described in section 1.12.2. The method directly provides the monthly evapotranspiration for a specific crop. The crop coefficients used in the Blaney-Criddle method are different from the reference crop coefficients. The climatic effects and crop parameters are not separated in the Blaney-Criddle relations. Application of the method is provided in Example 1.9 and a comparison with the Penman-Monteith method is shown in Example 2.13.

2.13 DIRECT RUNOFF FROM RAINFALL OR RAIN EXCESS

Information on rainfall excess is necessary in hydrograph analysis, discussed in Chapter 7. As indicated by the water balance equation (2.5), the direct runoff or rainfall excess contributing to immediate streamflow is assessed by subtracting the infiltration from the total rainfall. A simple model, a homogeneous soil column with a uniform initial water content, is considered. There are three distinct cases of infiltration.

1. When a rainfall intensity, i, is less than the saturated hydraulic conductivity, K_s,* all the rainfall infiltrates, as shown by line I in Figure 2.13.
2. The effect of the rainfall rate, which is greater than the saturated conductivity ($i > K_s$) is shown by curve II. Initially, water infiltrates at the application rate. After a time t_p, the capacity of soil to infiltrate water falls below the rainfall rate. Surface ponding begins, which results in depression storage and runoff.
3. For a rainfall intensity that exceeds the capacity of soil to infiltrate water from the beginning, water is always ponded on the surface. In this case, the rate of infiltration is controlled only by soil-related factors. This rate, shown by curve III in Figure 2.13, is called the infiltration capacity of a given soil, f_p.

The infiltration capacity, f_p, decreases with time, due primarily to reduction in the hydraulic gradient between the surface and the wetting front.† It approaches a constant rate, f_c, which is considered to be equal to the apparent saturated hydraulic conductivity, K_s.

After the surface ponding (beyond time t_p for case 2 and from the beginning for case 3), for a continuous uniform rain of intensity i, the surface runoff hydrograph has a shape indicated by q in Figure 2.14. The difference between rainfall and runoff appears as the curve marked $(i - q)$. The curve f_p relates to the infiltration rate. The difference between the dotted $(i - q)$ curve and the f_p curve signifies interception and other minor losses (storages) at the beginning. After the surface storage is filled in, the two curves coincide (i.e., direct runoff results from subtracting the infiltration from the rainfall). If there is knowledge of the minor losses,‡ these are deducted from the first part of the precipitation after ponding. Ordinarily, these are ignored because they

*Natural soils are usually not completely saturated, even below the water table, due to air entrapment during the wetting process. The hydraulic conductivity, K_s, is taken to be the residual air saturation conductivity and is sometimes referred to as the apparent saturated conductivity. For a definition of hydraulic conductivity, refer to Chapter 3.

†This is the limit of water penetration into the soil. The front separates the wet soil from the dry soil.

‡The minor losses are considered in several ways, depending on the available information: (1) only interception is excluded from the precipitation; (2) surface retention is excluded, comprising

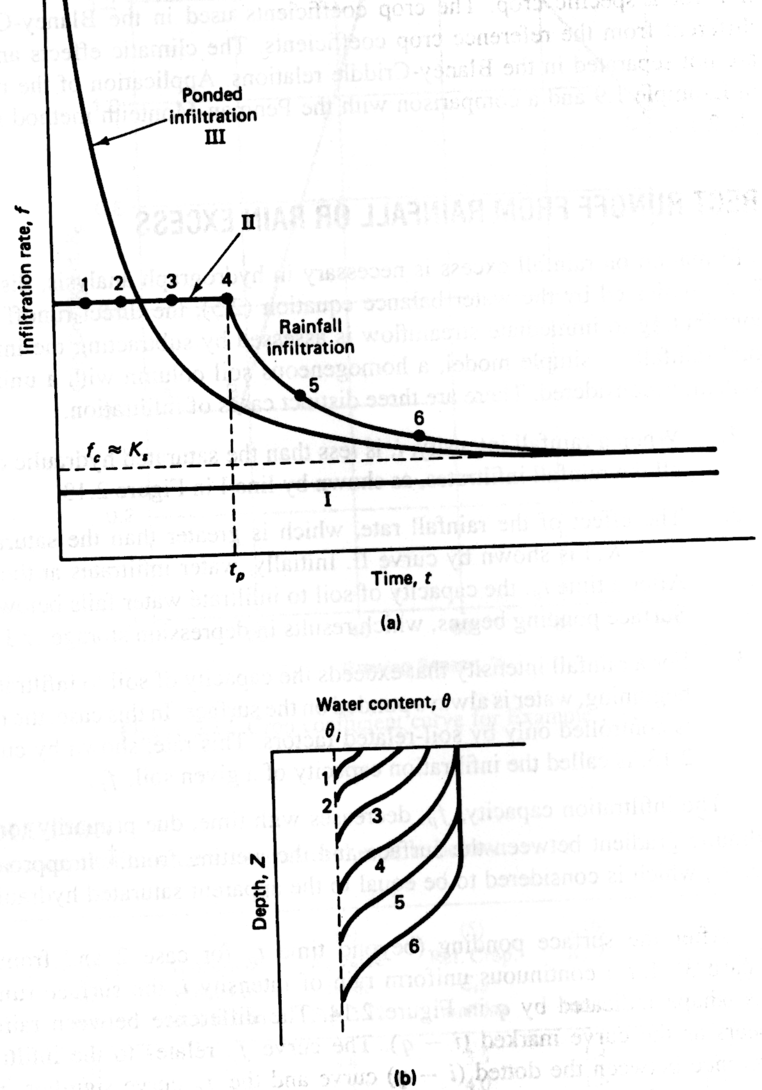

Figure 2.13 Infiltration behavior under different rainfall conditions (from Skaggs and Khaleel, 1982).

are relatively minor and cannot be assessed reliably. The basic problem thus relates to determination of the infiltration loss rate under different conditions. This is known as the infiltration approach to surface runoff assessment, as compared to the direct rainfall-runoff correlation (Section 7.15) and multivariate runoff relation (Linsley et al., 1982, pp. 244–249).

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interception, depression storage, and evaporation during the storm; or (3) initial storm loss is subtracted, which is the interception and only a small fraction of the depression storage. Other depressions are considered as a part of the drainage.

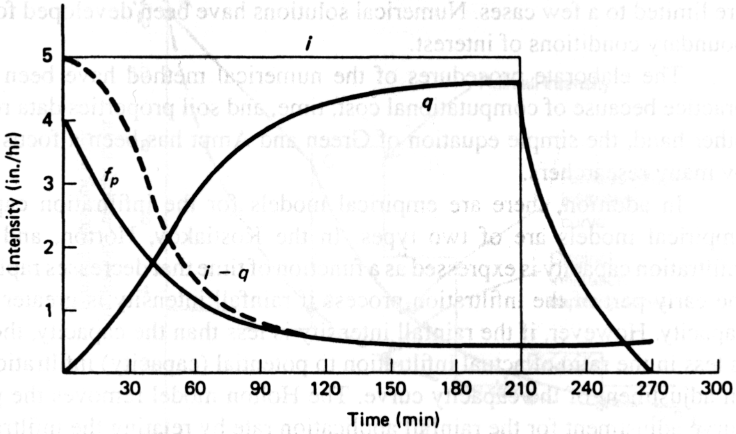


Figure 2.14 Water balance components of overland flow.

There are four approaches to determining the rainfall excess using the infiltration concept. Two of these, the infiltration capacity curve and the nonlinear loss rate function, are detailed methods that consider the time-varying infiltration rates. In the simplified index approach, the average rate of infiltration for the period of storm is used. The NRCS (formerly SCS) method uses the time-averaged parameters and indirectly considers the infiltration rate through the soil characteristics.

2.13.1 Infiltration Capacity Curve Approach

Green and Ampt proposed in 1911 a relation for infiltration capacity based on Darcy's law of soil water movement. Extensive research on the theory of infiltration was carried out during the 1930s and mid-1940s. Kostiakov and Horton suggested empirical relations for the infiltration capacity that became quite popular because of simplicity. Subsequent empirical equations were formulated by Philip in 1957 and Holton in 1961.

For unsaturated soil, the equation for flux (volume of water moving per unit area per unit time) is given by Darcy's law, in which the hydraulic conductivity is a function of water content. When combined with the equation of conservation of mass, this relation yields the following:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K \frac{dh}{d\theta}\frac{\partial \theta}{\partial z}\right) - \frac{\partial K}{\partial z} \quad [\mathrm{T}^{-1}] \tag{2.35}$$

where

$\theta =$ water content of soil

$K =$ hydraulic conductivity

$h =$ pressure head on soil medium

$z =$ distance measured positively downward from the surface

Equation (2.35), known as the Richards equation, is the governing equation of infiltration through saturated and unsaturated soil. Exact analytical solutions to the Richards equation are limited to a few cases. Numerical solutions have been developed for various initial and boundary conditions of interest.

The elaborate procedures of the numerical method have been of limited value in practice because of computational cost, time, and soil properties data requirements. On the other hand, the simple equation of Green and Ampt has been a focus of renewed interest by many researchers.

In addition, there are empirical models for the infiltration capacity curve. These empirical models are of two types. In the Kostiakov, Horton, and Philip models, the infiltration capacity is expressed as a function of time that decreases rapidly with time during the early part of the infiltration process if rainfall intensity is greater than the infiltration capacity. However, if the rainfall intensity is less than the capacity, the decay in the curve is less in the ratio of actual infiltration to potential (capacity) infiltration. This necessitates an adjustment of the capacity curve. The Holton model removes the problem of capacity curve adjustment for the rainfall application rate by relating the infiltration capacity to the soil moisture deficiency. The moisture deficiency (available storage) is reduced with time due to infiltrated water, and so is the infiltration capacity. The Green-Ampt model, though having a theoretical basis, is also based on the storage concept.

2.13.2 Horton Model

Horton (1939) presented a three-parameter equation expressed as

$$f_p = (f_0 - f_c)\,e^{-kt} + f_c \qquad [\mathrm{LT}^{-1}] \tag{2.36}$$

where

f_0 = initial infiltration capacity, in./hr

f_c = final constant infiltration capacity (equal to apparent saturated conductivity), in./hr

k = factor representing the rate of decrease in the capacity, 1/time

The parameters f_0 and k have no physical basis; that is, they cannot be determined from soil water properties and must be ascertained from experimental data.

The plot of eq. (2.36) is an asymptotic curve that starts at f_0 and attains a constant value of f_c as shown by ABD in Figure 2.15. The portion of the precipitation intensity above this $f_p - t$ curve during different time intervals designates the runoff. The following two modifications apply:

1. At the beginning of a storm, if the precipitation for a certain duration occurs at a rate less than the infiltration capacity, a soil moisture deficiency exists and the capacity for infiltration remains higher to a point C in Figure 2.15 rather than falling to point B according to eq. (2.36).
2. After runoff ensues, if the precipitation intensity in a certain period falls below the infiltration capacity curve, the moisture deficiency for this period has to be met from the subsequent excessive precipitation.

These are illustrated in the following example.

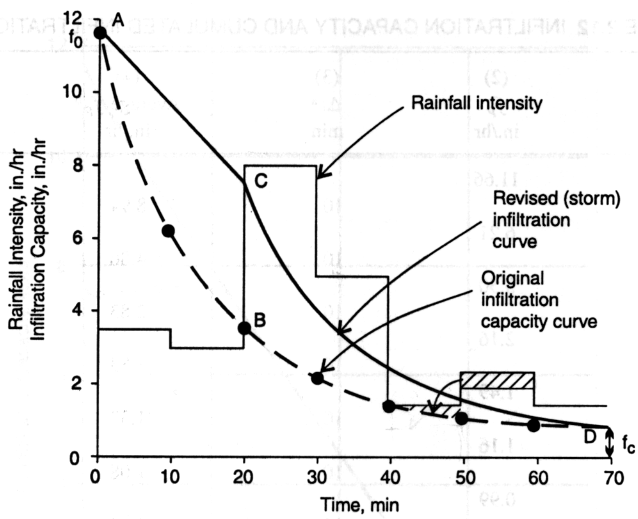


Figure 2.15 Rainfall intensity and infiltration capacity curves.

EXAMPLE 2.14

The infiltration capacity curve for a watershed is given by $f_p = (11.66 - 0.83)\,e^{-0.07t} + 0.83$ where t is in min and f_p in in./hr. The storm pattern is as follows:

t, min	Intensity, in./hr
0–10	3.5
10–20	3.0
20–30	8.0
30–40	5.0
40–50	1.5
50–60	2.4
60–70	1.5

Determine the rainfall excess for the successive 10-min period.

SOLUTION

1. The infiltration capacity f_p is computed in col. 2 of Table 2.12 at various times by the given formula.

2. During the first 20 min, the rainfall intensity is less than the infiltration capacity; hence all rainfall is infiltrated.

$$\text{Total rainfall during 20 min} = 3.5\left(\frac{10}{60}\right) + 3\left(\frac{10}{60}\right) = 1.08 \text{ in.}$$

3. To prepare the revised infiltration curve, the infiltration is cumulated in col. 6 of Table 2.12 for various time intervals. The end of each period infiltration capacity of col. 2 is plotted against the cumulated infiltration of the corresponding period (col. 6) in Figure 2.16, i.e., f_p of 11.66 plotted against F of 0.0, f_p of 6.21 against F of 1.49, and so on.

TABLE 2.12 INFILTRATION CAPACITY AND CUMULATED INFILTRATION

(1) Time min	(2) f_p in./hr	(3) Δt[a] min	(4) Average f_p[b] in./hr	(5) ΔF[c] in.	(6) F[d] in.
0	11.66				
		10	8.94	1.49	1.49
10	6.21				
		10	4.86	0.81	2.30
20	3.50				
		10	2.83	0.47	2.77
30	2.16				
		10	1.83	0.31	3.08
40	1.49				
		10	1.33	0.22	3.30
50	1.16				
		10	1.08	0.18	3.48
60	0.99				
		10	0.95	0.16	3.64
70	0.91				

[a]Successive difference col. 1
[b]Average of two successive values of col. 2
[c]col. 3 × col. 4 × $\left[\frac{1}{60}\frac{\text{hr}}{\text{min}}\right]$
[d]Cumulation of col. 5

4. From Figure 2.16, corresponding to $F = 1.08$ in. from step 2, f_p is 7.5 in./hr.

5. Set 7.5 in./hr as the initial value of f_0 at 20 min. From this point onward, the storm infiltration curve is given by

$$f_p' = [7.5 - 0.83]e^{-0.07t'} + 0.83$$

where t' is the time counted 20 min after the start of the storm.

6. Using the equation of step 5, the revised storm infiltration capacity at different times is calculated in Table 2.13 and plotted on Figure 2.15, shown as the revised curve.

7. The computations of rainfall excess during different time intervals are arranged in Table 2.14.

8. During the time interval 40–50 min, the rainfall amount is less than the cumulated infiltration during this period by 0.09 in. This deficiency is met from the excess rainfall of the succeeding period, as shown in Figure 2.15 and Table 2.14.

2.13.3 Holton Model

For agriculture watersheds, Holton and others in the Agriculture Research Service of the U.S. Department of Agriculture developed infiltration models during the mid-1960s and 1970s. The modified equation used in the USDAHL-70 Watershed Model has the form:

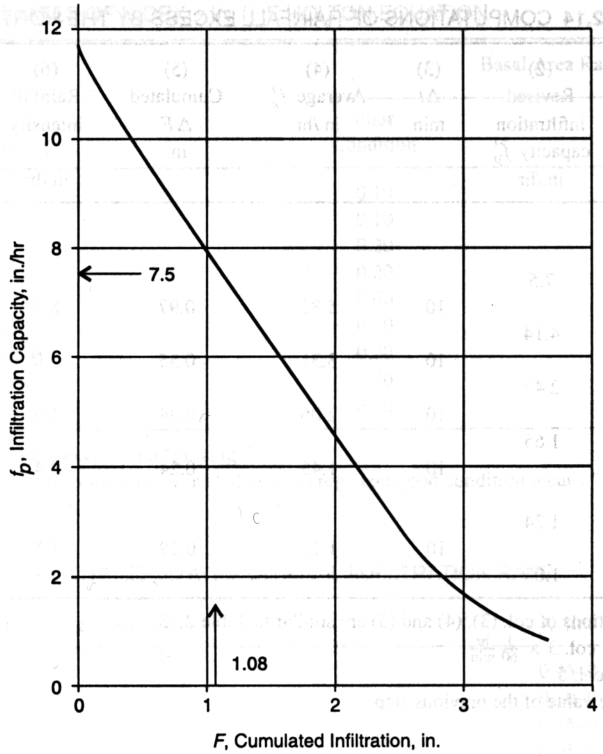


Figure 2.16 Cumulated infiltration curve.

TABLE 2.13 REVISED INFILTRATION CAPACITY FOR THE STORM OF EXAMPLE 2.14

(1) t' min	(2) Time from beginning of storm, t min	(3) f_p using t' in./hr
0	20	7.5
10	30	4.14
20	40	2.47
30	50	1.65
40	60	1.24
50	70	1.03

TABLE 2.14 COMPUTATIONS OF RAINFALL EXCESS BY THE HORTON METHOD

(1) Time min	(2) Revised infiltration capacity f'_p in./hr	(3) Δt min	(4) Average f'_p in./hr	(5) Cumulated ΔF in.	(6) Rainfall intensity i in./hr	(7) $\Delta P = i\Delta t$[a] in.	(8) RO[b]= $\Delta P - \Delta F$ in.
0							
10							
20	7.5						
		10	5.82	0.97	8.0	1.33	0.36
30	4.14						
		10	3.31	0.55	5.0	0.83	0.28
40	2.47						
		10	2.06	0.34	1.5	0.25	−0.09
50	1.65						
		10	1.45	0.24	2.4	0.4	0.16 (−).09[c] = 0.07
60	1.24						
		10	1.13	0.19	1.5	0.25	0.06
70	1.03						

Computations of col. (3), (4) and (5) are similar to Table 2.13.
[a]Col. 6 × col. 3 × $\frac{1}{60}\frac{\text{hr}}{\text{min}}$
[b]Col. 7 - col. 5
[c]Negative value of the previous step.

$$f_p = \text{GI} \cdot aS^{1.4} + f_c \tag{2.37}$$

where

f_p = infiltration capacity, in./hr
GI = growth index of crop, percent of maturity
a = index of surface connected porosity
S = available storage in the surface layer, in.
f_c = constant rate of infiltration after long wetting, in./hr

The Agriculture Research Service has developed the experimental GI curves for several crops (see for example, Holton et al., 1975).

Index a is a function of surface conditions and the density of plant roots. Estimates of a are given in Table 2.15.

The values for f_c are based on the hydrologic soil groups, as categorized in the *SCS National Engineering Handbook* and explained in Section 2.15. Estimates of f_c are given in Table 2.16.

Available storage, S, is computed by $S = (\theta_s - \theta)d$, where θ_s is the water content at saturation that equals porosity (in fact, it is the water content at residual air saturation), θ is the water content at any instant, and d is the surface-layer depth. For control depth, d, using the depth of the plow layer or the depth to the first impeding layer has been suggested by Holton and Creitz. However, Huggins and Monke (1966) consider that determining the depth is uncertain since it is highly dependent on surface condition and practices of preparing the seedbed.

TABLE 2.15 ESTIMATES OF INDEX *a* IN THE HOLTON EQUATION

	Basal Area Rating[a]	
Land Use or Cover	Poor Condition	Good Condition
Fallow[b]	0.10	0.30
Row crops	0.10	0.20
Small grains	0.20	0.30
Hay (legumes)	0.20	0.40
Hay (sod)	0.40	0.60
Pasture (bunch grass)	0.20	0.40
Temporary pasture (sod)	0.20	0.60
Permanent pasture (sod)	0.80	1.00
Woods and forests	0.80	1.00

[a]Adjustments needed for "weeds" and "grazing."
[b]For fallow land only, poor condition means "after row crop" and good condition means "after sod."
Source: Skaggs and Khaleel (1982).

TABLE 2.16 ESTIMATES OF FINAL INFILTRATION RATE

Hydrologic Soil Grade	f_c (in./hr)
A	0.45–0.30
B	0.30–0.15
C	0.15–0.05
D	0.05–0

Source: Skaggs and Khaleel (1982).

The procedure for applying the Holton model is as follows: (1) first measure or estimate the initial moisture content, θ_i; (2) compute the initial available storage by $S_0 = (\theta_s - \theta_i)d$; (3) determine the initial infiltration capacity f_p from eq. (2.37); (4) determine S after a period of time Δt by $S = S_0 - F + f_c\Delta t + \text{ET}\Delta t$, where F is the minimum of $f_p\Delta t$ and $i\,\Delta t$ (the available storage is reduced by the infiltration water but partly recovered due to drainage from the surface layer at the rate of f_c and by evapotranspiration, ET, through plants); (5) determine f_p after period Δt by eq. (2.37); and (6) repeat the process.

2.13.4 Approximate Infiltration Model of Green-Ampt

The Green-Ampt model (1911) has received considerable renewed research attention recently and has found favor in field applications because (1) it is a simple model, (2) it has a theoretical base on Darcy's law (it is not strictly empirical), (3) its parameters have physical significance that can be computed from soil properties, and (4) it has been used with good results for profiles that become dense with depth, for profiles where hydraulic conductivity increases with depth, for soils with partially sealed surfaces, and for soils having nonuniform initial water contents. The model is developed as follows.

Consider a column of homogeneous soil of unlimited depth with an initial uniform water content θ_i. It is assumed that a ponding depth H is maintained over the surface from

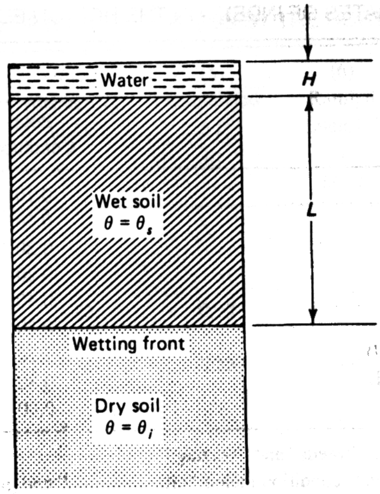


Figure 2.17 Simplified wetting front in the Green-Ampt model.

time 0 and a sharply defined wetting front is formed as shown in Figure 2.17. The length of the wet zone increases as infiltration progresses.

The application of Darcy's law results in the following form of the Green-Ampt equation:

$$f_p = K_s(H + S_f + L)/L \qquad [\text{LT}^{-1}] \tag{2.38}$$

where

K_s = effective hydraulic conductivity

H = ponding depth

S_f = suction (capillary) head at the wetting front

L = depth to the wetting front

If the total (cumulative) infiltration is expressed as $F = (\theta_s - \theta_i)L$ or ML, θ_s being porosity, and the ponding depth is very shallow, $H \approx 0$, then eq. (2.38) can be written as

$$f_p = K_s + \frac{K_s M S_f}{F} \qquad [\text{LT}^{-1}] \tag{2.39}$$

where $M = (\theta_s - \theta_i)$ is the initial soil water deficit.

Since $f_p = dF/dt$, the integration of eq. (2.39) with the condition $F = 0$ at $t = 0$ provides a cumulative infiltration as

$$K_s t = F - MS_f \ln\left(1 + \frac{F}{MS_f}\right) \qquad [\text{L}] \tag{2.40}$$

Morel-Seytoux and Khanji (1974) indicated that the form of eqs. (2.38) through (2.40) remain the same when simultaneous movement of both water and air take place. The terms on the right-hand side would, however, have to be divided by a viscous resistance correction factor, ranging from 1.1 to 1.7.

The effective suction at the wetting front, S_f, has been a subject of further research (refer to Skaggs and Khaleel, 1982). Many suction-related terms have been used to represent it. Mein and Larson (1973) suggested the average suction at the wetting front, S_{av}, to represent S_f and used the ratio of unsaturated hydraulic conductivity to effective conductivity as a weighting factor to define it, as given by eq. (2.46) subsequently. Many investigators found the application of S_{av} satisfactory.

Equations (2.38) through (2.40) apply when a ponding exists ($i \geq f_p$) from the beginning. If $i < f_p$,* the surface ponding effect will not take place until time t_p. Under this condition, for a steady rainfall, the actual infiltration rate, f, can be summarized as follows:

1. For $t < t_p$,

$$f = i \qquad [\mathrm{LT}^{-1}] \tag{2.41}$$

2. For $t = t_p$,

$$f = f_p = i \qquad [\mathrm{LT}^{-1}] \tag{2.42a}$$

The cumulative infiltration at the time of surface ponding, F_p, can be obtained from eq. (2.39) after substituting S_{av} for S_f.

$$F_p = \frac{S_{av} M}{i/K_s - 1} \qquad [\mathrm{L}] \tag{2.42b}$$

$$t_p = \frac{F_p}{i} \qquad [\mathrm{T}] \tag{2.42c}$$

3. For $t > t_p$, as given in eq. (2.39),

$$f = f_p = K_s + \frac{K_s S_{av} M}{F} \qquad [\mathrm{LT}^{-1}] \tag{2.43a}$$

For cumulative infiltration, Mein and Larson suggested an equation analogous to eq. (2.40):

$$K_s(t - t_p + t'_p) = F - M S_{av} \ln\left(1 + \frac{F}{M S_{av}}\right) \qquad [\mathrm{L}] \tag{2.43b}$$

where t'_p is the equivalent time to infiltrate F_p under the condition of surface ponding from the beginning as obtained from eq. (2.40) after substituting S_{av} for S_f.

For unsteady rainfall, the Green-Ampt model provides good results if the rainfall variations are not excessive and the rainfall contributes to an extension of the wetted profile. However, if there are relatively long periods of low or zero rainfall, the model predictions are less accurate, due to redistribution of the soil water. For rainfall after a long dry period, a new soil water distribution should be considered.

Rainfall excess or runoff is computed from the following equation of the water balance at the surface, disregarding evaporation:

$$\mathrm{RO} = i\Delta t - \Delta F - \Delta S \qquad [\mathrm{L}] \tag{2.44}$$

*It is assumed that $i > K_s$. If not, surface ponding will not occur at all as discussed in Section 2.13.

where

RO = rainfall excess during time Δt

ΔF = difference during Δt in cumulated infiltration F, computed by eq. (2.43b)

ΔS = change in surface storage during Δt

The application of eq. (2.44) is made two ways.

1. It is used to determine ΔS until the depression storage is not full. For each time interval, ΔS is the minimum of the following two:

$$\Delta S = i\Delta t - \Delta F \qquad [L] \tag{2.45a}$$

or

$$\Delta S = \text{Storage capacity} - \text{Cumulated storage } (\Sigma\Delta S) \text{ from previous step} \qquad [L] \tag{2.45b}$$

2. When the depression storage is full, the runoff is calculated by

$$RO = i\Delta t - \Delta F \qquad [L] \tag{2.45c}$$

2.13.5 Determination of Parameters in the Green-Ampt Model

As stated earlier, an advantage of the Green-Ampt model as compared to the empirical models is that its parameters can be ascertained from the physical properties of soil. The saturated volumetric water content, θ_s, is measured by the porosity of soil, although it is somewhat less due to entrapped air even below the water table. Similarly, the value of K_s is less than the saturated hydraulic conductivity, K_0. Bouwer (1966) described an air-entry parameter to measure K_s. In the absence of a field-measured value, he suggested that K_s be estimated as $K_s \approx 0.5K_0$.

Mein and Larson (1973) provided the relations of capillary suction (S_f) versus relative conductivity (K/K_s) for selected soils. The parameter of average capillary suction is defined as

$$S_{av} = \int_0^1 S_f dK_r \qquad [L] \tag{2.46}$$

where K_r = relative hydraulic conductivity = K/K_s. Thus S_{av} is the area under the S_f vs K_r curve of a particular soil. The values of porosity, saturated hydraulic conductivity, and average wetting front suction are given in Table 2.17.

Usually, it proves advantageous to determine the parameters of the model from field measurements by fitting measured infiltration data into the equation (Skaggs and Khaleel, 1982).

EXAMPLE 2.15

Rainfall at a constant intensity of 6 mm/hr falls on a homogeneous soil which has an initial uniform moisture content of 0.23. The soil property data obtained are $K_s = 1.24$ mm/hr and θ_s (porosity) = 0.48. The estimated value of S_{av} is 150 mm. Determine the rainfall excess. Assume no interception and depression storage.

TABLE 2.17 GREEN-AMPT INFILTRATION PARAMETERS

Soil texture class	Porosity θ_s	Wetting front soil suction head S_f, cm	Effective hydraulic conductivity K_s, cm/h
Sand	0.437 (0.374–0.500)	4.95 (0.97–25.36)	11.78
Loamy sand	0.437 (0.363–0.506)	6.13 (1.35–27.94)	2.99
Sandy loam	0.453 (0.351–0.555)	11.01 (2.67–45.47)	1.09
Loam	0.463 (0.375–0.551)	8.89 (1.33–59.38)	0.66
Silt loam	0.501 (0.420–0.582)	16.68 (2.92–95.39)	0.34
Sandy clay loam	0.398 (0.332–0.464)	21.85 (4.42–108.0)	0.15
Clay loam	0.464 (0.409–0.519)	20.88 (4.79–91.10)	0.10
Silty clay loam	0.471 (0.418–0.524)	27.30 (5.67–131.50)	0.10
Sandy clay	0.430 (0.370–0.490)	23.90 (4.08–140.2)	0.06
Silty clay	0.479 (0.425–0.533)	29.22 (6.13–139.4)	0.05
Clay	0.475 (0.427–0.523)	31.63 (6.39–156.5)	0.03

Source: Rawls and Brakensiek (1993).

SOLUTION

A. Time to surface ponding, t_p:

1. $M = \theta_s - \theta_i = 0.48 - 0.23 = 0.25$

2. From eq. (2.42b),

$$F_p = \frac{150(0.25)}{6/1.24 - 1} = 9.8 \text{ mm}$$

3. From eq. (2.42c), $t_p = 9.8/6 = 1.63$ hr.

B. Infiltration after the ponding:

4. First determine t'_p from eq. (2.40) as if ponding is from the beginning

$$(1.24)t'_p = (9.8) - (0.25)150 \ln\left[1 + \frac{9.8}{0.25(150)}\right]$$

$$t'_p = 0.88 \text{ hr}$$

5. From eq. (2.43a),

$$f = 1.24 + \frac{1.24(150)(0.25)}{F}$$

or

$$f = 1.24 + \frac{46.5}{F} \tag{a}$$

6. From eq. (2.43b),

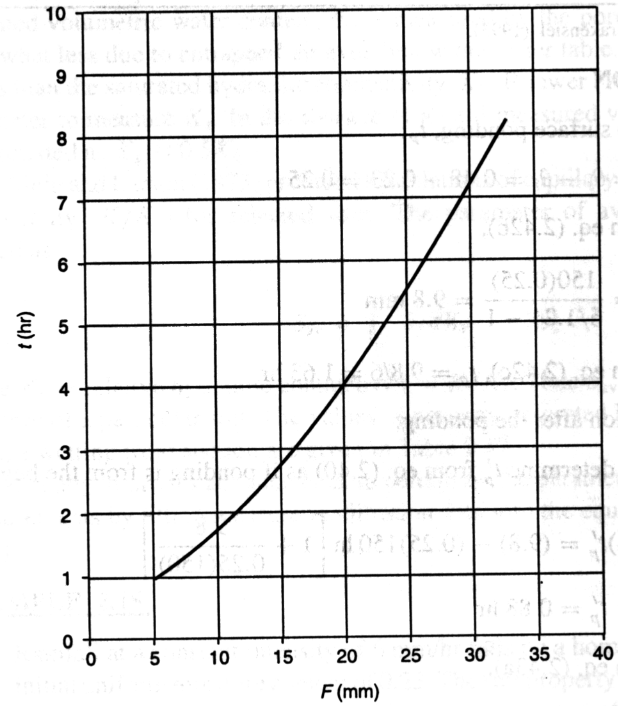
$$1.24(t - 1.63 + 0.88) = F - 0.25(150)\ln\left[1 + \frac{F}{0.25(150)}\right]$$

or

$$t = 0.75 + 0.81F - 30.24\ln(1 + 0.0267F) \tag{b}$$

A graph of F versus t for eq. (b) is plotted in Figure 2.18.

7. At successive time levels, the value of F is noted in col. 2 of Table 2.18 (derived from Figure 2.18). Using eq. (2.45c), since there is no storage, the rainfall excess for successive intervals is computed in the table. Actual infiltration, f, for various values of F can be computed from eq. (a), although it is not required to calculate the net rainfall.



F, mm select	t, hr
5	1.01
10	1.69
15	2.71
20	4.01
25	5.53
30	7.26

Figure 2.18 Plot for graphical solution of infiltration equation in Example 2.15.

TABLE 2.18 INFILTRATION AND RAINFALL EXCESS COMPUTATIONS WITH THE GREEN-AMPT MODEL[a]

(1) Time t (hr)	(2) F (mm)	(3) Δt (hr)	(4) ΔF (mm)	(5) $i\,\Delta t$[b] (mm)	(6) RO (i.e., $i\Delta t - \Delta F$) (mm)
1.63	9.8 (F_p)				
		0.37	2.0	2.2	0.2
2.0	11.8				
		1.00	4.5	6.0	1.5
3.0	16.3				
		1.00	3.7	6.0	2.3
4.0	20.0				

[a]Columns 3 and 4 indicate the difference in successive values (increment) of columns 1 and 2, respectively.
[b]$i = 6$ mm/hr

EXAMPLE 2.16

A storm pattern for a watershed is as follows:

t (min)	Intensity (in./hr)
0–10	0.5
10–20	2.0
20–30	6.5
30–40	5.0
40–50	0.9
50–60	2.0
60–70	3.0

The soil texture is sandy with a saturated moisture content (porosity) of 0.50, an effective hydraulic conductivity of 1.0 in./hr, and an average capillary suction of 6 in. The initial moisture content is 0.3. Determine the rainfall excess for successive 10-min periods. Assume a depression storage of 0.5 in.

SOLUTION

A. First rainfall period (0–10 min)

1. Since $i < K_s$, there is no ponding and the entire rain infiltrates.
2. Cumulated infiltration, $F_1 = 0.5(10/60) = 0.08$ in.
3. The values are listed in Table 2.19 to determine the rainfall excess.

B. Second rainfall period (10–20 min)

4. $F_p = \dfrac{6(0.2)}{2/1 - 1} = 1.2$ in.
5. $\Delta F_p = 1.2 - 0.08 = 1.12$ in.
6. $t_p = \dfrac{1.12}{2} = 0.56$ hr or 33.6 min > 10 min. Hence there is no ponding in the second period.

7. Infiltration during second period, $\Delta F_2 = 2(10/60) = 0.33$ in.

8. Cumulative infiltration to end of the period, $F_2 = 0.33 + 0.08 = 0.41$ in.

9. Infiltration capacity, f_p [from eq. (2.39)]; $M = 0.5 - 0.3 = 0.2$

$$f_p = 1 + \frac{(1)(0.2)(6)}{0.41} = 3.93 \text{ in./hr}$$

C. Third rainfall period (20–30 min)

10. Rainfall rate increases to 6.5 in./hr, but f_p is 3.93 in. /hr, so the surface ponding occurs at the outset of this period (i.e., $t_p = 20$ min or 0.33 hr).

11. From eq. (2.40), computing t'_p;

$$(1) \cdot t'_p = 0.41 - 6(0.2) \ln \left[1 + \frac{0.41}{0.2(6)} \right]$$

$$t'_p = 0.06 \text{ hr}$$

12. From eq. (2.43b)

$$1(t - 0.33 + 0.06) = F - 0.2(6) \ln \left[1 + \frac{F}{0.2(6)} \right]$$

or

$$t = 0.27 + F - 1.2 \ln(1 + 0.83F)$$

A plot of F versus t for this equation is given in Figure 2.19.

13. At the end of the period, when $t = 30$ min or 0.5 hr, $F = 0.90$ in. from Figure 2.19.

14. Ponding will accumulate up to depression storage capacity of 0.5 in., then runoff will commence to be computed by eq. (2.45c) as explained in Table 2.19.

D. Fourth rainfall period (30–40 min)

15. Surface ponding continues from the third period; hence the equation of step 12 holds good.

16. At the end of the period, when $t = 40$ min or 0.67 hr, $F = 1.25$ in., from Figure 2.19. Depression storage is full, runoff is computed by eq. (2.45c) in Table 2.19.

E. Fifth rainfall period (40–50 min)

17. Infiltration capacity at the beginning of the period from eq. (2.43a):

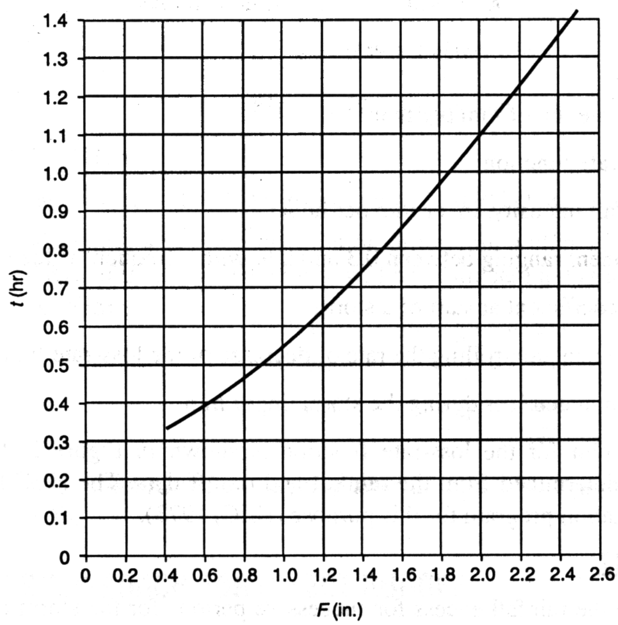
$$f_p = (1) + \frac{(1)(6)(0.2)}{1.25} = 1.96 \text{ in./hr}$$

18. Since the rainfall rate of 0.9 in./hr is less than f_p but the depression storage is full at 0.5 in. in the previous period (see Table 2.19), the infiltration at full capacity will continue meeting the deficiency of rainfall from the depression storage.

TABLE 2.19 COMPUTATIONS FOR UNSTEADY RAINFALL WITH THE GREEN-AMPT MODEL

(1) Time		(2) F	(3) Δt	(4) ΔF[a]	(5) i	(6) $i\Delta t$	(7) $i\Delta t - \Delta F$[b]	(8) ΔS[c]	(9) $\Sigma\Delta S$	(10) RO[d]
(min)	(hr)	(in.)	(hr)	(in.)	(in./hr)	(in.)	(in.)	(in.)	(in.)	(in.)
0	0	0								
			0.167	0.08	0.5	0.08	0	0	0	0
10	0.167	0.08								
			0.166	0.33	2.0	0.33	0	0	0	0
20	0.333	0.41								
			0.167	0.49	6.5	1.09	0.6	0.5	0.5	0.10
30	0.50	0.90								
			0.167	0.35	5.0	0.84	0.49	0	0.5	0.49
40	0.667	1.25								
			0.166	0.35	0.9	0.15	−0.20	−0.20	0.3	0
50	0.833	1.60								
			0.167	0.25	2.0	0.33	0.08	0.08	0.38	0
60	10	1.85								
			0.167	0.25	3.0	0.50	0.25	0.12	0.50	0.13
70	1.167	2.10								

[a] Successive difference of column 2.
[b] Col. 6–Col. 4.
[c] Eq. (2.45a) or eq. (2.45b), whichever is minimum.
[d] When Col. 9 ($\Sigma\Delta S$) equals the depression storage capacity, use eq. (2.45c), otherwise zero.



F, in. select	t, hr
0.4	0.33
0.6	0.39
0.8	0.46
1.0	0.54
1.5	0.80
2.0	1.10
2.5	1.42

Figure 2.19 Graphical solution of cumulated infiltration equation in Example 2.16.