Chapter 6
Infiltration/Loss Analysis

6-1. General

a. Role of infiltration/loss computations in flood-runoff analysis. This chapter describes the methods typically available for computing the time history of direct runoff volume due to a single rainfall event. This is determined by subtracting from the rainfall hyetograph the losses due to interception, surface storage, and soil infiltration (Figure 6-1). The rainfall excess is routed to the subbasin outlet, usually by unit hydrograph or kinematic wave techniques, and combined with base flow to obtain the subbasin hydrograph.

b. Physical process. Soil infiltration and surface loss of rainfall involve many different processes at different scales of observation. The most basic of the processes is the infiltration of water into an "ideal" soil, a soil of uniform properties and infinite depth as shown in Figure 6-2. Initially, the soil is assumed to have a uniform water content. The initial water content or an initial condition related to the water content must be specified for any of the methods which are used for single rainfall event analysis. At the commencement of rainfall, water is infiltrated until the rainfall exceeds the capacity of water to be absorbed by the soil. At this point, the surface becomes saturated and rainfall in excess of the soil infiltration capacity is assumed to be runoff. As the volume of infiltrated water increases, the infiltration capacity of the soil decreases to a minimum rate equal to the soil's saturated hydraulic conductivity. The saturated hydraulic conductivity is a proportionality constant between hydraulic gradient and flow in Darcy's law for saturated flow in porous (soil) media and is assumed to be a characteristic of the soil.

(1) Theoretically, the transport of infiltrated rainfall through the soil profile and the infiltration capacity of the soil is governed by Richards' equation (Richards 1931 and Eagleson 1970). Richards' equation is derived by combining an unsaturated flow form of Darcy's law with the requirements of mass conservation. Solutions to Richards' equation show an exponential decrease of infiltration capacity with cumulative infiltration. Conceptual or empirical loss-rate equations attempt to duplicate this in computing rainfall excess.

(2) The predictions of infiltration by Richards' equation may at best be an approximation to actual field losses because the ideal soil model does not correspond particularly well to field conditions. The deviations occur for several reasons: (a) the soil is heterogenous, usually layered and of finite depth; (b) the soil matrix is not an inert structure but is continually being affected by chemical and biologic processes; (c) surface losses and cover have a major impact on the available excess; and (d) the ideal soil model is a gross approximation to the dynamics of direct runoff production. Consider the impact of these additional processes on rainfall loss rates. Soil heterogeneity makes both the formulation of a physical model and the estimation of model parameters much more complicated. Formulating the equations of fluid motion in a heterogenous, layered soil is a difficult problem. The equations could be formulated, but estimating the parameters of the model, such as soil hydraulic conductivity, is totally impractical given the information typically available to the engineer. Furthermore, the detail needed to capture the small scale changes of soil properties is impractical. At best, some average estimate of soil properties for a relatively large area, a lumped approach to modeling, must be employed to model infiltration.

(3) Far from being inert materials developed strictly from the weathering of bedrock, soils owe their properties to the chemistry of rainwater, the chemical properties of the parent material, organic matter content and the presence of roots and burrowing animals. The chemistry of water is important because it can affect the shrink/swell potential of clays and the osmotic pressures within the soil. Clay soils may shrink and crack resulting in a desiccated surface which results in infiltration capacities far in exceedance of anything that would be expected from a material with a clay's saturated hydraulic conductivity. The hydraulic conductivity of the soil, being inversely proportional to water viscosity, is sensitive to the water temperature. The soil porosity, the ability to hold water, increases with the organic matter content. Burrowing animals and decaying tree roots create what has been termed "macropores" that are very effective in conveying water.

(4) Surface losses are categorized as being due to interception, depression, and detention storage. Interception storage results from the absorption of rainfall by surface cover such as plants and trees. Depression storage results from micro- and macrorelief depressions in the surface topography that store water which eventually infiltrates or evaporates. Also a function of topography, detention storage acts as minireservoirs, increasing the retention time of overland flow and providing more opportunity for infiltration.

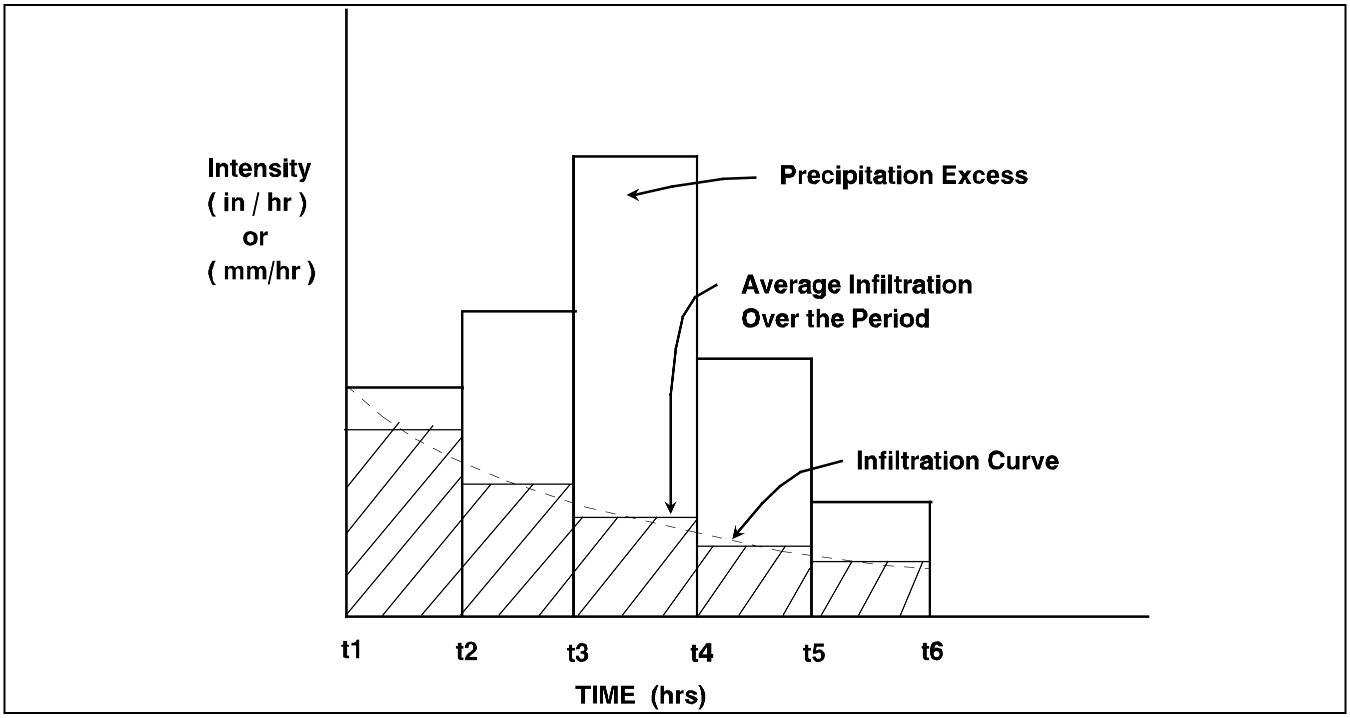


Figure 6-1. Loss rate, rainfall excess hyetograph

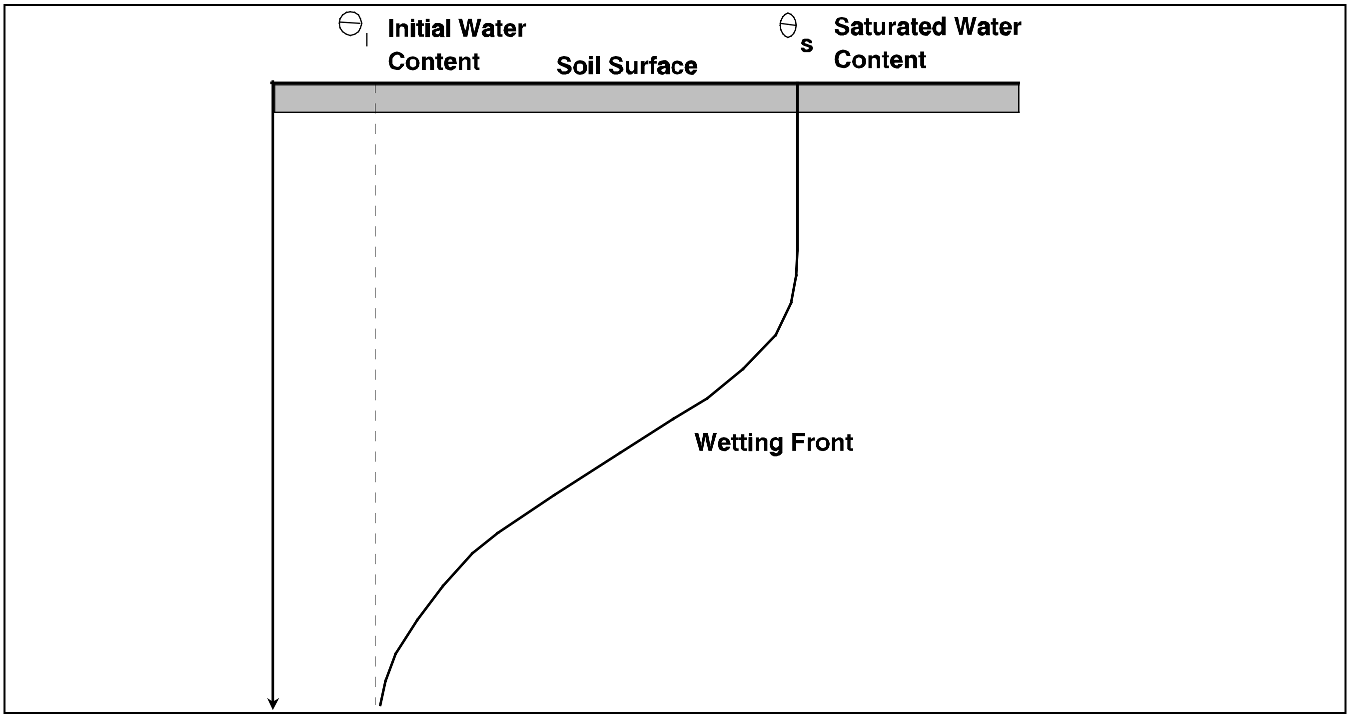


Figure 6-2. Wetting front in ideal soil

(5) Surface cover also increases loss rates by delaying overland flow. In addition, surface cover impacts on rainfall losses by protecting the soil surface from the impact of rainfall, preventing the formation of surface crusts that decrease the hydraulic conductivity of the soil surface.

(6) The extent to which surface conditions affect rainfall excess is a function of land use. Forested areas exhibit the greatest surface losses because of their well-developed canopies and significant surface storage provided by surface litter. Range land is less effective in storing water because of sparser cover. The presence of grazing further reduces cover and increases runoff potential. Bare surface conditions in agricultural areas can potentially result in relatively high runoff rates due to crusted surfaces formed from rainfall impact. Management practices, such as contour plowing or mulching, have been employed to protect the soil or store overland flow. Urban area runoff increases in proportion to the amount of impervious area and how this area is connected to outflow points by the drainage system.

(7) Even if the ideal soil model could account for all the processes mentioned so far, there would still be the problem of accounting for the dynamics of direct runoff production. Direct runoff can be simulated by either the Horton or Hillslope process (Ward 1967). The Horton process, named for the famous hydrologist, corresponds more closely to the ideal soil model (Figure 6-3). In this process, overland flow results when all surface storages are filled and the rainfall rate exceeds the infiltration rate. Overland flow that does not infiltrate along the flow path to a channel results in direct runoff. The potential for infiltration along the flow path is not accounted for when an average soil property is used to calculate runoff in an ideal soil model.

(8) The Horton process is most likely to be important in urban and agricultural areas where the infiltration capacity of soils is relatively small due to cultural activities. However, overland flow, the cornerstone of the Horton process, rarely occurs in forested soils. Forest soils generally have extremely high infiltration capacities in the upper horizon due to a well-developed surface cover and extensive tree root structure. In these soils, direct runoff is due to the Hillslope process. In this process, direct runoff results due to the mixture of surface and subsurface flow. Prior to direct runoff, the initial watershed moisture conditions are characterized by drier conditions at the top of the hillslope and wetter conditions at lower elevations near the channel (Figure 6-4). At the commencement of rainfall, water infiltrates at the top of the hillslope and moves vertically through the soil until it reaches a low conductivity soil zone. Lateral movement of the infiltrated water occurs along the lower conductivity layer as either saturated or unsaturated flow until it seeps out to the surface nearer the bottom of the hillslope. At this point, the infiltrated water combines with overland flow generated by rainfall on the initially wetter areas near the stream channel. These areas are termed variable source areas because as the rainfall continues they grow in size, comprising more of the watershed area. Observations have shown that the subsurface movement of water down the hillslope combined with overland flow from the source areas is the flood mechanism in forested areas. In some respects, the apparent rainfall excess in a flood hydrograph in a forested area is a combination of interflow, subsurface flow, and overland flow.

(9) In summary, the rainfall infiltration/loss process is complex and affected by many factors. Soil properties are important, but chemistry of the water, biologic activity, soil heterogeneity, and surface cover modify the soil's infiltration capacity. Surface cover and topography also are involved in losses by intercepting, storing, and detaining rainfall. Finally, the dynamics of the rainfall-runoff process are important in determining the volume of rainfall available for direct runoff. Even though excess may be generated at some point in an agricultural or urban area, some of this excess may infiltrate as overland flow traveling to a channel. In forested areas, flow that has infiltrated is a major contributor to direct runoff.

c. Approaches to infiltration/loss analysis. Watershed modeling for flood prediction is an exercise in finding adequate estimates of watershed properties over watershed size areas. The methods used to model infiltration/loss rates reflect this approach.

(1) The methods can be categorized as physically based, conceptual, or empirical. The physically based models, such as Green and Ampt, are based on simplified solutions to the Richards equation. This approach was developed for three reasons: (a) the solution of the Richards equation is difficult and not justified given that this equation is, at best, only a rough approximation of the actual field infiltration; (b) a simplified solution still produces the exponentially decreasing relationship between infiltration capacity and cumulative infiltration; and (c) the parameters of the methods can be related to soil properties that can be measured in the laboratory, such as porosity and hydraulic conductivity.

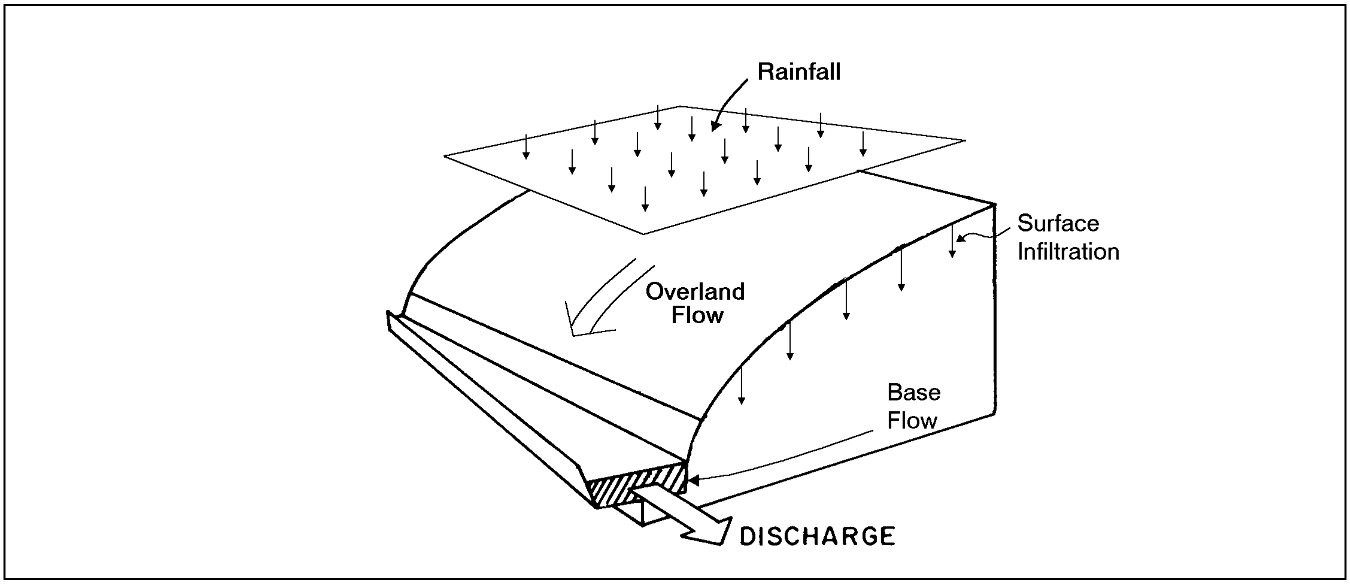


Figure 6-3. Horton runoff

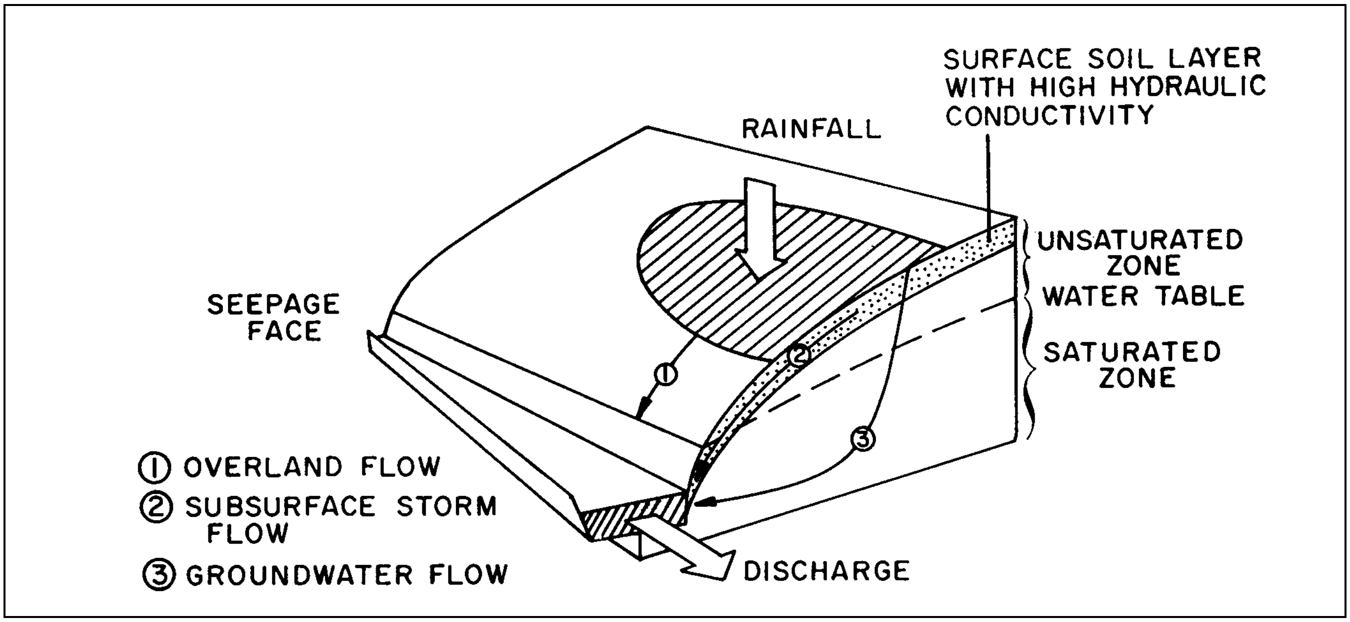


Figure 6-4. Hillslope process

(2) Methods such as the Holtan loss rate conceptually mix parameters which have a physical basis such as a deep percolation rate with empirical ones such as an exponent which controls the infiltration capacity as a function of storage. Empirical methods, such as the Soil Conservation Service (SCS) curve number (CN), are based on correlating parameters estimated from rainfall-runoff records to factors affecting loss rates such as soil type and surface cover. The initial and constant loss rate method can be considered either an empirical method or a gross representation of an infiltration curve. Each of these methods have been applied in watershed models and will be discussed in the following sections.

6-2. Gauged versus Ungauged Parameter Estimation

a. Parameter estimation techniques generally are categorized by application to gauged or ungauged analysis. In the description of loss rate methods, parameter estimation is discussed only with regard to estimating parameters from the physical characteristics of the watershed. These estimates can be useful in an ungauged or gauged situation. In an ungauged situation, physical characteristics may be the only information available for estimating parameters.

b. Gauged estimation procedures are used to estimate model parameters, including loss rate parameters, from rainfall-runoff records. The basic element of a gauged estimation is to utilize an "optimization" algorithm to choose model parameters so that some measure of the difference between observed and predicted hydrographs is minimized. This approach to parameter estimation is essentially a regression analysis, as pointed out by Dawdy, Lichty, and Bergman (1972). An important principle of regression analysis is parsimony, i.e., inclusion of the minimum number of parameters in the model that are needed to explain the data. In this respect, a simple two-parameter loss rate method, such as the initial and constant loss rate method, is probably adequate because it is parsimonious. Experience has shown that simple empirical methods with a minimum number of parameters do a satisfactory job when simulating observed hydrograph parameters.

c. Although not as parsimonious as simple empirical methods, methods with physically based or measurable parameters, such as the Green and Ampt method, can be advantageous in gauged analysis. The advantage stems from the ability to place bounds on the values of these parameters. The bounds can be applied using two different approaches when applying an optimization procedure. One approach would be to evaluate whether or not the derived parameter estimates are within a reasonable range based on the physical characteristics of the watershed. A second approach is to constrain the parameter values to a reasonable range within the optimization. The second approach may prove difficult because of errors in rainfall-runoff data which dictate that parameters assume unrealistic values. Constraining the parameters may prevent a reasonable prediction of observed runoff.

d. A reasonable procedure to follow when applying a physically based loss rate method in a gauged analysis is to only perform parameter estimation with a maximum of two parameters. Additional parameters in the method should be estimated based on the physical characteristics of the watershed. Certainly, optimized parameters will have estimated values which are not reasonable due to observation errors. However, over a number of events, the errors should balance resulting in an acceptable estimate of loss rate parameters. Acceptance can be based on what seems reasonable from watershed characteristics.

6-3. Antecedent Moisture Conditions

a. The application of the methods discussed requires an estimation of the antecedent moisture condition (AMC) of the watershed surface cover and soils. Unfortunately, there is no simple answer as to how the AMC might be established. The approaches to use are a function of the intended application. Different approaches may be used depending upon whether individual or design events are being simulated or a gauged or ungauged analysis is being performed. Consider the simulation of individual events. The gauged analysis is straightforward, with the AMC used as another parameter that is adjusted to improve correspondence between the observed and predicted hydrograph. Ungauged analysis is much more difficult in that some methodology must be developed to determine AMC. The usual technique is to rely on an antecedent precipitation index (API) which is presumably based on regional information. API is a poor indicator of AMC due to various factors, most notably the impact of weather conditions on evapotranspiration. However, it's the only indicator usually available.

b. Estimation of AMC for design events depends on the type of event. AMC for probability-based design storms might be based on calibration to a gauged or regional discharge or volume frequency curve. In contrast, AMC (and in general loss rates) determination for deterministic design events such as the probable maximum precipitation is set by policy.

c. Certainly, the techniques for establishing AMC are varied and subject to some argument. When gauged information is not available, reliance on regional information is essential in establishing an AMC. Otherwise, the engineer may be forced to assume a conservative estimate for this parameter.

6-4. Surface Loss Estimation

a. Rainfall losses are due to both surface storage and soil infiltration. In the field, the surface storage and infiltration of rainwater are dynamically interconnected. The interconnection occurs primarily via surface depression and detention storage. Detention storage increases infiltration rate by adding a small (less than an inch) pressure head to the wetting front. This additional head is insignificant when compared to the suction head which drives soil infiltration. Detention storage increases apparent infiltration by delaying surface flow and providing more catchment retention time for water to infiltrate. In general, these effects are minor when compared to the problem of estimating the magnitude of surface loss and the in-situ capacity of soils to infiltrate water. Consequently, the typical approach is to separate these two contributions to rainfall loss unless surface losses are empirically included in the loss rate method. For example, the SCS curve number method includes surface losses directly into the method.

b. Surface loss is a function of land use and differs greatly between forested, agricultural, and urban areas. According to Viessman et al. (1977), interception of rainfall by surface cover is greatest for a forest and decreases for agricultural and urban land uses. Schomaker's (1966) measured values of interception for a spruce forest were 30 percent of the annual rainfall and for a birch forest were 9.5 percent of annual rainfall. Horton (1919) reported that the interception for rainfall events greater that 0.25 in. is approximately 25 percent of the total rainfall. The Viessman et al. (1977) conclusion from this information is that interception for forested regions is approximately 10 to 20 percent of the total precipitation, at least for rainfall events less than 2.0 in. In general, one should not expect interception losses to exceed 0.5 in. for a particular rainfall event.

c. Agricultural watershed surface losses are a function of crop development and management practice. Interception of rainfall by crops was computed by Linsley, Kohler, and Paulhus (1975) using equations developed by Horton (1919). They found that for a storm depth of 1.0 in., the interception ranged from 3 to 16 percent for small grain crops such as wheat and milo. This compares well to the study by Schomaker (1966), since interception by these crops should be less than that of a forest due to the smaller leaves and sparser cover provided by these crops.

d. Detention storage in agricultural areas is strongly affected by the time since tillage occurred and the overall management practice. Linden (1979) used random roughness and land surface slope in microrelief models to predict depression storage due to tillage (note random roughness is essentially a measure of the variation of soil heights from the surface plane). He predicted that depression storage could be as high as 0.5 in. immediately after tillage. The depression storage will decrease with time after tillage due to the impact of rainfall. Linden's results do not account for increased storage capabilities due to management practice such as contour plowing. Horton (1935) estimated that detention storage for agricultural lands, natural grass lands, and forests range from 0.5 to 1.5 in.

e. Surface losses in urban areas differ for open and impervious areas. Interception losses for open areas (lawns, parks etc.) can probably be considered of the same magnitudes as forest or pasture land. However, the depression storage in the open areas is probably not as great as in natural areas because grading has taken place and there is probably less surface litter. The surface loss for impervious areas is small and usually taken as 0.1 to 0.2 in. Table 6-1 summarizes the surface losses that can be used for each land use type. The values listed in Table 6-1 are a suggested range based on previous research work and experience. If these values are not in line with local experience of a particular watershed, the modeler should by all means use any local information.

6-5. Infiltration Methods

a. Green and Ampt. The Green and Ampt method is explained and illustrated in detail below.

(1) Method development. The Green and Ampt (GA) method (Mein and Larson 1973) assumes the same simple soil model and initial conditions as that of the Richards equation, a uniform soil profile of infinite extent, and constant initial water content. As the water content at the soil surface increases, the method models the movement of the infiltrated water by approximating the wetting front with a piston type displacement (Figure 6-5).

(a) The piston displacement model, as originally developed, must be modified to account for surface losses and variable rainfall rates (time varying surface moisture

Table 6-1
Surface Losses

Interception Losses Agricultural Areas		
Crop	Height ft.	Interception in.
Corn	6	0.03
Cotton	4	0.33
Tobacco	4	0.07
Small grains	3	0.16
Meadow grass	1	0.08
Alfalfa	1	0.11
(from Linsley, Kohler, and Paulhus 1975)		
Forest Areas (from Viessman et al. 1977) 10-20% total rainfall, maximum 0.5 in.		
Detention Storage (from Horton 1935)		
Agricultural Areas (Depending on time sense tillage)	0.5 - 1.5 in.	
Forests/Grasslands	0.5 - 1.5 in.	
Total Surface Loss		
Urban Areas Open Areas	0.1 - 0.5 in.	
Impervious Areas	0.1- 0.2 in.	

conditions). The surface loss is modeled for an initial loss as follows:

$$r(t) = 0 \qquad for \quad P(t) \le I_a \quad t \ge 0 \tag{6-1}$$

$$r(t) = r_o(t) \qquad for \quad P(t) > I_a \quad t \ge 0 \tag{6-2}$$

where

$P(t)$ = cumulative precipitation over the watershed

$r(t)$ = rainfall intensity adjusted for surface losses

t = time since the start of rainfall

$r_o(t)$ and I_a = depth of surface loss assumed to be uniform over the watershed

The cumulative infiltration loss is calculated by the GA method:

$$I = \frac{S_f}{[(i/K) - 1]} = \frac{KS_f}{[(dI/dt) - K]} \quad i > K \tag{6-3}$$

where

$dI/dt = i(t)$ = infiltration rate

K = soil's hydraulic conductivity

S_f = product of the wetting front suction, h_f, and the soil volumetric deficit at the beginning of the storm

$\Delta\theta$ and I = cumulative infiltration

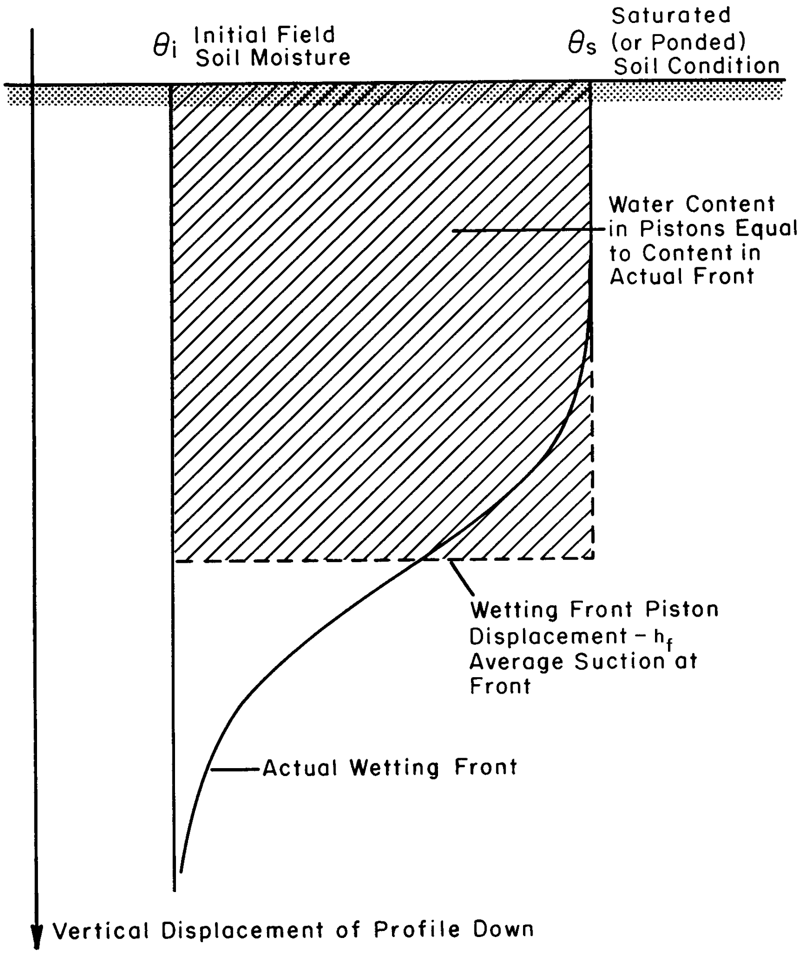


Figure 6-5. Green and Ampt piston wetting front

The GA equation as originally developed, is only strictly applicable to a uniform moisture condition at the soil surface or, in the case of rainfall infiltration, a ponded surface condition. Modifications were made as suggested by Mein and Larson (1973) and Morel-Seytoux (1980) to use the GA equation for unponded surface conditions and variable rainfall rates. In the absence of ponding, infiltration is estimated for any period by (Figure 6-6):

$$\Delta I = I_j - I_{j-1} = \frac{S_f}{(r_j/K)-1} - \sum_{i=1}^{j-1} r_i \Delta t_i \quad r_j \geq K \qquad (6\text{-}4)$$

where

I_j and I_{j-1} = cumulative depth of infiltration at the end of time period j and j-1

r_j = average rainfall rate over the period Δt_j

ΔI = potential depth of water infiltrated during the period

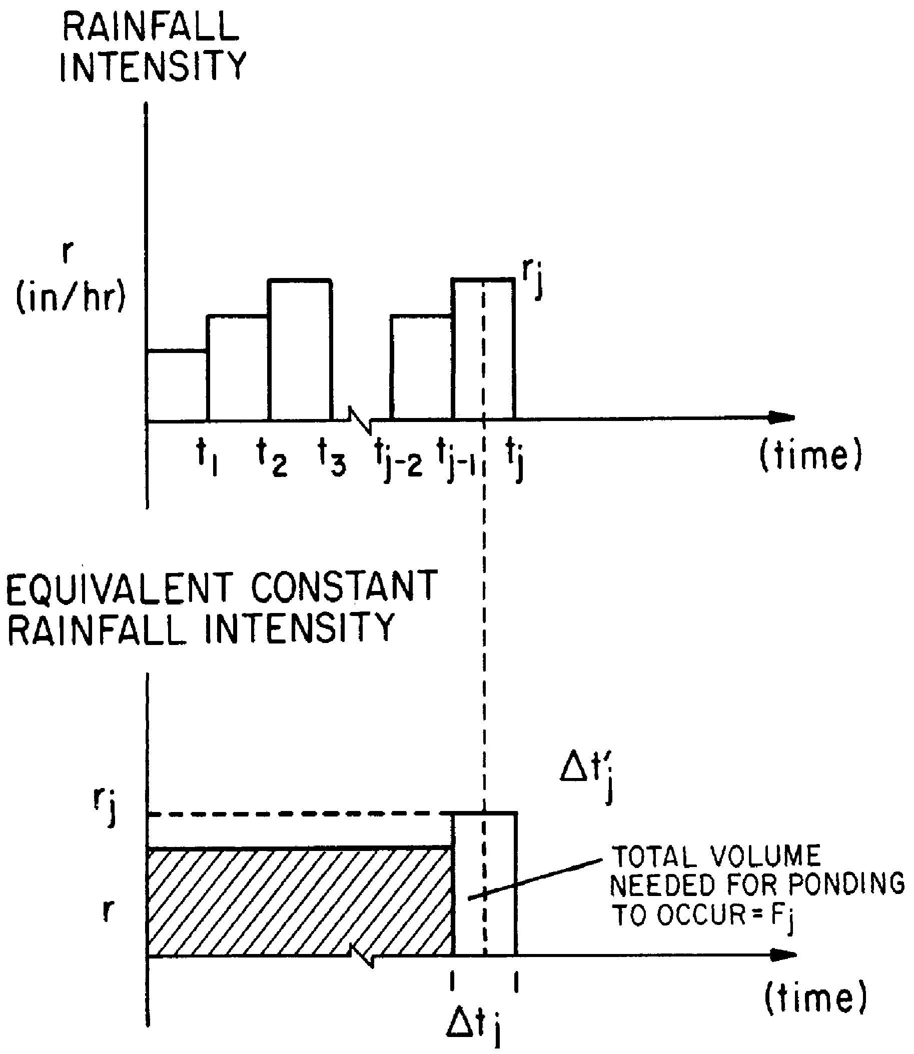


Figure 6-6. Green and Ampt application of variable rainfall rate

If the rainfall rate is less than K or if:

$$\Delta t_j^1 = \frac{\Delta I}{r_j} > \Delta t_j \qquad (6\text{-}5)$$

then ponding does not occur. Otherwise, the ponding time is equal to:

$$t_p = t_{j-1} + \Delta t_j^1 \qquad (6\text{-}6)$$

Once ponding has occurred, the cumulative infiltration is computed by integrating Equation 6-3 to obtain:

$$(I/S_f) - In(1 + (I/s_f)) = (K/S_f)\ (t + t_e - t_p) \qquad (6\text{-}7)$$

with the initial condition that at $t = t_p$, $I = I_p$ where I_p is the cumulative infiltration at ponding and:

$$t_e = (S_f/K)\ ((I_p/S_f) - In(1 + (I_p/S_f))) \qquad (6\text{-}8)$$

(b) Prior to ponding, the rainfall excess rate is zero. The rainfall excess rate after ponding is determined by subtracting the incremental infiltration from the rainfall during a period:

$$e_j = (r_j\ \Delta\ t_j - \Delta\ I) / \Delta\ t_j \qquad (6\text{-}9)$$

where

e_j = excess rate during any period

ΔI = incremental infiltration, which is equal to the difference between applying Equation 6-7 for times t_j and t_{j-1}

Notice that Equation 6-7 does not give an explicit expression for I. An approximate technique described by Li, Stevens, and Simons (1976) is one approach that can be used to solve for I at any t.

(c) There may be instances when the rainfall rate during a storm drops below the infiltration rate after an initial ponding time has been calculated. In this case, a new ponding time is calculated by keeping track of the accumulated infiltration and reapplying Equation 6-4; then Equation 6-7 is applied as before to calculate the excess rate.

(d) The infiltrated volume computed by this method should always be compared with the total storage volume available in the soil profile. The storage volume in the soil profile may be computed as:

$$S_a = (\Delta\ \theta)\ d \qquad (6\text{-}10)$$

where

S_a = available initial soil storage

d = depth of the soil profile

The GA method is not constrained by storage considerations because of the assumption of an infinite profile.

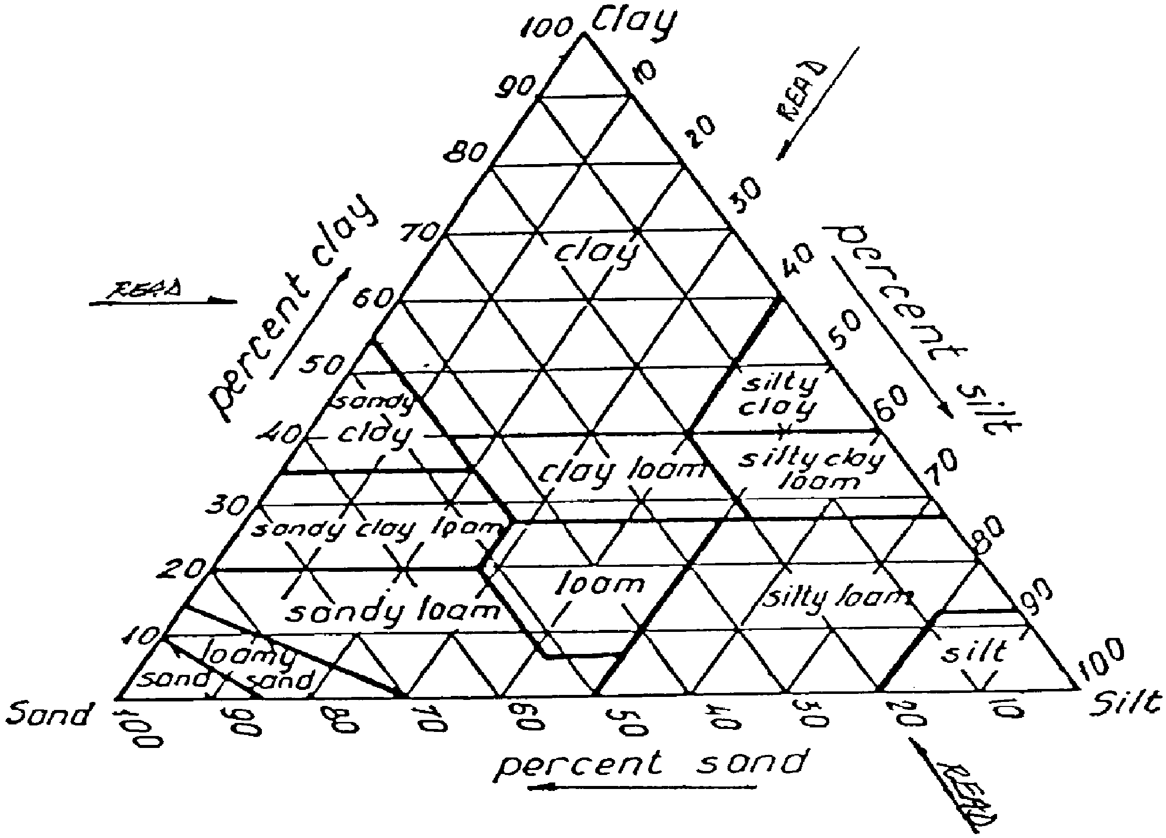
(2) Parameter estimation. Readily available information from soil surveys, texture class, and particle size distribution has been used to estimate the GA parameters. Texture class differentiates between types of soils (sand, sandy loam) as shown in Figure 6-7 based on ranges in particle size distribution, the percent sand, silt, and clay contained in the soil. The general procedure involved has been to relate this information to the GA parameters via the water retention characteristics of the soil. The moisture retention characteristics are defined by the relationship of water content to the soil suction (Figure 6-8). Soil suction is essentially a capilary effect, the drier and finer textured the soil (a clay is a finer textured soil than a sand), the greater the suction. Brooks and Corey (1964) suggested that the water retention versus suction relationship could be represented by:

$$S_e = (\theta - \theta_r) / (\theta_s - \theta_r) = (h_c / h_{cb})$$

where

S_e = effective saturation

TEXTURE CLASS ?



SOILS GROUPED BASED ON RANGES
OF PARTICLE SIZE DISTRIBUTION

PARTICLE SIZE DISTRIBUTION IS THE
THE SOIL'S PERCENT SAND, SILT AND CLAY

Figure 6-7. USDA texture triangle

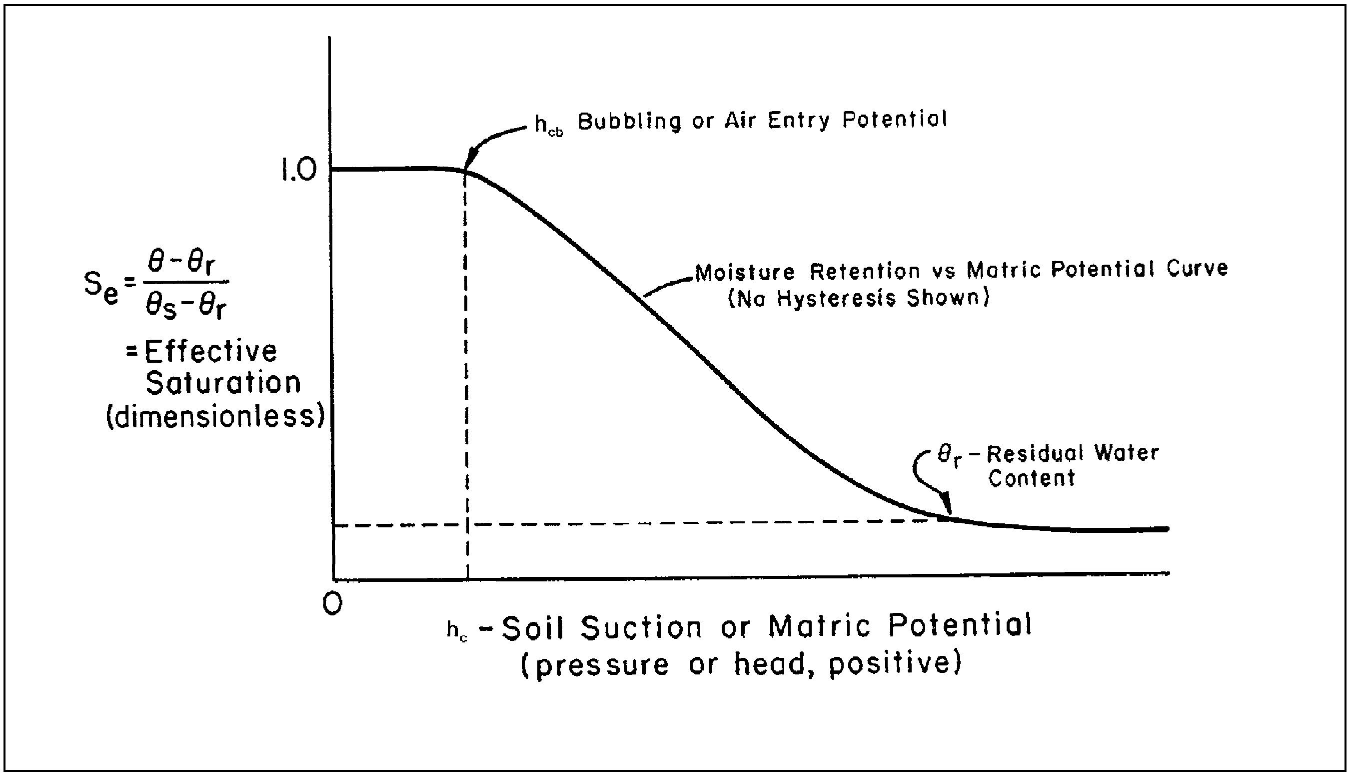


Figure 6-8. Water content versus suction

Θ = volumetric water content at suction, h_c

θ_r = residual saturition

θ_s = water content at saturation

h_{cb} = bubbling pressure

λ = pore size distribution

The Brooks and Corey parameters are then used to calculate the wetting front sucfion, h_f, by:

$$h_f = h_{ce} + [(\eta^{h_{ce}})/(1 - \eta)][h_{ci}^{(1-\eta)} - h_{ce}^{(1-\eta)}] \qquad (6\text{-}12)$$

$$h_{ce} = h_{cb}/2 \qquad (6\text{-}13)$$

where

h_{ce} = water entry pressure

h_{ci} = water content corresponding to the initial soil water content of the soil prior to ponded infiltration

$$\eta = 3\lambda + 2 \qquad (6\text{-}14)$$

Assuming that the initial water content is equal to the residual saturation, the formula finally derived by Brakensiek (1977) and applied by Rawls and Brakensiek (1982a) is obtained as:

$$h_f = \frac{\eta}{\eta - 1} h_{ce} \qquad (6\text{-}15)$$

Research performed by Rawls and Brakensiek (1983) and Rawls, Brakensiek, and Soni (1983) related the GA parameter total porosity and the Brooks and Corey parameters to soil texture class as shown in Table 6-2. The information shown in the table can be used together with an estimate of the initial water content via Equation 6-12 to estimate h_f. Estimates of h_f for initial water content equal to the residual saturation are shown in Table 6-2 for informational purposes.

(a) Attempts made by these researchers to find a relationship between texture class and saturated hydraulic

Table 6-2
Texture Class Estimates
(from Rawls and Brakensiek 1982 and Rawls, Brakensiek, and Saxton 1982)

Texture class	Sample size	Total porosity[1] θ cm^3/cm^3	Residual saturation[1] θ_r cm^3/cm^3	Bubbling pressure[1] h_{cb}		Pore size distribution[1] λ		Saturated hydraulic conductivity K_s cm/h	λ	h_f cm
				Arithmetic cm	Geometric[2] cm	Arithmetic	Geometric			
Sand	762	0.437* (0.374-0.500)	0.020 (0.001-0.039)	15.98 (0.24-31.72)	7.26 (1.36-38.74)	0.694 (0.298-1.09)	0.592 (0.334-1.05)	21.00	0.694	10.6
Loamy sand	338	0.437 (0.368-0.506)	0.035 (0.003-0.067)	20.58 (0.0-45.20)	8.69 (1.80-41.85)	0.553 (0.234-0.872)	0.474 (0.271-0.827)	6.11	0.553	14.2
Sandy loam	666	0.453 (0.351-0.555)	0.041 (0.0-0.106)	30.20 (0.0-64.01)	14.66 (3.45-62.24)	0.378 (0.140-0.616)	0.322 (0.186-0.558)	2.59	0.378	22.2
Loam	383	0.463 (0.375-0.551)	0.027 (0.0-0.074)	40.12 (0.0-100.3)	11.15 (1.63-76.40)	0.252 (0.086-0.418)	0.220 (0.137-0.355)	1.32	0.252	31.5
Silt loam	1206	0.501 (0.420-0.582)	0.015 (0.0-0.058)	50.87 (0.0-109.4)	20.76 (3.58-120.4)	0.234 (0.105-0.363)	0.211 (0.136-0.326)	0.68	0.234	40.4
Sandy clay loam	498	0.398 (0.332-0.464)	0.068 (0.0-0.137)	59.41 (0.0-123.4)	28.08 (5.57-141.5)	0.319 (0.079-0.559)	0.250 (0.125-0.502)	0.43	0.319	44.9
Clay loam	366	0.464 (0.409-0.519)	0.075 (0.0-0.174)	56.43 (0.0-124.3)	25.89 (5.80-115.7)	0.242 (0.070-0.414)	0.194 (0.100-0.377)	0.23	0.242	44.6
Silty clay loam	689	0.471 (0.418-0.524)	0.040 (0.0-0.118)	70.33 (0.0-143.9)	32.56 (6.68-158.7)	0.177 (0.039-0.315)	0.151 (0.090-0.253)	0.15	0.177	58.1
Sandy clay	45	0.430 (0.370-0.490)	0.109 (0.0-0.205)	79.48 (0.0-179.1)	29.17 (4.96-171.6)	0.223 (0.048-0.398)	0.168 (0.078-0.364)	0.12	0.223	63.6
Silty clay	127	0.479 (0.425-0.533)	0.056 (0.0-0.136)	76.54 (0.0-159.6)	34.19 (7.04-166.2)	0.150 (0.040-0.260)	0.127 (0.074-0.219)	0.09	0.150	64.7
Clay	291	0.475 (0.427-0.523)	0.090 (0.0-0.195)	85.60 (0.0-176.1)	37.30 (7.43-187.2)	0.165 (0.037-0.293)	0.131 (0.068-0.253)	0.06	0.165	71.4

NOTE: The wetting front suction, h_f, value shown, assume dry initial moisture conditions.

[1] First line is the mean value, second line is + one standard deviation about the mean
[2] Antilog of the log mean

conductivity, *K*, were unsuccessful because the variance of *K* within the texture class is too large. However, Rawis and Brakensiek (1983) and Rawls, Brakensiek, and Soni (1983) did provide average estimates of *K* for the soils sampled in their survey as shown in Table 6-2. Note that variances about the mean value for each of the parameters are shown in this table except for *K* because texture class was not found to be a discriminator of this variable.

(b) Additional work has been performed by Ahuja et al. (1988) and Rawis and Brakensiek (1989) to improve predictions of GA parameters using particle size distribution and/or soil porosity. Further modifications to the estimates for surface cover characteristics, stones, and surface crusts have been developed by Rawls and Brakensiek (1983); Rawls, Brakensiek, and Soni (1983); and Rawls, Brakensiek, and Savabi (1988).

(c) An initial water content θ_i must be selected prior to determining $\Delta\theta$ and h_f. A means for estimafing θ_i may be to relate watershed moisture conditions to an antecedent precipitation index.

b. Holtan loss rate method. The Holtan loss rate method is expuned and illustrated in detail below.

(1) Method development. Holtan et al. (1975) used a conceptual soil storage element to compute infiltration rates based on the formula:

$$i = (GI)\,A\,S_a^{\beta} + f_c \qquad (6\text{-}16)$$

where

i = potenfial infiltration rate in inches per hour

GI = "growth index" representing the relative maturity of the ground cover

A = inches per hour per inch of available storage and is an empirical factor discussed in more detail in the next section

S_a = soil storage capacity in inches of equivalent depth of pore space in the surface layer of the soil, f_c is the constant rate of percolation of water through the soil profile below the surface layer

β = empirical exponent, typically taken equal to 1.4

The available storage, S_a, is decreased by the amount of infiltrated water and *increased at the percolation rate, f_c*. Note that by calculating S_a in this manner, soil moisture recovery occurs at the deep percolation rate. The method is applied to a variable rainfall rate by continuously accounting for storage using the following relationship, given the initial soil deficit S_{a0}:

$$S_{a_i} = S_{a_{i-1}} - i\Delta t + f_c\Delta t \qquad (6\text{-}17)$$

where

S_{a_i}, $S_{a_{i-1}}$ = storage deficit at the beginning and ending of period Δt
i = average infiltration rate during this period
$(f_c\Delta_t)$ = drainage volume out of storage

The volume draining from storage is limited by the maximum allowable deficit S_a. The average infiltration over the period is the minimum of the available rainfall or the potential infiltration rate. The potential infiltration rate is calculated as:

$$i = \frac{\left(i_i + i_{i-1}\right)}{\Delta t} \qquad (6\text{-}18)$$

where

$$i_{i-1} = (GI)AS_{a_{i-1}}^{\beta} + f_c \qquad (6\text{-}19)$$

$$i_i = (GI)AS_{a_i}^{\beta} + f_c \qquad (6\text{-}20)$$

The potential infiltration rate (essentially the average infiltration rate) must be calculated implicitly or iteratively since it is a function of the storage deficit at the end of the period. The excess rate is the difference between the rainfall rate and average infiltrafion rate.

(2) Parameter estimation. The factor "A" is interpreted as an index of the pore volume which is directly connected to the soil surface. The number of surface-connected pores is related to the root structure of the vegetation, so the factor "A" is related to the cover crop as well as the soil texture. Since the surface-connected porosity is related to root structure, the growth index (GI) is used to indicate the development of the root system. In agricultural basins, GI will vary from near zero when the crop is planted to 1.0 when the crop is full-grown.

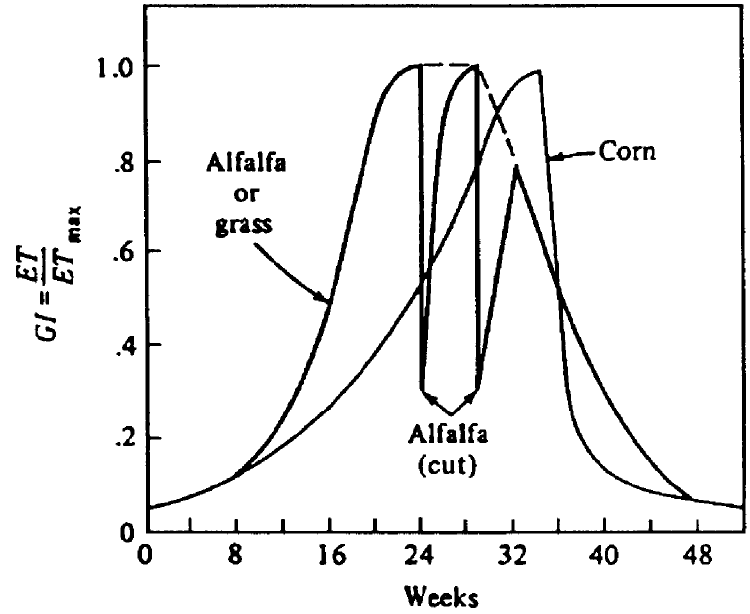
(a) Holtan et al. (1975) have made estimates of the value of "A" for several vegetation types. Their estimates were evaluated as the percent of the ground surface occupied by plant stems or root crowns at plant maturity. Skaggs and Kahleel (1982) provide estimates as shown in Table 6-3.

(b) Estimates of f_c can be based on either the values given in Table 6-3 (Skaggs and Kahleel 1982) or the hydrologic soil group given in the SCS Handbook (1972). Musgrave (1955) has given the following values of f_c in inches per hour for the four hydrologic soil groups: A, 0.45 to 0.30; B, 0.30 to 0.15; C, 0.15 to 0.05; D, 0.05 or less.

(c) The total soil storage capacity can be computed using information in Table 6-2 as:

$$S_a = (\phi - \theta_r)d \qquad (6\text{-}21)$$

Table 6-3
Holtan Parameters



Growth index GI = ET/ET$_{max}$ from lysimeter records, irrigated corn, and hay for 1955, Coshocton, Ohio.

Estimates of Holtan A

Land use or cover	Basal Area Rating[1]	
	Poor Condition	Good Condition
Fallow[2]	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 (bunchgrass)	0.20	0.40
Temporary pasture (sod)	0.40	0.60
Permanent pasture (sod)	0.80	1.00
Woods and forests	0.80	1.00

[1] Adjustments needed for "weeds" and "grazing."
[2] For fallow land only, "poor condition" means "after row crop," and "good condition" means "after sod."

Source: Holtan et al. (1975)

where d = depth of the soil horizon. The inifial deficit is given by Equation 6-10. The initial water content would have to be determined from an assessment of past conditions.

c. Soil Conservation Service curve number method. The SCS curve number method is explained in detail below.

(1) Method development. The curve number (CN) method depends on the following basic relationship:

$$\frac{F}{S} \text{ and } \frac{Q}{P} \rightarrow 1 \text{ as } P \rightarrow \infty \tag{6-22}$$

where

F = watershed retention of water

S = maximum available retention capacity

Q = direct runoff

P = total storm precipitation (in consistent units of volume; for example, basin-inches)

The retention parameter, S, is related to the CN by a relationship that will be discussed in the next section on parameter estimation. The supposition that $F = S$ as the amount of precipitation becomes large seems reasonable, since most of the precipitation will directly runoff as the watershed soils become saturated. $Q = P$ is a fair approximation for the same reason.

(a) A parametric relationship for calculating direct runoff can be developed by setting $F = (P - Q - I_a)$ and then solving for Q, assuming that Equation 6-22 applies:

$$\frac{F}{S} = \frac{(P - Q - I_a)}{S} = \frac{Q}{P} \tag{6-23}$$

where I_a = basin volume is equal to the initial abstraction of rainfall (i.e., the observed rainfall depth prior to the observafion of runoff). Solving Equation 6-23 for Q gives the desired direct runoff:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \tag{6-24}$$

in terms of the precipitation and the parameters of the methods I_a and S.

(b) The CN method does not incorporate time explicitly into the formulation. Consequently, the application of the method to a rainfall hyetograph requires that time be incorporated rather simply into Equation 6-24 as:

$$Q(t) = \frac{(P(t) - I_a)^2}{(P(t) - I_a + S)} \tag{6-25}$$

where

$Q(t)$ = cumulative runoff at time t

$P(t)$ = cumulative rainfall minus I_a at time t

The incremental runoff depth over a period $\Delta t = t_2 - t_1$:

$$\Delta Q = Q(t_2) - Q(t_1) \tag{6-26}$$

Note, the computation of cumulative excess by Equation 6-25 is entirely dependent on the cumulative precipitation at any time. The total infiltration, therefore (like the runoff) is independent of the storm pattem.

(2) Parameter estimation. The parameters of the CN method were estimated by examining a great deal of data from small (less than 10 acres) agricultural watersheds in the midwestern United States. The goal was to relate 1. and S to physical characteristics of the watershed. To simplify this problem, Equation 6-24 is transformed to use only a single parameter by developing the following relationship from test watershed data:

$$I_a = 0.2S \tag{6-27}$$

A further simplification was made by relating S to CN as:

$$CN = \frac{1000}{S + 10} \tag{6-28}$$

This transformation was performed according to Victor Mockus (1964) so that the rainfall-runoff curves from Equation 6-26 would plot at nearly equal intervals across a graph sheet. The CN was assumed to be related to the soil and cover conditions of a watershed. A search was made by Mockus for test watersheds with a single cover characteristic and soil type. Total rainfall versus runoff volumes were analyzed graphically to determine the appropriate CN for the soil type and cover for each watershed. As might be expected, there was a great deal of scatter in the observed data when plotted in this manner. The CN that resulted in a curve that divided the plotted data in half was deemed appropriate.

(a) A relationship between CN and watershed potential runoff was developed by determining enveloping CN for the scattered data. This results in three sets of curves that divide and bound test data for an individual watershed. In the past (SCS 1972), the upper and lower enveloping curves were assumed to be related to relatively wet (AMC III) and dry (AMC I) watershed soil moisture conditions and the dividing curve by average soil moisture conditions (AMC II). The CN associated with these different soil moisture conditions was then related to the 5-day antecedent rainfall. However, the relationship between antecedent rainfall and AMC has been poor and the SCS no longer relates the potential runoff to an AMC. Rather, the potential runoff defined by the curves enveloping the scattered data is now related to three antecedent runoff conditions, ARC(III) for relatively high runoff potential, ARC(I) for relatively low runoff potential, and ARC(II) for average runoff potential.

(b) The average CN value for a parficular watershed and the effect of ARC on CN should be determined based on observed rainfall versus runoff. The SCS now recommends that the calibration method used by Mockus or a statistical analysis of rainfall versus runoff data be used to determine the CN for each ARC value. Table 64 displays the effect of ARC condition on curve number based on the past work by Mockus in developing envelope curves of CN for observed rainfall versus runoff. McCuen (1989, pg. 299) cautions that this table is only applicable for the region where the CN was calibrated and should be adjusted based on regional information. His recommended caution refers to the use of the now obsolete AMC designations but is equally relevant to the ARC designations in the table. If data are not available for making adjustments to the curve number, then the ARC(II) curve numbers of Table 64 should be used.

(c) The CN corresponding to a large number of soil types and cover characteristics are reported by the SCS. Consequently, application of the method requires that soil survey information be available for the watershed of interest. A soil survey provides the information needed to choose CN based on soil type, cover, management practice, and hydrologic condition. Hydrologic group indicates in-situ infiltration capacity by classifying the soils as type A, B, C, or D, with A having the highest and D the lowest capacities. The CN associated with each group (Table 6-5) is determined based on the cover (agricultural versus forest), management practice (tillage practice and mulching), and hydrologic condition (degree of grazing or percentage of area with good cover characteristics). A more detailed table of curve numbers can be found in SCS TR-55 (SCS 1986) or the National Engineering Handbook, Chapter 4 (SCS 1972).

(d) Although the CN method is easily the most popular method for performing ungauged analysis, there has been extensive criticism of the method because it does not lead to accurate reproduction of runoff hydrographs, the predicted infiltration rates are not in accordance with classical unsaturated flow theory, the method is applied to watersheds for which it was not calibrated, and the original calibration results are not available. As pointed out by Rallison and Miller (1981), p 361:

> The CN procedure continues to be most satisfactory when used for the type of hydrologic problem that it was developed to solve--evaluating effects of land use changes and conservation practices on direct runoff. Since it was not developed to reproduce individual historical events, only limited success has been achieved by those using it for that purpose.

Despite this well recognized deficiency, the method remains popular for simulating rainfall hydrographs.

(e) The method has received crificism because it is at variance with the results of classical unsaturated flow theory, as can be seen by examining the infiltration rate implied by Equation 6-25 (Smith 1976, Aron, Miller, and Lakatos 1977, and Morel-Seytoux and Verdin 1981):

$$i = \frac{S^2 r}{(P - I_a + S)^2} \tag{6-29}$$

where

i = infiltrafion rate

r = rainfall intensity

Morel-Seytoux (1981) points out that i and P are inversely related. As one would expect, the proportionality of i and r is "in direct disagreement with field experience, laboratory evidence and physical theory," which

Table 6-4
Antecedent Runoff Condition Adjustments

CN Adjustment for Wetness

ARCII	ARCI	ARCIII
100	100	100
95	87	98
90	78	96
85	70	94
80	63	91
75	57	88
70	51	85
65	45	82
60	40	78
55	35	74
50	31	70
45	26	65
40	22	60
35	18	55
30	15	50
25	12	43
20	9	37
15	6	30
10	4	22
5	2	13

shows that *i* is independent of *r* for a ponded surface condition.

(f) Perhaps the most disturbing aspect of the CN method is that the original calibration results obtained by Victor Mockus (1964) have not been preserved. Consequently, the only means of evaluating the observed performance of the method is to examine current results from the literature or from personal experience.

(g) However, despite the missing calibration results, it is clear that the method is being used for watersheds where data did not exist to calibrate the method. Rallison and Miller (1981) p 361 point out:

> Data for developing reliable curve numbers are not equally available throughout the United States. Information on rainfall, runoff and soil is deficient for many range and forest areas, particularly in the Western States and, as a consequence, there are many soil complexes that are either unclassified or lack data for verification. The sparseness of rainfall-runoff data in urban or urbanizing areas has forced reliance on interpretive values with litlle "hard" data available for verification....

Despite these caveats about the CN method, engineers continue to use the method because it has been the only

Table 6-5
Runoff CN's for Hydrologic Soil-Cover Complexes
(Antecedent runoff condition II, and $I_a = 0.2S$)

Cover			Hydrologic Soil Group			
Land use	Treatment or practice	Hydrologic Condition	A	B	C	D
Fallow	Straight row		77	86	91	94
Row crops	Straight row	Poor	72	81	88	91
		Good	67	78	85	89
	Contoured	Poor	70	79	84	88
		Good	65	75	82	86
	Contoured and terraced	Poor	66	74	80	82
		Good	62	71	78	81
Small grain	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Contoured	Poor	63	74	82	85
		Good	61	73	81	84
	Contoured and terraced	Poor	61	72	79	82
		Good	59	70	78	81
Close-seeded legumes[1] or rotation meadow	Straight row	Poor	66	77	85	89
		Good	58	72	81	85
	Contoured	Poor	64	75	83	85
		Good	55	69	78	83
	Contoured and terraced	Poor	63	73	80	83
		Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
		Fair	25	59	75	83
		Good	6	35	70	79
Meadow		Good	30	58	71	78
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads			59	74	82	86
Roads (dirts)[2]			72	82	87	89
(hard surface)[2]			74	84	90	92

[1] Closed-drilled or broadcast.
[2] Including right-of-way.

Note: For a more detailed table of CN's, see SCS (1986) or SCS (1972).

one available that relates readily available watershed characteristics to a loss rate method.

(h) Caution should be used in applications to areas where the CN method has not been calibrated. Information on regional rainfall-runoff characteristics should be obtained, if possible, to judge whether or not the CN method predictions are useful.

(i) Rallison and Miller's comments with regard to applications in urban areas are particularly noteworthy. The CN usually chosen for open land uses in urban areas are generally based on CN values determined for pasture land use. However, runoff tends to be greater from the open urban areas than that from a pasture land use. A common approach for adjusting for this affect is to reduce the value of I_a, thus relaxing the constraint that $I_a = 0.2S$. This approach is not appropriate since the relationship between the initial abstraction and watershed retention is critical to the reported CN calibration (1986). Either attempts should be made to find regional or local information for recalibrating CN, or the CN should be adjusted based on some judgment for open land use in urban areas.

(j) Researchers have suggested means for utilizing the empirical data present in the curve number method in more physically based infiltration equations. Hjelmfelt (1980) suggested a procedure for incorporating CN information into the Holtan equation. Morel-Seytoux and Verdin (1981) suggested a procedure for doing the same with the Green and Ampt equation. However, one might wonder about the efficacy of this approach since there is no information available which details the accuracy of the original CN calibration to observed data or whether or not it is useful for rainfall-runoff simulations.

d. Initial and constant loss rate method. The initial and constant loss rate method is described in detail below.

(1) Method development. This is a very simple method and does not need much explanation. An initial loss (units of depth) and a constant loss rate (units of depth/hour) are specified for this method. All rainfall is lost until the volume of initial loss is safisfied. After the initial loss is satisfied, rainfall is lost at the constant rate. As in the case of the GA method, infiltrated volumes computed by the initial and constant loss rate method are not constrained by the storage capacity of the soil profile. Consequently, a comparison should be made of the infiltrated volume and soil storage capacity to be sure that the parameters chosen for the method are appropriate.

(2) Parameter estimation. The initial and constant loss rate method, having only two parameters, is valuable in the application of automatic parameter estimation procedures. However, the method could also be used in ungauged analysis by assuming a physical interpretation of the parameters. The constant loss might be interpreted as the ultimate infiltration capacity of the soils. The initial loss might reflect both antecedent moisture conditions and losses prior to reaching the ultimate infiltration capacity.

6-6. Impervious Areas

a. Estimation of losses from an urban area is complicated by the presence of impervious surfaces which are not hydraulically connected to drainage systems. Typically, these areas are roof tops with downspouts that drain to flower beds or lawns. The critical part of the analysis is to determine if the pervious area can infiltrate the flow received from the unconnected impervious area. A method applied by SCS (1986) considered this problem in detemining corrections for the curve number based on the percent of total and unconnected impervious areas as shown in Figure 6-9. The correcfions are only applicable for areas with up to 30 percent total impervious area. If the percent impervious area exceeded this amount, then the assumption was that the unconnected impervious area runoff would not infiltrate because of the small retention time on pervious areas.

b. Figure 6-9 was established by calculating the amount of runoff from the unconnected impervious watershed area due to a given rainfall depth and *uniformly* distribufing this volume over the pervious area (McCuen 1989). The runoff from the pervious area was then calculated based on the pervious area curve number and the combined volume from rainfall and unconnected impervious area runoff. The apparent curve number for the entire watershed is then back calculated from knowing the total rainfall and the combined runoff from the pervious area and connected impervious area. This procedure could be duplicated for methods other than the curve number.

c. Caution should be used when applying Figure 6-9 because of the assumptions used in its development. In many instances, conveyance of flow from unconnected impervious areas may not exist or may be very direct. For example, portions of a rooftop may directly drain to a backyard which does not drain easily into the street gutter. However, the drainage path from the downspouts draining the front portion of the rooftop may be rather short, providing little opportunity for infiltration. Certainly, local knowledge of drainage design is needed to judge to what degree unconnected impervious area acts as if it were hydraulically connected.

d. Caution should also be used when composite impervious/pervious values for loss rate parameters are provided for a particular land use. For example, SCS (1986) provides Table 6-6 for applications in urban hydrology. Notice that in this table composite curve number are given for urban land uses as a function of

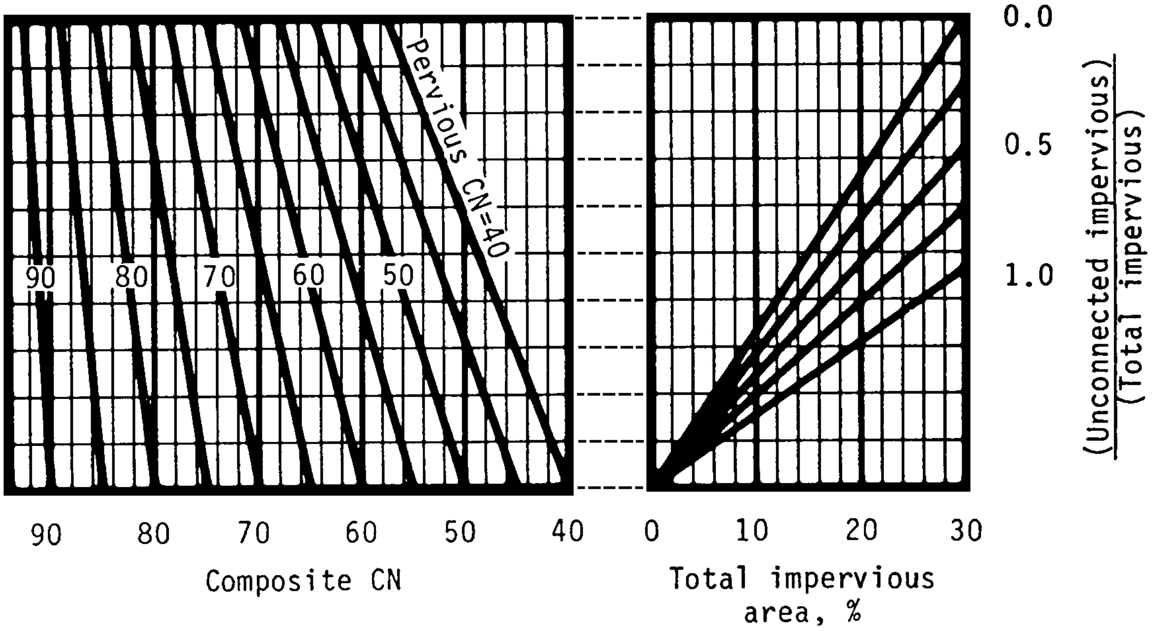


Figure 6-9. Correction for unconnected impervious area (SCS 1986)

zoning and hydrologic soil group. The assumption made in deriving these values is that the impervious areas have a CN of 98, and the open areas correspond to pastures in good condition. Weighting these values with percent impervious area CN's when computing the CN for a particular watershed area would lead to double accounting of the impervious area.

6-7. Method Seloolon

a. The selection of the loss rate method is a function of the data availability, land use, and the purpose of the loss rate calculation. If a reasonably long gauge record is available, then any of the methods discussed will be adequate when determining parameter estimates with automatic calibration techniques. A possible exception is the CN method. The loss rate function implied by the method is very unappealing and should relegate the method to a last resort application when using an automatic calibration technique. However, if the record is inadequate due to record length or data errors, then method selection depends on the preferred parameter estimation approach for ungauged analysis.

b. The ungauged analysis parameter estimation approaches are used alternatively: utilize texture class or particle size distribution in the Green and Ampt method, utilize USDA classifications for the Holtan method, determine the CN from soil hydrologic group and cover classification, and calibrate any method, the initial and constant loss rate method being simplest, to a regional frequency curve. Each method has its benefits depending on the purpose of the calculation and the experience that has been gained with the method.

c. A caution at this point concerning the application of the Green and Ampt and Holtan methods to forested areas is warranted. These methods assume an overland flow-type mechanism which is not entirely appropriate for forested areas where a subsurface mechanism tends to control direct runoff. Applications to forested areas probably should rely on empirical methods calibrated to regional information such as regional frequency curves or correlation between observed rainfall-runoff characteristics and watershed characteristics as is done by the CN method.

Table 6-6
Runoff CN's for Selected Agricultural, Suburban, and Urban Land Use

Land Use Description	Hydrologic Soil Group			
	A	B	C	D
Cultivated land[1]: without conservation treatment	72	81	88	91
with conservation treatment	62	71	78	81
Feature or range land: poor condition	68	79	86	89
good condition	39	61	74	80
Meadow: good condition	30	58	71	78
Wood or forest land: thin stand, poor cover, no mulch	45	66	77	83
good cover[2]	25	55	70	77
Open Spaces, lawns, parks, golf courses, cemeteries, etc.				
good conditions: grass cover on 75% or more of the area	39	61	74	80
fair conditions: grass cover on 50% to 75% of the area	49	69	79	84
Commercial and business areas (85% impervious)	89	92	94	95
Industrial districts (72% impervious)	81	88	91	93
Residential:[3]				
Average lot size / Average % Impervious[4]				
1/8 acre or less / 65	77	85	90	92
1/4 acre / 38	61	75	83	87
1/3 acre / 30	57	72	81	86
1/2 acre / 25	54	70	80	85
1 acre / 20	51	68	79	84
Paved Parking lots, roofs, driveways, etc.[5]	98	98	98	98
Streets and roads:				
paved with curbs and storm sewers[5]	98	98	98	98
gravel	76	85	89	91
dirt	72	82	87	89

---

[1] For a more detailed description of agricultural land use CN's, refer to SCS (1972).

[2] Good cover is protected from grazing, littering, and brush cover soil.

[3] CN's are computed assuming the runoff from the house and driveway is directed toward the street with a minimum of roof water directed to lawns where additional infiltration could occur.

[4] The remaining pervious areas (lawn) are considered to be in good pasture condition for these CN's.

[5] In some warmer climates of the country, a CN of 95 may be used.