4. INFILTRATION

Infiltration is the process of water entry into a soil from rainfall, or irrigation. Soil water movement (percolation) is the process of water flow from one point to another point within the soil. *Infiltration rate* is the rate at which the water actually infiltrates through the soil during a storm and it must be equal the infiltration capacities or the rainfall rate, which ever is lesser. *Infiltration capacity* the maximum rate at which a soil in any given condition is capable of absorbing water.

The rate of infiltration is primarily controlled by the rate of soil water movement below the surface and the soil water movement continues after an infiltration event, as the infiltrated water is redistributed.

Infiltration and percolation play a key role in surface runoff, groundwater recharge, evapotranspiration, soil erosion, and transport of chemicals in surface and subsurface waters.

4.1 Factors affecting infiltration

Infiltration rates vary widely. It is dependent on the condition of the land surface (cracked, crusted, compacted etc), land vegetation cover, surface soil characteristics (grain size & gradation), storm characteristics (intensity, duration & magnitude), surface soil and water temperature, chemical properties of the water and soil.

surface and soil factors

The surface factors are those affect the movement of water through the air-soil interface. Cover material protect the soil surface. A bare soil leads to the formation of a surface crust under the impact of raindrops or other factors, which breakdown the soil structure and move soil fines into the surface or near-surface pores. Once formed, a crust impedes infiltration.

Figure 4.1 illustrates that the removal of the surface cover (straw or burlap) reduces the steady-state infiltration rate from approximately 3 to 4 cm/hr to less than 1 cm/hr. Figure 4.2 illustrates the difference between crusted, tilled, grass cover soil on the infiltration curve. The bare tilled soil has higher infiltration than a crusted soil initially; however, its steady-state rate approaches that of the crusted soil because a crust is developing. Also, the grass-covered soil has a higher rate than a crusted soil partially because the grass protects the soil from crusting.

Natural processes such as soil erosion or man-made processes such as tillage, overgrazing and deforestation can cause change in soil surface configurations.

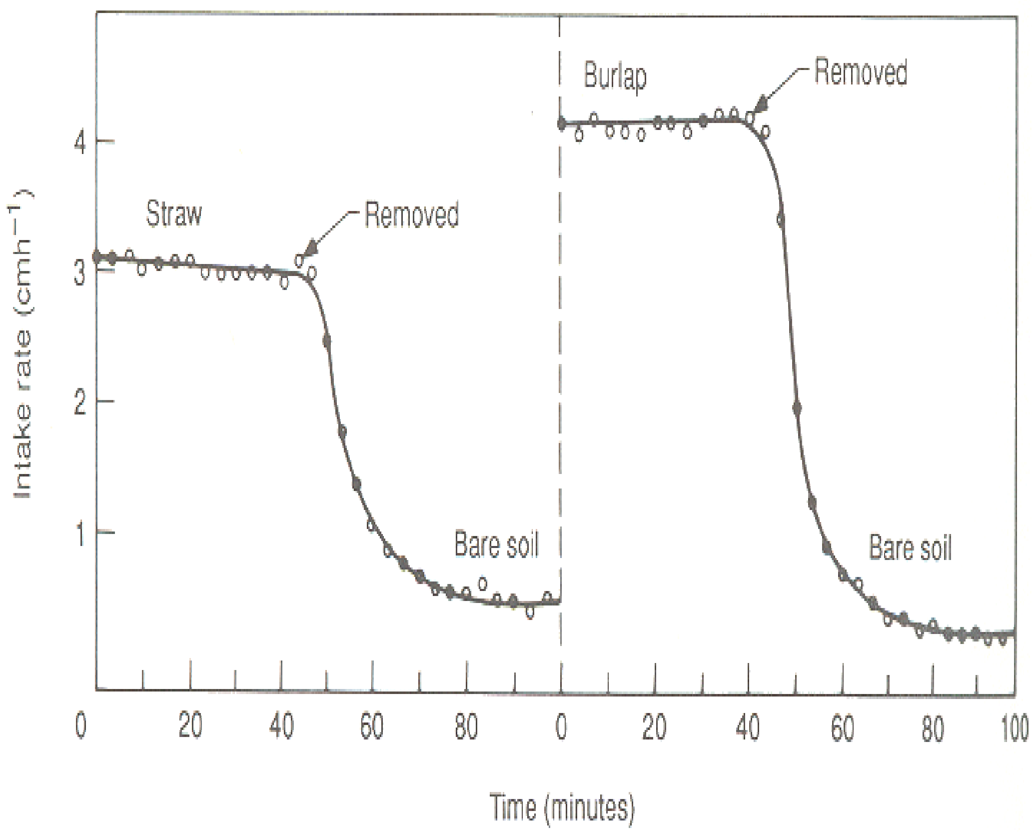


Figure 4.1 Effect of covered and bare soil on infiltration rates (Maidment, 1993)

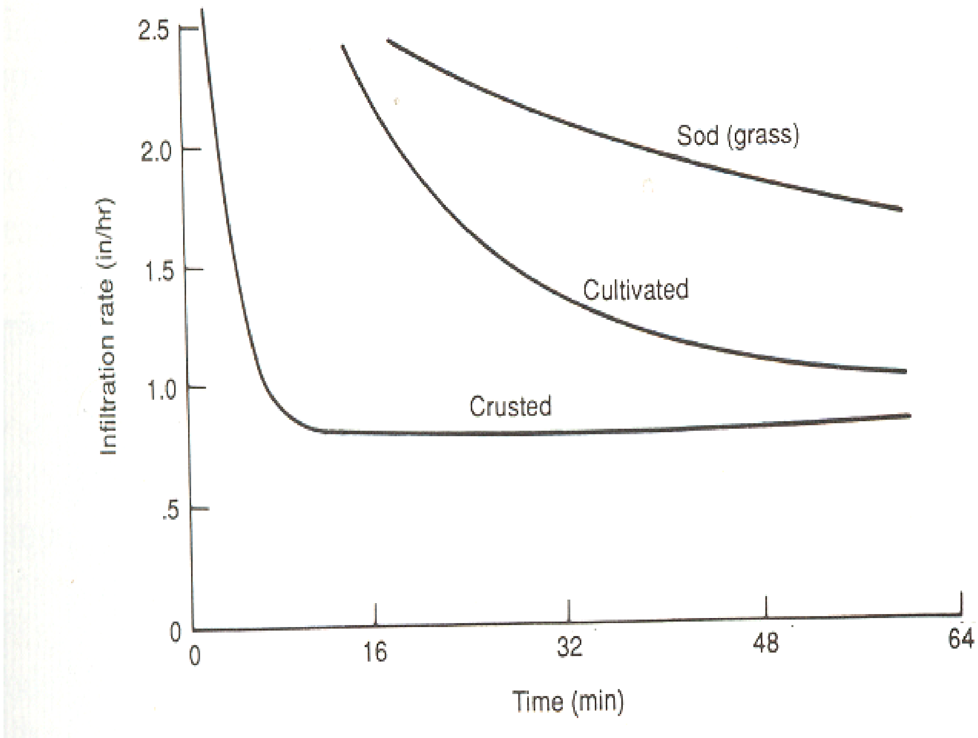


Figure 4.2 Effect of surface sealing and crusting on infiltration rates (Maidment, 1993)

The soil properties affecting soil water movement are hydraulic conductivity (a measure of the soil's ability to transmit water) and water-retention characteristics (the ability of the soil to store and release water). These soil water properties are closely related to soil physical properties.

Soil physical properties include particle size properties and morphological properties. Particle-size properties are determined from the size distribution of individual particles in a soil sample. Soil particles smaller than 2 mm are divided into three soil texture groups: sand, silt, and clay. The morphological properties having the greatest effect on soil water properties are bulk density, organic matter, and clay type. These properties are closely related to soil structure and soil surface area. Bulk density is defined as the ratio of the dry solid weight to the soil bulk volume. The bulk volume includes the volume of the solids and the pore space.

4.2 Measurements of infiltration

Infiltration is a very complex process, which can vary temporally and spatially. Selection of measurement techniques and data analysis techniques should consider these effects, and their spatial dimensions can categorize infiltration measurement techniques. A brief introduction of infiltration measurement techniques are described below.

4.2.1 Areal measurement

Areal infiltration estimation is accomplished by analysis of rainfall-runoff data from a watershed. For a storm with a single runoff peak, the procedure resembles that of the calculation of a ϕ index (see section 4.3.2). The rainfall hyetograph is integrated to calculate the total rainfall volume. Likewise, the runoff hydrograph is integrated to calculate the runoff volume. The infiltration volume is obtained by subtracting runoff volume from rainfall volume. The average infiltration rate is obtained by dividing infiltration volume by rainfall duration.

4.2.2 Point measurement

Point infiltration measurements are normally made by applying water at a specific site to a finite area and measuring the intake of the soil. There are four types of infiltrometers: the ponded-water ring or cylinder type, the sprinkler type, the tension type, and the furrow type. An infiltrometer should be chosen that replicates the system being investigated. For example, ring infiltrometers should be used to determine infiltration rates for inundated soils such as flood irrigation or pond seepage. Sprinkler infiltrometers should be used where the effect of rainfall on surface conditions influences the infiltration rate. Tension infiltrometers are used to determine the infiltration rates of soil matrix in the presence of macropores. Furrow infiltrometers are used when the effect of flowing water is important, as in furrow irrigation.

Ring or Cylinder Infiltrometers

These infiltrometers are usually metal rings with a diameter of 30 to 100 cm and a height of 20 cm. The ring is driven into the ground about 5 cm, water is applied inside the ring with a constant-head device, and intake measurements are recorded until a constant rate of infiltration is attained. To help eliminate the effect of lateral spreading use a double-ring infiltrometer, which is a ring infiltrometer with a second larger ring around it.

Sprinkler infiltrometer - Rain simulator

With the help of rain simulator, water is sprinkled at a uniform rate in excess of the infiltration capacity, over a certain experimental area. The resultant runoff R is observed, and from that the infiltration f using f = (P-R)/t. Where P = Rain sprinkled, R = runoff collected, and t = duration of rainfall.

Example 4.1: A USGS rain-simulator infiltrometer experiment was conducted on a sandy loam soil. Rainfall was simulated at the rate of 20 cm/hr. The rainfall and runoff data are given in Table ….

(a) Find and plot the mass-infiltration curve from the experimental data.

(b) Plot an infiltration rate curve.

Table E4.1. Rain-simulator infiltrometer data and infiltration capacity calculation.

Elapsed Time (min)	*Time (1)/60 (hr)*	*Simulated rainfall (cm)*	*Measured runoff (cm)*	*F (3)-(4) (cm)*	*f (5)/(2) (cm/hr)*
[1]	*[2]*	*[3]*	*[4]*	*[5]*	*[6]*
0	0.00	0.00	0.00	0.000	11.00
5	0.08	1.67	0.84	0.827	9.92
10	0.17	3.33	1.76	1.573	9.44
15	0.25	5.00	2.76	2.240	8.96
20	0.33	6.67	3.77	2.897	8.69
25	0.42	8.33	4.85	3.483	8.36
30	0.50	10.00	5.93	4.070	8.14
60	1.00	20.00	13.27	6.730	6.73
90	1.50	30.00	21.15	8.850	5.90
120	2.00	40.00	29.33	10.670	5.34
150	2.50	50.00	37.87	12.130	4.85

Solution. The measured data are given in Columns 1, 3 and 4. Cumulative infiltration F is calculated by subtracting the cumulative runoff from the cumulative rainfall. Infiltration rate is then determined by dividing the F by the total duration of infiltration. The result is plotted in Figure E4.1.

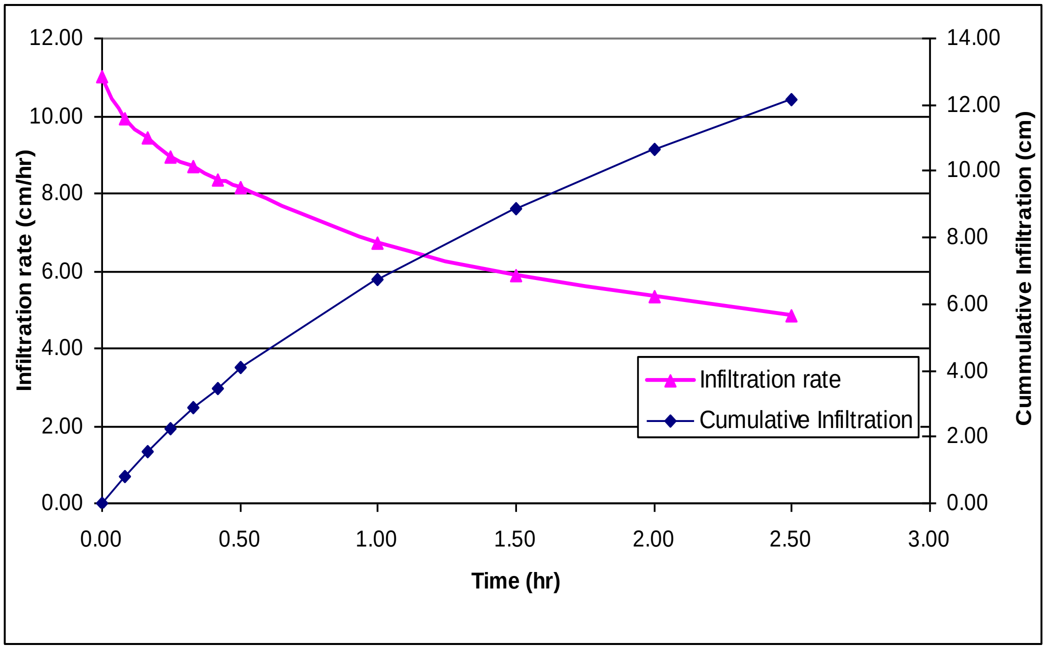


Figure E4.1. Infiltration rate and cumulative infiltration variation with time.

4.3 Estimating infiltration rate

In the following section four infiltration methods are discussed, that is the Horton Infiltration, the Φ-index, the Philip infiltration and the Green -Ampt infiltration equations.

4.3.1 Horton infiltration

In general, for a given constant storm, infiltration rates tend to decrease with time. The initial infiltration rate is the rate prevailing at the beginning of the storm and is maximum. Infiltration rates gradually decrease in time and reach a constant value.

Horton observed the above facts and concluded that infiltration begins at some rate f_o and exponentially decreases until it reaches a constant f_c. He proposed the following infiltration equation where rainfall intensity i greater than f_p at all times.

$$f_p = f_c + (f_0 - f_c)e^{-kt} \qquad (4.1)$$

where:
f_p = infiltration capacity in mm/hr at any time t
f_o = initial infiltration capacity in mm/hr
f_c = final constant infiltration capacity mm/hr at saturation, dependent on soil type and vegetation
t = time in hour from the beginning of rainfall
k = an exponential decay constant dependent on soil type and vegetation.

Note that infiltration takes place at capacity rates only when the intensity of rainfall i equals or exceeds f_p; that is $f = f_p$ when $i \geq f_p$, but when $i < f_p$, $f < f_p$ and $f = i$.

The cumulative infiltration equation F(t) for the Horton method is found from the relationship $d(F(t))/dt = f(t) = f_p$ and is given by

$$F(t) = f_c t + \frac{(f_0 - f_c)(1 - e^{-kt})}{k} \tag{4.2}$$

Indicative values for f_o, f_c, and K are given in Table 4.1.

Table 4.1: estimated values of Horton parameters

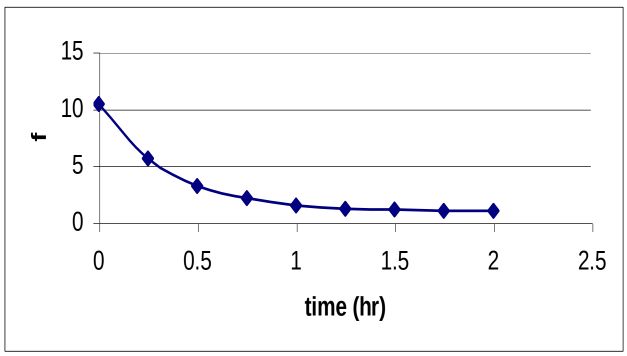
Soil / cover complex	f_o (mm/hr)	f_c (mm/hr)	K (1/hr)
Standard agricultural (bare)	280	6 – 220	1.6
Standard agricultural (vegetated)	900	20 – 290	.8
Peat	325	2 – 29	1.8
Fine sandy clay (bare)	210	2 – 25	2.0
Fine sandy clay (vegetated)	670	10 – 30	1.4

Example 4.2 The infiltration capacities of a given soil at different intervals of time are measured and values are given in Table E4.1. Find an equation for the infiltration capacity

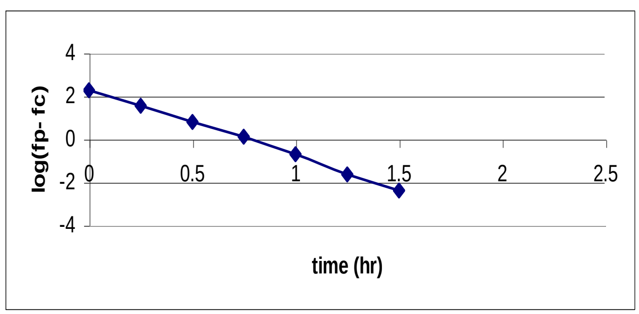
Table E4.1.

Time (hr)	0	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
f_p (cm/hr)	10.4	5.6	3.2	2.1	1.5	1.2	1.1	1.0	1.0

Solution The infiltration capacity reaches a constant value equals to f_c = 1.0 cm/hr. Now plotting $log_{10}\ (f_p - f_c)$ with t on linear scale and estimating slope of the line m = -1/1.31.



Time (hr)



From this m =-1/1.31= -1/ ($k\ log_{10}e$), k = 3.02. Thus the infiltration equation is given by

$$f_p = 1.0 + (10.4 - 1.0)\ e^{-3.02\, t} = 1.0 + 9.4\ e^{-3.02t}$$

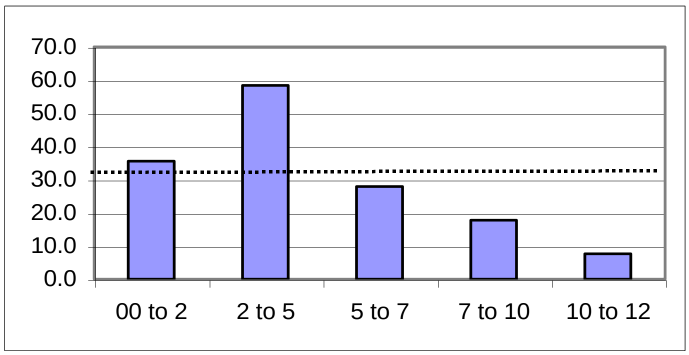
4.3.2 The Φ-index method

The *Φ*-index is the simplest method and is calculated by finding infiltration as a difference between gross rainfall and observed surface runoff. The Φ-index method assumes that the loss is uniformly distributed across the rainfall pattern.

Example 4.3 Estimate *Φ*-index of the catchment having an area 2.26 km^2.The observed runoff caused by the rainfall given in the Table E4.2 is 282 097 m^3.

Table E4.2:

Time (hr)	Rainfall (mm/hr)
00 to 2	35.6
2 to 5	58.4
5 to 7	27.9
7 to 10	17.8
10 to 12	7.6



Solution: First the rainfall hyetograph is graphed. The runoff depth rd is then calculated
runoff depth = 282097/(2.26*1000*1000) = 125 mm

Try *Φ*-index value of 25 mm/hr, then the first three rainfall will be used in the calculation. That is: *(2*(35.6 –Φ) + 3*(58.4-Φ) + 2*(27.9-Φ)) = 125*. This will give a *Φ* value of 25 mm/hr. The calculated *Φ value crosses the three selected rainfall intensity signifying that each of these intensities contributes to runoff*. The *Φ*-index method gives better estimate when losses is calculated after heavy rainfall and the soil profile is saturated.

4.3.3 The Phillip method

Phillip proposed an equation to estimate cumulative infiltration F(t) by

$$F(t) = St^{0.5} + Kt \qquad (4.3)$$

Where:

S = sorpitivity which is a function of the soil suction potential (representing soil suction head
K = the hydraulic conductivity of the soil (representing gravity head)
t = time from the beginning of the rainfall.

Noting that *f(t) = dF(t)/dt*, the Phillip equation for infiltration rate is

$$f(t) = 0.5St^{-0.5} + K \qquad (4.4)$$

Example 4.4 A small tube with a cross-sectional area of 40 cm^2 is filled with soil and laid horizontally. The open end of the tube is saturated, and after 15 minutes, 100 cm^3 of water have infiltrated into the tube. If the saturated hydraulic conductivity of the soil is 0.4 cm/hr, determine how much infiltration would have taken place in 30 minutes if the soil column had initially been placed upright with its surface saturated.

Solution The cumulative infiltration depth in the horizontal column is F = 100 cm^3 / 40 cm^2 . For horizontal infiltration, cumulative infiltration is a function of soil suction alone so that after t = 15 min = 0.25 hr

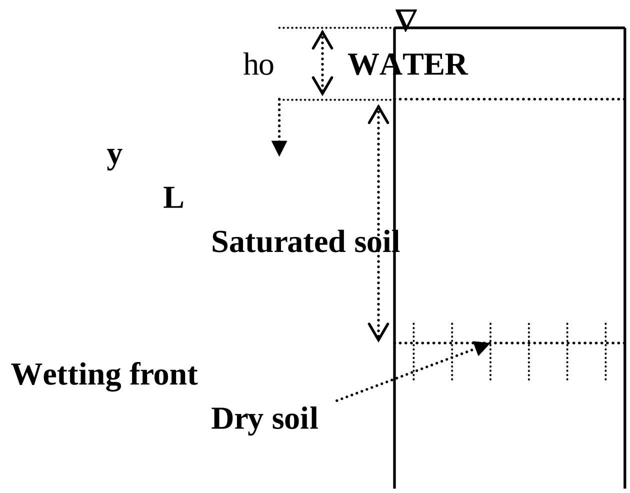
$F(t) = St^{1/2}$, $2.5 = S(0.25)^{1/2}$
$S = 5\ cm.hr^{(-1/2}$

For infiltration down a vertical column, the full equation is used with K = 0.4 cm/hr.

$F(t) = St^{1/2} + Kt$
$F(t) = 5(0.5)1/2 + 0.4(.5)$
$= 3.74\ cm$

4.3.4* The Green-Ampt method

The Green-Ampt model is an approximate model utilizing Darcy’s law. The model is developed with the assumption that water is ponded on the ground surface. Consider a vertical column of soil of unit horizontal cross-sectional area and let a control volume be defined around the wet soil between the surface and depth L.



If the soil was initially of moisture content θ_i throughout its entire depth, the moisture content will increase from θ_i to n (the porosity) as the wetting front passes.

The increase in the water stored with in the control volume as a result of infiltration is $L(n- \theta_i) = L\Delta\theta$ for a unit cross-section. By definition the cumulative depth of water infiltrated into the soil *F* is given by:

$$F(t) = L(n - \theta_i) \tag{4.5}$$

Now from Darcy's law

$$q = -K \frac{\partial h}{\partial z} \tag{4.6}$$

And in this case $q = -f$ because q is positive upward while f is positive downward. Eq.(4.6) can be written as

$$f = K(\frac{h_1 - h_2}{z_1 - z_2}) \tag{4.7}$$

Here the head at h_1 is h_0 and the head at the dry soil below the wetting front $h_2 = -\psi - L$.

$$f = K(\frac{h_0 - (-\psi - L)}{L}) \approx K(\frac{\psi + L}{L}) \tag{4.8}$$

h_0 is negligible if it is assumed that ponded water becomes surface runoff.

Replacing L by $F(t)/(\Delta\theta)$ in (4.8), we get

$$f = K(\frac{\psi\Delta\theta + F}{F}) \tag{4.9}$$

And we know that $dF/dt = f$, thus we can develop the Green-Ampt equation for $F(t)$ and this is

$$F(t) - \psi\Delta\theta \ln(1 + \frac{F(t)}{\psi\Delta\theta}) = Kt \tag{4.10}$$

and

$$f = K(\frac{\psi\Delta\theta}{F(t)} + 1) \tag{4.11}$$

Equation (4.10) is a non-linear equation in F. It may be solved by the method of successive substitution in

$$F(t) = Kt + \psi\Delta\theta \ln(1 + \frac{F(t)}{\psi\Delta\theta}) \tag{4.12}$$

Given K, t, Ψ and $\Delta\theta$, a trial value of F is substituted on the right-hand side (a good trial value is $F = Kt$), and a new value of F calculated on the left-hand side, which is substituted as a trial value on the right-hand side, and so on, until the calculated values of F converge to a constant.

Note that when the ponded depth h_o is not negligible, the value $\Psi - h_o$ is substituted for Ψ in Eqs. (4.10) and (4.11).

Parameters in the Green-Ampt model

To apply Green-Ampt model the effective hydraulic conductivity K, the wetting front suction ψ, the porosity n, and the initial moisture θ_i need to be measured or estimated. These parameters can be determined by fitting to experimental infiltration data, however, for specific application purposes it is easier to determine the parameters from readily available data such as soils and land-use data. Table 4.1 gives average values Green-Ampt parameters.

To incorporate the effects of land cover on infiltration, it is recommended to divide the area into the following three categories: (1) the area which is bare and outside the canopy cover, (2) the area which has ground cover, and (3) the bare area under canopy, and to develop an effective hydraulic conductivity for each area. Compute the infiltration separately for each area and then sum the three infiltration amounts weighted to their areal cover to obtain the infiltration for the area. This method of determining the infiltration assumes that the three areas do not cascade. If the areas do cascade, this method over predicts infiltration.

Note that for bare ground cover conditions $K = K_s/2$, for the area which is bare under canopy the effective hydraulic conductivity can be assumed to be equal to the saturated hydraulic conductivity K_s of the soil.

The area which has ground cover is assumed to contain macroporosity, and the effective hydraulic conductivity is equal to the saturated hydraulic conductivity Ks times a macroporosity factor A. For areas which don not undergo mechanical disturbance like range land macroporosity factor A is determined from

Table 4.1 USDA Soil Texture Green-Ampt Infiltration Parameters (Maidment, 1993)

Soil texture classes	Porosity n	Wetting front soil suction head ψ (cm)	Saturated hydraulic conductivity Ks (cm/hr)
Sand	0.437 (0.374-0.500)	4.95 (0.97-25.36)	23.56
Loamy sand	0.437 (0.363-506)	6.13 (1.35-27.94)	5.98
Sandy loam	0.453 (0.351-0.555)	11.01 (2.67-45.47)	2.18
Loam	0.463 (0.375-0.551)	8.89 (1.33-59.38)	1.32
Silt loam	0.501 (0.420-0.582)	16.68 (2.92-95.39)	0.68
Sandy clay loam	0.398 (0.332-0.464)	21.85 (4.42-108.0)	0.30
Clay loam	0.464 (0.409-0.519)	20.88 (4.79-91.10)	0.20
Silty clay loam	0.471 (0.418-0.524)	27.30 (5.67-131.5)	0.20
Sandy clay	0.430 (0.370-0.490)	23.90 (4.08-140.2)	0.12
Silty clay	0.479 (0.425-0.533)	29.22 (6.13-139.4)	0.10
Clay	0.475 (0.427-0.523)	31.63 (6.39-156.5)	0.06

$$A = \exp\,(2.82 - 0.099S + 1.94BD) \qquad (4.13)$$

And for undisturbed agricultural areas A can be determined from

$$A = \exp(0.96 - 0.032S + 0.04C - 0.032BD) \qquad (4.14)$$

Where S = Percent sand
C = percent clay
BD = bulk density of the soil (< 2 mm), g/cc, and $A > 1.0$.

The area which is bare outside canopy is assumed to be crusted and the effective hydraulic conductivity is equal to the saturated hydraulic conductivity *Ks* times a crust factor *CRC* which is estimated by

$$CRC = \frac{SC}{1+(\psi_i / L)} \tag{4.15}$$

where: *CRC* = crust factor

SC = correction factor for partial saturation of the soil subcrust (see Table 4.2)

= 0.736 – 0.0019 (percent sand)

Ψi = matric potential drop at the crust-subcrust interface, cm (Table 4.2)

= 45.19 – 46.68 (SC)

L = wetting front depth, cm

Table4.2: Mean steady-state matric potential drop Ψi across seals by soil texture (Maidment 1993)

Soil texture	Matric, potential drop Ψi (cm)	Reduction factor for sub-crust conductivity SC
Sand	2	0.91
Loamy sand	3	0.89
Sandy loam	6	0.86
Loam	7	0.82
Silt loam	10	0.81
Sandy clay loam	5	0.85
Clay loam	8	0.82
Silty clay loam	10	0.76
Sandy clay	6	0.80
Silty clay	11	0.73
Clay	9	0.75

Example 4.4 Compute the infiltration rate f and cumulative infiltration F after one hour of infiltration into a silt loam soil that initially had an effective saturation of 30 %. Assume water is ponded to a small but negligible depth on the surface.

Solution:

For a silt loam soil Ψ = 16.7 cm, K =0.65 cm/hr, n = 0.501, θi = 30% x 0.501

$\Delta\theta = n - \theta i = 0.501 - 30\% \times 0.501 = 0.35.$

$\Psi\Delta\theta = 16.7 \times 0.35 = 5.84$ cm.

The cumulative infiltration at t = 1 hour is calculated employing Eq. (4.10), taking a trial value of F(t) = Kt =0.65 cm.

$$F(t) = Kt + \psi\Delta\theta \ln(1 + \frac{F(t)}{\psi\Delta\theta})$$

= 1.27 cm

$$F(1) = 0.65*1 + 5.68\ln(1 + \frac{0.65}{5.68})$$

Substituting F = 1.27 cm in Eq(4.10) we get 1.79 cm and aftera number of iteration F converges to a constant value of 3.17 cm.

Infiltration rate after one hour is estimated by Eq. (4.11)

$$f = K(\frac{\psi\Delta\theta}{F(t)} + 1)$$

$$f = 0.63(\frac{5.68}{3.17} + 1)$$

= 1.81 cm/hr.

4.4. Practice Problems

4.1 The infiltration rate as a function of time for silt loam are given below. Determine the best values for the parameters fo, fc, and k for Horton's equation to describe the infiltration of the silt loam soil at the locality.

Time in hrs	0	0.07	0.16	0.27	0.43	0.67	1.10	2.53
f_p (mm/hr)	6.6	5.3	4.3	3.3	2.2	1.3	0.7	0.25

4.2 For clay soil at a given location parameters of Philip's equation were found as S = 45 cm/hr $^{0.5}$, and K = 10 cm/hr. Determine the cumulative infiltration and the infiltration rate at 0.5 hr increments for a 3-hour period. Plot both as functions of time. Assume continuously ponded conditions.

4.3. For a sandy loam soil, calculate the infiltration rate (cm/hr) and depth of infiltration (cm) after one hour if the effective saturation is initially 40 percent, using the Green-Ampt method. Assume continuously ponded conditions.

4.4. Use the Green-Ampt method to evaluate the infiltration rate and cumulative infiltration depth of a silty clay soil at 0.1 hour increments up to 6 hours from the beginning of infiltration. Assume initial effective saturation 20 percent and continuous ponding.