFFERENCE METHOD
C
C ##########################################################
C
C    THIS PROGRAM IS TO COMPARE FOK'S SOLUTION
C            TO TWO-DIM. FINITE DIFFERENCE SOLUTION
C
C ##########################################################
C
C
      DIMENSION W1(41,33), W2(41,33), A(39,3), B(39), X(39)
      DIMENSION D(41,33), P(41,33)
C
C
      READ(5,100) NT, NY, NX, DT, DX, WRI, WRS
 100 FORMAT(3I5, 4F10.0)
C
      DY = DX
      GAMMA = DT/DX**2.
      BETTA = DT/2./DY
C
C ##############################
C #    INITIAL CONDITIONS     #
C ##############################
C
```

```
      IT = 0
      DO 300 J = 1, NY-27
       DO 250 I = 1, NX
        W1(J,I) = WRI
250    CONTINUE
300 CONTINUE
      W1(15,7) = .1000
      W1(16,7) = .2868
      W1(17,7) = .3290
      W1(18,7) = .3487
      W1(19,7) = .3615
      W1(20,7) = .3709
      W1(21,7) = .3785
      W1(22,7) = .3849
      W1(23,7) = .3905
      W1(24,7) = .3955
      W1(25,7) = .4001
      W1(26,7) = .4043
      W1(27,7) = .4083
      W1(28,7) = .4122
      W1(29,7) = .4159
      W1(30,7) = .4197
      W1(31,7) = .4234
      W1(32,7) = .4272
      W1(33,7) = .4312
      W1(34,7) = .4343
      W1(35,7) = .4700
      DO 302 J = 15, 35
```

```
      DO 301 I = 8, 27
       W1(J,I) = W1(J,7)
 301  CONTINUE
 302 CONTINUE
C
C
C  ##################################################
C  #    ALTERNATING DIRECTION IMPLICIT SCHEME       #
C  ##################################################
C
C       ##########  X - DIRECTION  ##########
C
C
 1000 IT = IT + 1
     CALL BOUND1(W1, WRI, WRS)
     CALL FUNCT(W1, D, P)
     DO 500 J = 7, NY-6
      IXX = NX - 2
      DO 310 KK = 1, IXX
       I = KK + 1
       D1 = (D(J,I-1)+D(J,I))/2.
       D2 = (D(J,I)+D(J,I+1))/2.
       A(KK,1) = -GAMMA * D1
       A(KK,2) = 1 + GAMMA*(D1+D2)
       A(KK,3) = -GAMMA * D2
 310  CONTINUE
      DO 350 I = 2, IXX+1
       D1 = (D(J-1,I)+D(J,I))/2.
```

```
      D2 = (D(J,I)+D(J+1,I))/2.
      B(I-1) = GAMMA*D1*W1(J-1,I) + (1.-GAMMA*D2-GAMMA*D1)*W1(J,I)
   %          + GAMMA*D2*W1(J+1,I) - BETTA*(P(J+1,I)-P(J-1,I))
 350  CONTINUE
      CALL SOLVER(A, B, X, IXX)
      DO 400 I = 1, IXX
       W2(J,I+1) = X(I)
 400  CONTINUE
 500 CONTINUE
     CALL EXCHAN(W1, W2)
C
C
C
C     ##########  Y - DIRECTION  ##########
C
     IT = IT + 1
     CALL BOUND2(W1, WRI, WRS)
     CALL FUNCT(W1, D, P)
     DO 800 I = 7, NX-6
      IYY = NY-2
      IF (I.NE.22) GO TO 520
      DO 510 J = 1, 12
       W1(J,21) = WRS
       D(J,21) = 3.33*EXP(29.34*W1(J,21)) / 10.**5.
       P(J,21) = 3.33*EXP(54.11*W1(J,21)) / 10.**13.
 510  CONTINUE
 520  DO 550 KK = 1, IYY
       J = KK + 1
```

```
      D1 = (D(J-1,I) + D(J,I))/2.
      D2 = (D(J,I) + D(J + 1,I))/2.
      A(KK,1) = -GAMMA*D1
      A(KK,2) = 1 + GAMMA*(D1 + D2)
      A(KK,3) = -GAMMA*D2
550   CONTINUE
     DO 600 J = 2, IYY + 1
      D1 = (D(J,I-1) + D(J,I))/2.
      D2 = (D(J,I) + D(J,I + 1))/2.
      B(J-1) = GAMMA*D1*W1(J,I-1) + (1.-GAMMA*D2-GAMMA*D1)*W1(J,I)
   %          + GAMMA*D2*W1(J,I + 1) - BETTA*(P(J,I + 1)-P(J,I-1))
600   CONTINUE
     CALL SOLVER(A, B, X, IYY)
     DO 700 J = 1, IYY
      W2(J + 1,I) = X(J)
700   CONTINUE
800 CONTINUE
    CALL EXCHAN(W1, W2)
C
C
C
    IF (IT.NE.NT/DT) GO TO 1000
C
C
    CALL BOUND1(W1, WRI, WRS)
    WRITE(6,900) ((W1(J,I), J = 7,35), I = 7,27)
```

```
 900 FORMAT(10F8.4)
C
C
      STOP
      END
C
C
C
C
C   ###################################
      SUBROUTINE BOUND1(W1, WRI, WRS)
C   ###################################
C
      DIMENSION W1(41,33)
C
      DO 1050 J = 7, 12
        DO 1040 I = 22, 33
          W1(J,I) = WRS
 1040   CONTINUE
 1050 CONTINUE
C
      DO 1010 I = 1, 33
        W1(6,I) = W1(7,I)
        W1(35,I) = WRS
        W1(36,I) = WRS
 1010 CONTINUE
C
      DO 1020 J = 8, 34
```

```
        W1(J,6) = W1(J,7)
        W1(J,5) = W1(J,6)
        W1(J,4) = W1(J,5)
        W1(J,3) = W1(J,4)
        W1(J,2) = W1(J,3)
        W1(J,1) = W1(J,2)
 1020 CONTINUE
C
      DO 1070 J = 7, 35
        DO 1060 I = 28, 33
          W1(J,I) = W1(J,27)
 1060   CONTINUE
 1070 CONTINUE
      RETURN
      END
C
C
C ####################################
      SUBROUTINE BOUND2(W1, WRI, WRS)
C ####################################
C
      DIMENSION W1(41,33)
C
      DO 1020 J = 8, 34
        W1(J,6) = W1(J,7)
 1020 CONTINUE
C
      DO 1035 J = 1, 12
```

```
      DO 1034 I = 22, 28
       W1(J,I) = WRS
 1034  CONTINUE
 1035 CONTINUE
C
      DO 1010 I = 6, 28
       W1(6,I) = W1(7,I)
       W1(5,I) = W1(6,I)
       W1(4,I) = W1(5,I)
       W1(3,I) = W1(4,I)
       W1(2,I) = W1(3,I)
       W1(1,I) = W1(2,I)
       W1(35,I) = WRS
       W1(36,I) = WRS
       W1(37,I) = WRS
       W1(38,I) = WRS
       W1(39,I) = WRS
       W1(40,I) = WRS
       W1(41,I) = WRS
 1010 CONTINUE
C
      DO 1070 J = 13, 35
       W1(J,28) = W1(J,27)
 1070 CONTINUE
      RETURN
      END
C
C
```

```
C
C ##############################
      SUBROUTINE FUNCT(W1, D, P)
C ##############################
C
      DIMENSION W1(41,33), D(41,33), P(41,33)
C
      DO 1090 J = 1, 41
       DO 1080 I = 1, 33
         D(J,I) = 3.33*EXP(29.34*W1(J,I)) / 10.**5.
         P(J,I) = 3.33*EXP(54.11*W1(J,I)) / 10.**13.
 1080   CONTINUE
 1090 CONTINUE
      RETURN
      END
C
C
C
C ##################################
      SUBROUTINE SOLVER(A, B, X, IXX)
C ##################################
C
      DIMENSION A(39,3), B(39), X(39)
C
      M = IXX - 1
      A(1,3) = A(1,3)/A(1,2)
      DO 1100 I = 2, M
       A(I,2) = A(I,2) - A(I,1)*A(I-1,3)
```

```
   A(I,3) = A(I,3)/A(I,2)
1100 CONTINUE
  A(IXX,2) = A(IXX,2) - A(IXX,1)*A(M,3)
  B(1) = B(1)/A(1,2)
  DO 1200 I = 2, IXX
   B(I) = (B(I)-A(I,1)*B(I-1))/A(I,2)
1200 CONTINUE
  X(IXX) = B(IXX)
  DO 1300 I = M, 1, -1
   X(I) = B(I) - A(I,3)*X(I+1)
1300 CONTINUE
  RETURN
  END
C
C
C
C ##############################
  SUBROUTINE EXCHAN(W1, W2)
C ##############################
C
  DIMENSION W1(41,33), W2(41,33)
C
  DO 1500 J = 7, 35
   DO 1400 I = 7, 22
    W1(J,I) = W2(J,I)
1400  CONTINUE
1500 CONTINUE
  DO 1700 J = 12, 35
```

```
      DO 1600 I = 23, 27
       W1(J,I) = W2(J,I)
1600   CONTINUE
1700 CONTINUE
      RETURN
      END
```

```
C ###########################################################################
C   THIS PROGRAM IS TO FIND THE OUTFLOW HYDROGRAPH FROM
C      TRENCH AS WELL AS THE WATER DEPTH IN TRENCH
C
C           ########################################
C           ##        HYDRAULIC ROUTING          ##
C           ########################################
C
      DIMENSION QIN(100), WC(21), S(101), SS(100)
      COMMON QOUT1, QOUT2, QOUT4, QI1, ICOUNT, X, Y, TT0, TT1
      COMMON H1, XP, YP, LLL, KKK
      ICOUNT = 0
C
       READ(5,100) TC, TD, DELT, C, RI,
     %           AREA, TRENL, TRENW, ITREND, IDISWT,
     %           PORSO, PORAG, PC, EHC
  100 FORMAT(5F10.0//3F10.0,2I10//4F10.0/)
C
       WRITE(6,200)
  200 FORMAT(15X,'**********************************************************'
     %,/,15X,' TIME     QIN     QOUT      H     X     Y  ',/,
     %  15X,' (MIN)    (CFS)    (CFS)    (FT)   (FT)   (FT)  ',/,
     %  15X,'**********************************************************')
C
C   #################
C        INFLOW
C   #################
C
```

```
      QPEAK = C * RI * AREA * 60.
      TOTALT = TD + 1.67*TC
      LIMIT = INT(TOTALT/DELT) + 1
      QIN(1) = 0.
      DO 300 I = 1, LIMIT
       TIME = DELT * I
       IF (TIME.LE.TC) QIN(I+1) = TIME * QPEAK/TC
       IF (TIME.GT.TC .AND. TIME.LE.TD) QIN(I+1) = QPEAK
       IF (TIME.GT.TD .AND. TIME.LE.TOTALT)
     %       QIN(I+1) = QPEAK - (TIME-TD)*QPEAK/(1.67*TC)
       IF (TIME.GT.TOTALT) QIN(I+1) = 0.
  300 CONTINUE
C
C    ##########################################
C      SATURATION DEGREE S FOR EACH LAYER
C    ##########################################
C
      DO 400 I = 1, 21
       READ(5,500) WC(I)
  400 CONTINUE
  500 FORMAT(F10.0)
       DO 600 I = 0, 19
       DIFF = (WC(I+2)-WC(I+1))/5.
       SS(5*I+1) = WC(I+1) + DIFF/2.
       SS(5*I+2) = SS(5*I+1) + DIFF
       SS(5*I+3) = SS(5*I+2) + DIFF
       SS(5*I+4) = SS(5*I+3) + DIFF
       SS(5*I+5) = SS(5*I+4) + DIFF
```

```
 600 CONTINUE
     S(101) = (PORSO-0.1)/PORSO * 0.8
     DO 700 I = 1, 100
      S(I) = (PORSO-SS(I))/PORSO * 0.8
 700 CONTINUE
C
C
     IGAP = IDISWT - ITREND
     CASE = 1.
     KKK = 0
     H1 = 0.
     Y = 0.
     QOUT2 = 0.
     QOUT4 = 0.
     BONUS = 0.
     CALL ROUTE(CASE,BONUS,QIN,LIMIT,DELT,PORAG,
    %        TRENL,TRENW,EHC,PC,PORSO,IGAP,S)
     CASE = 2.
     BONUS = LIMIT * DELT
     RESIDU = 360. - TOTALT
     CALL ROUTE(CASE,BONUS,QIN,LIMIT,DELT,PORAG,
    %        TRENL,TRENW,EHC,PC,PORSO,IGAP,S)
     WRITE(6,800)
 800 FORMAT(15X,'****************************************************')
     STOP
     END
C
```

```
C
C    ######################################################
     SUBROUTINE ROUTE(CASE,BONUS,QIN,LIMIT,DELT,PORAG,
    %          TRENL,TRENW,EHC,PC,PORSO,IGAP,S)
C    ######################################################
C
     DIMENSION QIN(100), S(101)
     COMMON QOUT1, QOUT2, QOUT4, QI1, ICOUNT, X, Y, TT0, TT1
     COMMON H1, XP, YP, LLL, KKK
     ERR = 1.0
     DO 100 I = 1, LIMIT
      ICOUNT = ICOUNT + 1
      TT1 = DELT * (I-1) + BONUS
      TT0 = TT1 - DELT
      IF (CASE.GT.1.) GO TO 150
      QI1 = QIN(I)
      QI2 = QIN(I+1)
      QITOT = QI1 + QI2
      GO TO 200
 150  QI1 = 0.
      QI2 = -1.
      QITOT = 0.
 200  S1 = TRENL * TRENW * PORAG * H1
      AMINUS = 2.*S1/DELT - QOUT2
      PLUS = QITOT + AMINUS
      IF (H1.LT.1.) GO TO 300
      DL = H1 - 1.
      HH = DL
```

```
      GO TO 400
300   DL = 0.
400   HH = DL
      CALL OUTPUT(HH,EHC,PC,PORSO,TRENW,TRENL,DELT,IGAP,S)
      FA = 2.*TRENL*TRENW*PORAG*DL/DELT + QOUT2 - PLUS
      UL = H1 + 1.
      HH = UL
      CALL OUTPUT(HH,EHC,PC,PORSO,TRENW,TRENL,DELT,IGAP,S)
      FB = 2.*TRENL*TRENW*PORAG*UL/DELT + QOUT2 - PLUS
500   H2 = (DL + UL)/2.
      HH = H2
      CALL OUTPUT(HH,EHC,PC,PORSO,TRENW,TRENL,DELT,IGAP,S)
      FF = 2.*TRENL*TRENW*PORAG*H2/DELT + QOUT2 - PLUS
550   IF (ABS(FF).LT.ERR) GO TO 800
      IF (FF*FA) 700, 800, 600
600   DL = H2
      GO TO 500
700   UL = H2
      GO TO 500
800   QI1 = QI1 / 60.
      QOUT2 = QOUT2 / 60.
      WRITE(6,900) TT1, QI1, QOUT2, H1, X, Y
900   FORMAT(16X,F5.1,3X,F7.2,3X,F7.2,5X,F5.2,3X,F5.2,3X,F5.2)
      QI1 = QI1 * 60.
      QOUT2 = QOUT2 * 60.
      QOUT4 = QOUT1
      IF (QI2.GE.QI1) GO TO 1000
      LLL = 1
```

```
      KKK = KKK + 1
 1000  H1 = H2
      XP = X
      YP = Y
  100 CONTINUE
      RETURN
      END
C
C     ###################################################################
      SUBROUTINE OUTPUT(HH,EHC,PC,PORSO,TRENW,TRENL,DELT,IGAP,S)
C     ###################################################################
C
      DIMENSION S(101)
      COMMON QOUT1, QOUT2, QOUT4, QI1, ICOUNT, X, Y, TT0, TT1
      COMMON H1, XP, YP, LLL, KKK
      H = HH + EHC
      IF (TT1.GT.DELT) GO TO 100
      X = SQRT(2.*PC*H/PORSO/S(101)*TT1)
      GO TO 150
  100 H10 = (H1+H)/2.
      X1 = SQRT(2.*PC*H10/PORSO/S(101)*TT0)
      X2 = SQRT(2.*PC*H10/PORSO/S(101)*TT1)
      XDIFF = X2 - X1
      X = XP + XDIFF
  150 TCOM = PORSO * S(101) * H / PC
      T1 = .00476 * TCOM
      T2 = .316 * TCOM
      T3 = 3.26 * TCOM
```

```
      T4 = 26.86 * TCOM
      SLICE = 2. / 30.48
      IF (TT1.GT.T1) GO TO 200
      IF (TT1.GT.DELT) GO TO 160
      Y = 1.45*SQRT(PC*H*TT1/PORSO/S(101))
      GO TO 400
  160 Y1 = 1.45*SQRT(PC*H10*TT0/PORSO/S(101))
      Y2 = 1.45*SQRT(PC*H10*TT1/PORSO/S(101))
      YDIFF = Y2 - Y1
      Y = YP + YDIFF
      GO TO 400
  200 IF (TT1.GT.T2) GO TO 300
      IF (TT1.GT.DELT) GO TO 250
      Y = 1.82*(PC*H**0.818*TT1/PORSO/S(101))**0.55
      GO TO 400
  250 Y1 = 1.82*(PC*H10**0.818*TT0/PORSO/S(101))**0.55
      Y2 = 1.82*(PC*H10**0.818*TT1/PORSO/S(101))**0.55
      YDIFF = Y2 - Y1
      Y = YP + YDIFF
      GO TO 400
  300 IF (TT1.GT.DELT) GO TO 350
      Y = 2.19*(PC*H**0.47*TT1/PORSO/S(101))**0.68
      GO TO 400
  350 Y1 = 2.19*(PC*H10**0.47*TT0/PORSO/S(101))**0.68
      Y2 = 2.19*(PC*H10**0.47*TT1/PORSO/S(101))**0.68
      YDIFF = Y2 - Y1
      Y = YP + YDIFF
  400 IF (Y.LE.IGAP) GO TO 1500
```

```
500 IF (TT1.GT.T2) GO TO 550
    TTT=(IGAP/1.82)**(1./0.55)*PORSO*S(101)/PC/H**0.818
    GO TO 560
550 TTT = (IGAP/2.19)**(1./0.68)*PORSO*S(101)/PC/H**0.47
560 TTT4 = 0.
    DO 800 J = 1, 100
      IF ((TTT+TTT4).GT.T2) GO TO 600
      TTT1=((IGAP+SLICE*(J-1))/1.82)**(1./0.55)*PORSO*S(J)/PC/H**0.818
      TTT2=((IGAP+SLICE*J)/1.82)**(1./0.55)*PORSO*S(J)/PC/H**0.818
      GO TO 700
 600  TTT1=((IGAP+SLICE*(J-1))/2.19)**(1./0.68)*PORSO*S(J)/PC/H**0.47
      TTT2 = ((IGAP+SLICE*J)/2.19)**(1./0.68)*PORSO*S(J)/PC/H**0.47
 700  TTT3 = TTT2 - TTT1
      TTT4 = TTT4 + TTT3
      IF ((TTT+TTT4).GE.TT1) GO TO 900
800 CONTINUE
900 Y = IGAP + SLICE*(J-1) + SLICE*(TTT3-TTT-TTT4+TT1)/TTT3
    SUB1 = 0.
    IF (Y.GT.(IGAP+SLICE)) GO TO 1100
    YREST = Y - IGAP
    SUB1 = (AREA(IGAP,Y)*2.*(TRENW+TRENL)+TRENW*TRENL*YREST
  %        + VOLUME(IGAP,Y))*S(1)
    GO TO 1300
1100 DO 1200 I = 1, J-1
      DIS1 = IGAP+SLICE*(I-1)
      DIS2 = IGAP+SLICE*I
      SSUB1=AREA(DIS1,DIS2)*2.*(TRENW+TRENL)+TRENW*TRENL*SLICE
      SSUB2 = VOLUME(DIS1,DIS2)
```

```
      SUB1 = SUB1 + (SSUB1 + SSUB2)*S(I)
1200 CONTINUE
     YREST = Y - IGAP - I*SLICE
     SUB1=SUB1+(AREA(DIS2,Y)*2.*(TRENW+TRENL)+TRENW*TRENL*YREST
   %        + VOLUME(DIS2,Y))*S(J)
1300 VOL1 = AREA(0,IGAP)*2.*(TRENW+TRENL)+TRENW*TRENL*IGAP
     VOL2 = VOLUME(0,IGAP)
     VOL = (VOL1 + VOL2)*S(101)
     SUB2 = VOL + (TRENW*X*HH + TRENL*X*HH + 3.1416/2*X*X*HH)*S(101)*2.
     QOUT1 = (SUB1 +SUB2)*PORSO
     GO TO 1600
1500 IF (LLL.EQ.1) GO TO 1550
     QOUT1 = ( 3.1416*X**2.*(2./3.*HH+2./3.*Y) + X*(TRENL+TRENW)*
   % 3.1416*(2.*HH/4.+Y/2.) + TRENW*TRENL*Y)*PORSO*S(101)
     GO TO 1600
1550 IF (KKK.GT.120) GO TO 1570
     QOUT11 = (3.1416*X**2.*(HH+2./3.*Y)+X*(TRENL+TRENW)*(2.*HH+
   %          3.1416/2.*Y) + TRENW*TRENL*Y)*PORSO*S(101)
     QOUT10 = (3.1416*X**2.*(2./3.*HH+2./3.*Y)+X*(TRENL+TRENW)*
   % 3.1416*(2.*HH/4.+Y/2.) + TRENW*TRENL*Y)*PORSO*S(101)
     QOUT1 = QOUT10 + (QOUT11-QOUT10)*(KKK-.5)/120.
     GO TO 1600
1570 QOUT1 = (3.1416*X**2.*(HH+2./3.*Y)+X*(TRENL+TRENW)*(2.*HH+
   %          3.1416/2.*Y) + TRENW*TRENL*Y)*PORSO*S(101)
1600 QOUT3 = QOUT1 - QOUT4
     QOUT2 = QOUT3 / DELT
     IF (ICOUNT.GT.10) GO TO 1700
```

```
      IF (QOUT2.GT.QI1) QOUT2=QI1
1700 RETURN
     END
C
C    #####################
     FUNCTION AREA(A, B)
C    #####################
     COMMON QOUT1, QOUT2, QOUT4, QI1, ICOUNT, X, Y
     AREAB = X/2./Y * (B*SQRT(Y**2.-B**2.)+Y**2.*ASIN(B/Y))
     AREAA = X/2./Y * (A*SQRT(Y**2.-A**2.)+Y**2.*ASIN(A/Y))
     AREA = AREAB - AREAA
     RETURN
     END
C
C    #######################
     FUNCTION VOLUME(A, B)
C    #######################
     COMMON QOUT1, QOUT2, QOUT4, QI1, ICOUNT, X, Y
     VOLB = 3.1416*X**2. * (B-B**3./3./Y**2.)
     VOLA = 3.1416*X**2. * (A-A**3./3./Y**2.)
     VOLUME = VOLB - VOLA
     RETURN
     END
```

The vita has been removed from the scanned document