4 RAINFALL LOSSES

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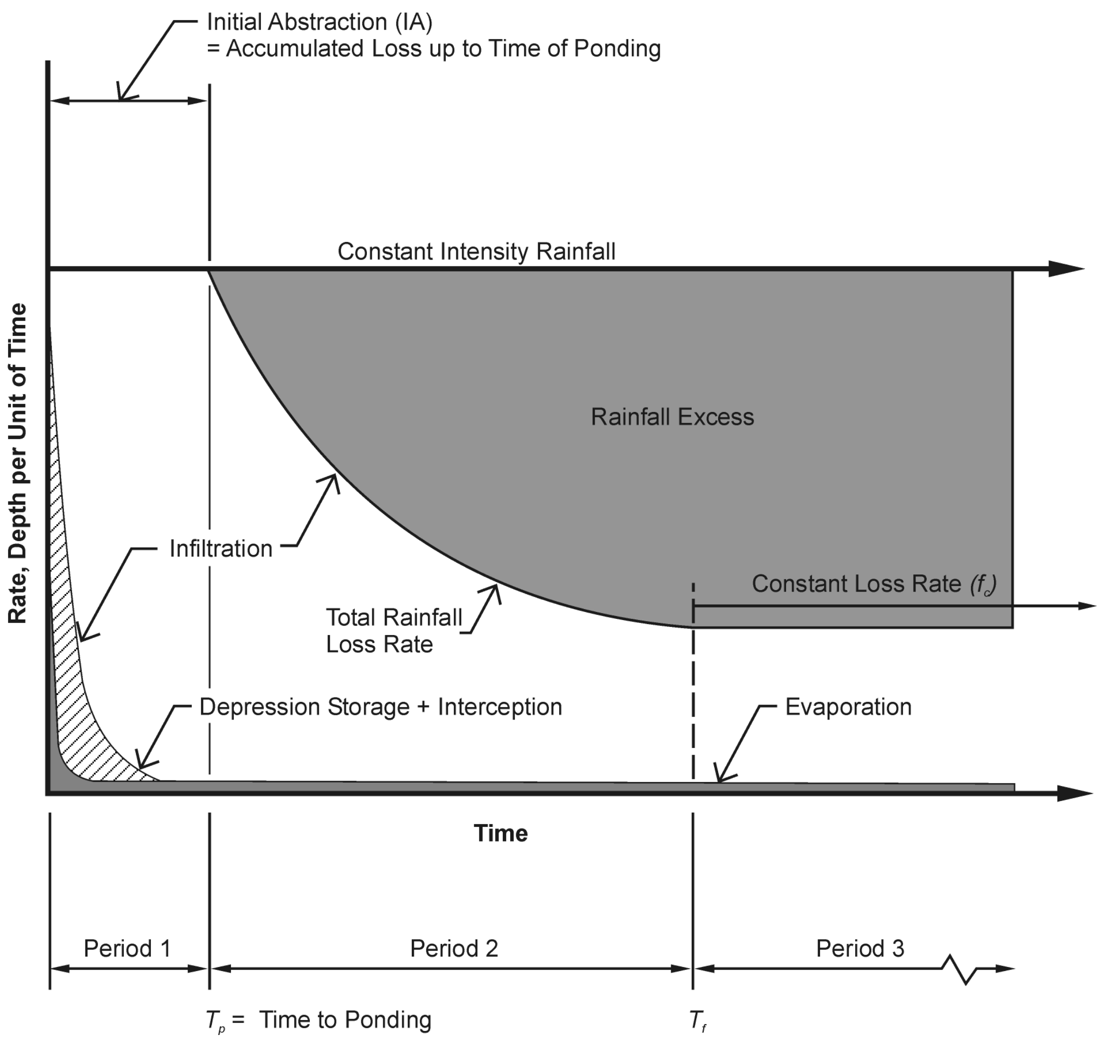
4.1 GENERAL

Rainfall excess is the portion of the total rainfall depth that drains directly from the land surface by overland flow. By a mass balance, rainfall excess plus rainfall loss equals precipitation. When performing a flood analysis using a rainfall-runoff model, the determination of rainfall excess is of utmost importance. Rainfall excess integrated over the entire watershed surface results in runoff volume and the temporal distribution of the rainfall excess will, along with the hydraulics of runoff, determine the peak discharge. Therefore, the estimation of the magnitude and time distribution of rainfall losses should be performed with the best practical technology, considering the objective of the analysis, economics of the project, and consequences of inaccurate estimates.

Rainfall losses are generally considered to be the result of evaporation of water from the land surface, interception of rainfall by vegetal cover, depression storage on the land surface (paved or unpaved), and the infiltration of water into the soil matrix. A schematic representation of rainfall losses for a uniform intensity rainfall is shown in Figure 4.1. As shown in the figure, evaporation can start at an initially high rate depending on the land surface temperature, but the rate decreases very rapidly and eventually reaches a low, steady-state rate. From a practical standpoint, the magnitude of rainfall loss that can be realized from evaporation during a storm of sufficient magnitude to cause flood runoff is negligible.

Interception, also illustrated in Figure 4.1, varies depending upon the type of vegetation, maturity, and extent of canopy cover.

FIGURE 4.1
SCHEMATIC REPRESENTATION OF RAINFALL LOSSES FOR A UNIFORM INTENSITY RAINFALL



No interception estimates are known for the natural vegetation that occurs in Maricopa County. For most applications in Maricopa County, the magnitude of interception losses is essentially zero. Interception is considered for flood hydrology in Maricopa County, but for practical purposes an actual value is not assigned.

Depression storage and infiltration losses comprise the majority of the rainfall loss as illustrated in Figure 4.1. The estimates of these two losses will be discussed in more detail in later sections of this manual.

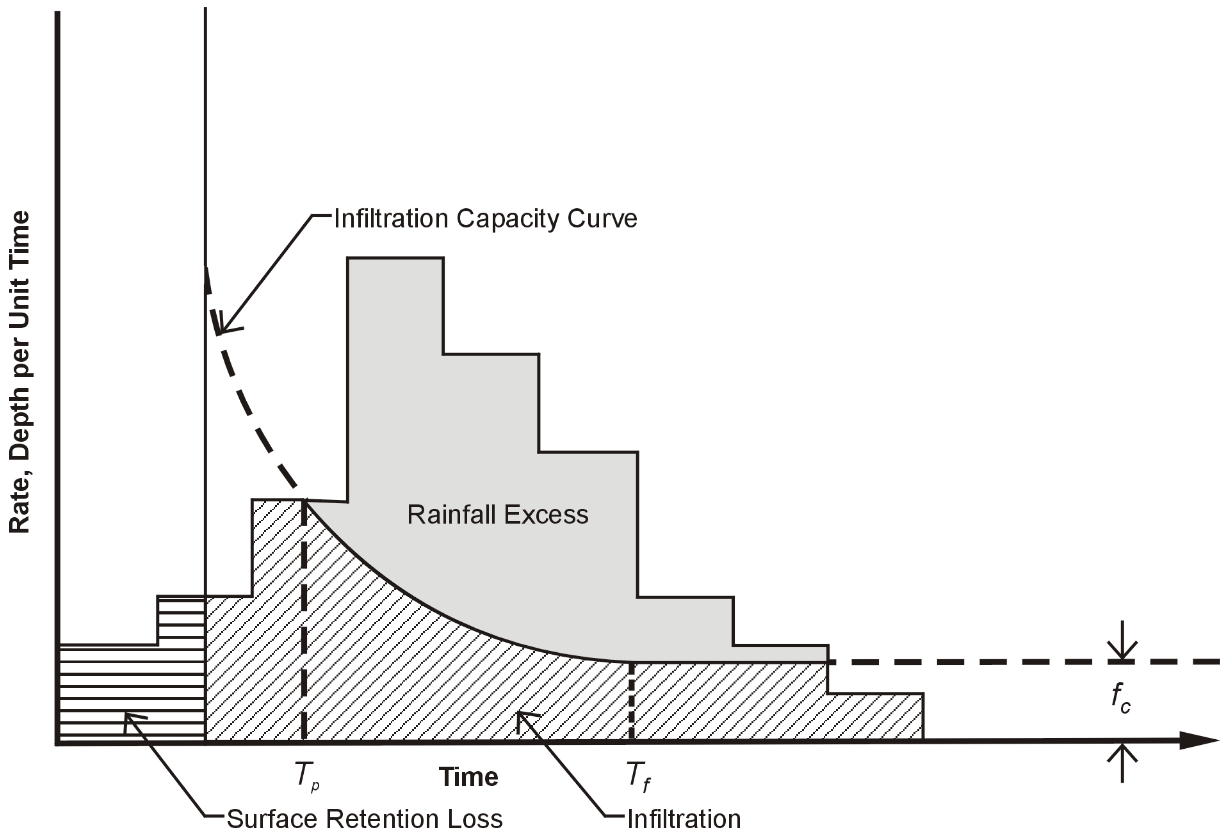
Three periods of rainfall losses are illustrated in Figure 4.1, which must be understood and their implications appreciated before applying the procedures in this manual. First, there is a period of initial loss when no rainfall excess (runoff) is produced. During this initial period, the losses are a function of the depression storage, interception, and evaporation rates plus the initially high infiltration capacity of the soil. The accumulated rainfall loss during this period with no runoff is called the initial abstraction. The end of this initial period is noted by the onset of ponded water on the surface, and the time from the start of rainfall to this time is the time of ponding (T_p). It is important to note that losses during this first period are a summation of losses due to all mechanisms including infiltration.

The second period is marked by a declining infiltration rate and generally very little losses due to other factors.

The third, and final, period occurs for rainfalls of sufficient duration where the infiltration rate reaches the steady-state, equilibrium rate of the soil (f_c). The only appreciable loss during the final period is due to infiltration.

The actual loss process is quite complex and there is a good deal of interdependence of the loss mechanisms on each other and on the rainfall itself. Therefore, simplifying assumptions are usually made in the modeling of rainfall losses. Figure 4.2 represents a simplified set of assumptions that can be made. In Figure 4.2, it is assumed that surface retention loss is the summation of all losses other than those due to infiltration, and that this loss occurs from the start of rainfall and ends when the accumulated rainfall equals the magnitude of the capacity of the surface retention loss. It is assumed that infiltration does not occur during this time. After the surface retention is satisfied, infiltration begins. If the infiltration capacity exceeds the rainfall intensity, then no rainfall excess is produced. As the infiltration capacity decreases, it may eventually equal the rainfall intensity. This would occur at the time of ponding (T_p) which signals the beginning of surface runoff. As illustrated in both Figure 4.1 and Figure 4.2, after the time of ponding the infiltration rate decreases exponentially and may reach steady-state, equilibrium rate (f_c). It is these simplified assumptions and processes, as illustrated in Figure 4.2, that are to be modeled by the procedures in this manual.

FIGURE 4.2
SIMPLIFIED REPRESENTATION OF RAINFALL LOSSES
A FUNCTION OF SURFACE RETENTION LOSSES PLUS INFILTRATION



4.2 SURFACE RETENTION LOSS

Surface retention loss, as used herein, is the summation of all rainfall losses other than infiltration. The major component of surface retention loss is depression storage; relatively minor components of surface retention loss are due to interception and evaporation, as previously discussed. Depression storage is considered to occur in two forms. First, in-place depression storage occurs at, and in the near vicinity of, the raindrop impact. The mechanism for this depression storage is the microrelief of the soil and soil cover. The second form of depression storage is the retention of surface runoff that occurs away from the part of the raindrop impact in surface depressions such as puddles, roadway gutters and swales, roofs, irrigation bordered fields and lawns, and so forth.

The relatively minor contribution by interception is also considered as a part of the total surface retention loss. Experimental data on interception have been collected by numerous investigators

(Linsley et al. 1982), but little is known of the interception values for most hydrologic problems. Estimates of interception for various vegetation types (Linsley et al. 1982) are:

Table 4.1
ESTIMATED INTERCEPTION VALUES

Vegetation Type	Interception, inches
(1)	(2)
Hardwood tree	0.09
Cotton	0.33
Alfalfa	0.11
Meadow grass	0.08

Estimates of surface retention loss are difficult to obtain and are a function of the physiography and land-use of the area. The surface retention loss on impervious surfaces has been estimated to be in the range 0.0625 inch to 0.125 inch by Tholin and Keefer (1960), 0.11 inch for 1 percent slopes to 0.06 inch for 2.5 percent slopes by Viessman (1967), and 0.04 inch based on rainfall-runoff data for an urban watershed in Albuquerque by Sabol (1983). Hicks (1944) provides estimates of surface retention losses during intense storms as 0.20 inch for sand, 0.15 inch for loam, and 0.10 inch for clay. Tholin and Keefer (1960) estimated the surface retention loss for turf to be between 0.25 and 0.50 inch. Based on rainfall simulator studies on undeveloped alluvial plains in the Albuquerque area, the surface retention loss was estimated as 0.1 to 0.2 inch (Sabol et al. 1982a). Rainfall simulator studies in New Mexico result in estimates of 0.39 inch for eastern plains rangelands and 0.09 inch for pinon-juniper hillslopes (Sabol et al. 1982b).

Table 4.2
ESTIMATED SURFACE RETENTION LOSSES

Study	Physiography/Land use	Surface Retention Loss, Inches
(1)	(2)	(3)
Tholin and Keefer (1960)	turf	0.25 - 0.5
Tholin and Keefer (1960)	impervious surfaces	0.0625 - 0.125
Viessman (1967)	1 percent slopes	0.11
Viessman (1967)	2.5 percent slopes	0.06
Sabol (1983)	urban area	0.04
Hicks (1944)	sand	0.20
Hicks (1944)	loam	0.15
Hicks (1944)	clay	0.10

Table 4.2 (Continued)
ESTIMATED SURFACE RETENTION LOSSES

Study	Physiography/Land use	Surface Retention Loss, Inches
(1)	(2)	(3)
(Sabol et al. 1982a)	undeveloped alluvial plains	0.1 -0.2
(Sabol et al. 1982a)	eastern New Mexico plain rangelands	0.39
(Sabol et al. 1982a)	pinion-juniper hillslopes	0.09

The Desert Research Institute (DRI) performed field measured rainfall simulation studies in several Maricopa County watersheds from 2010 through 2016 (DRI 2010, DRI 2012, DRI 2014, DRI 2016). The average values of field measured surface retention loss plus infiltration up to the time of ponding from all test sites by watershed are listed in Table 4.3. Surface retention losses for various land-uses and surface cover conditions in Maricopa County have been extrapolated from those reported estimates and these are shown in Table 4.6.

Table 4.3
FIELD MEASURED IA VALUES (DRI VARIOUS YEARS)

Watershed	Surface Type	Field Measured IA, in
(1)	(2)	(3)
Rainbow Wash	Desert Rangeland	0.09
7 Springs Wash	Hillslope/Mountain	0.15
Rawhide Wash	Hillslope/Mountain	0.19
Daggs Wash	Desert Rangeland	0.14

4.3 INFILTRATION

Infiltration is the movement of water from the land surface into the soil. Gravity and capillary are the two forces that drive infiltration by drawing water into and through the pore spaces of the soil matrix. Infiltration is controlled by soil properties, by vegetation influences on the soil structure, by surface cover of rock and vegetation, and by tillage practices. The distinction between infiltration and percolation is that percolation is the movement of water through the soil subsequent to infiltration.

Infiltration can be controlled by percolation if the soil does not have a sustained drainage capacity to provide access for more infiltrated water. However, before percolation can be assumed to restrict infiltration for the design rainfalls being considered in Maricopa County, the extent by which percolation can restrict infiltration of rainfall should be carefully evaluated. Consider what NRCS soil scientists have defined as hydrologic soil group D:

"Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with claypan or clay layer at or near the surface, and shallow soils over nearly impervious material."

This definition indicates that hydrologic soil groups A, B, or C could be classified as D if a near impervious strata of clay, caliche, or rock is beneath them. When these soils are considered in regard to long-duration rainfalls (the design events for many parts of the United States) this definition may be valid. However, when considered for short-duration and relatively small design rainfall depths in Maricopa County, this definition could result in underestimation of the rainfall losses. This is because even a relatively shallow horizon of soil overlaying an impervious layer still has the ability to store a significant amount of infiltrated rainfall.

For example, consider the situation where only 4 inches of soil covers an impervious layer. If the effective porosity is 0.30, then 1.2 inches (4 inches x 0.30) of water can be infiltrated and stored in the shallow soil horizon. For design rainfalls in Maricopa County, this represents a significant storage volume for infiltrated rainfall and so when developing loss rate parameters for areas of Maricopa County that contain significant areas classified as hydrologic soil group D, the reason for that classification should be determined.

Hydrologic soil group D should be retained only for:

- clay soils,
- soils with a permanent high water table, and
- rock outcrop.

Hydrologic soil group D should probably not be retained in all situations where the classification is based on shallow soils over nearly impervious layers. Site specific studies and sensitivity analyses should be performed to estimate the loss rates to be used for such soils.

4.4 RECOMMENDED METHODS FOR ESTIMATING RAINFALL LOSSES

Many methods have been developed for estimating rainfall losses; five are listed as options in the HEC-1 Flood Hydrology Package (HEC-1). They are:

1. Holtan Infiltration Equation
2. Exponential Loss Rate
3. NRCS Curve Numbers (CN) Loss Rate
4. Green and Ampt Infiltration Equation
5. Initial Loss Plus Uniform Loss Rate (IL+ULR)

The Holtan Infiltration Equation is not available for use in the HEC-HMS Hydrologic Modeling System (HEC-HMS) software package, but the other four are available. Of these five, however, only the Green and Ampt and IL+ULR are recommended for estimating rainfall losses in Maricopa County for the reasons discussed below. The Green and Ampt method is also available for two-dimensional modeling in the HEC-RAS River Analysis System (HEC-RAS) and the FLO-2D Pro dynamic flood routing models. Within Maricopa County, use of HEC-HMS, HEC-RAS, FLO-2D Pro and other applicable softwares are subject to FCDMC approval.

The Holtan Infiltration Equation is an exponential decay type of equation for which the rainfall loss rate asymptotically diminishes to the minimum infiltration rate (f_c). The Holtan equation is not extensively used and there is no known application of this method in Arizona. Data and procedures to estimate the parameters for use in Maricopa County are not available. Therefore, the Holtan equation is not recommended for general use in Maricopa County.

The Exponential Loss Rate Method is a four parameter method that is not extensively used, but it is a method preferred by the U.S. Army Corps of Engineers. Data and procedures are not available to estimate the parameters for this method for all physiographic regions in Maricopa County, but Exponential Loss Rate parameters have been developed from the reconstitution of flood events for a flood hydrology study in a portion of Maricopa County (U.S. Army Corps of Engineers, 1982). However, adequate data are not available to estimate the necessary parameters for all soil types and land uses in Maricopa County, and therefore this method is not recommended for general use in Maricopa County.

The National Resource Conservation Service (NRCS) CN method previously was (pre-1990) the most extensively used rainfall loss rate method in Maricopa County and Arizona, and it had wide acceptance among many agencies, consulting engineering firms, and individuals throughout the community. However, because of both theoretical concerns and practical limitations (Ponce and Hawkins, 1996), the NRCS CN method is not recommended for general use in Maricopa County.

As mentioned previously, the two recommended methods for estimating rainfall losses in Maricopa County are the Green and Ampt infiltration equation and the initial loss and uniform loss rate (IL+ULR) method. Both methods, as programmed into HEC-1 can be used to simulate the rainfall loss model as depicted in Figure 4.2. For a full discussion of these methods, see Section 4.4.1 and Section 4.4.2. The IL+ULR method is a simplified model that is used extensively for flood hydrology. Datasets are often available to estimate the two parameters for the IL+ULR method. The Green and Ampt Infiltration Equation is a physically based model that has been in existence since 1911.

The preferred method, and the most theoretically accurate of the five methods listed in HEC-1, is the Green and Ampt Infiltration Equation. That method should be used for most studies in Maricopa County where the land surface is soil, the infiltration of water is controlled by soil texture (see APPENDIX C), and the bulk density of the soil is affected by vegetation. Procedures were developed, and are presented, to estimate the three parameters of the Green and Ampt infiltration equation. The alternative method of IL+ULR can be used in situations where the Green and Ampt infiltration method is recommended, but its use in those situations is not encouraged, and, in general, should be avoided. Rather, the IL+ULR method should be used in situations where the Green and Ampt infiltration equation with parameters based on soil texture is not appropriate. Examples of situations where the IL+ULR method is recommended are: large areas of rock outcrop, talus slopes, forests underlain with a thick mantle of duff, land surfaces of volcanic cinder, and surfaces that are predominantly sand and gravel. Because of the diversity of conditions that could exist for which the IL+ULR method is to be used, it is not possible to provide extensive guidance for the selection of the two parameters of the IL+ULR method.

Other methods should be used only if there is technical justification for a variance from these recommendations and if adequate information is available to estimate the necessary parameters. Use of rainfall loss methods other than those recommended should not be undertaken unless previously approved by the District and/or the local regulatory agency.

4.4.1 Green and Ampt Infiltration Equation

Since the early 1970s, this model - first developed in 1911 by W.H. Green and G.A. Ampt - has received increased interest for estimating rainfall infiltration losses. The model has the form:

$$f = K\left(1 + \frac{\Psi\theta}{F}\right) \quad \text{for } f < i \tag{4.1}$$

$$f = i \quad \text{for } f \geq i$$

where:

f	=	infiltration rate (L/T),
i	=	rainfall intensity (L/T),
K	=	hydraulic conductivity, wetted zone, steady-state rate (L/T),
ψ	=	average capillary suction in the wetted zone (L),
θ	=	soil moisture deficit (dimensionless), equal to effective soil porosity times the difference in final and initial volumetric soil saturations, and
F	=	depth of rainfall that has infiltrated into the soil since the beginning of rainfall (L).

A sound and concise explanation of the Green and Ampt equation is provided by Bedient and Huber (1988).

It is important to note that as rain continues, F increases and f approaches K, and therefore, f is inversely related to time. Equation (4.1) is implicit with respect to f which causes computational difficulties. Eggert (1976) simplified Equation (4.1) by expanding the equation in a power series and truncating all but the first two terms of the expansion. The simplified solution (Li et al. 1976) is:

$$F = -0.5(2F - K\Delta t) + 0.5\left[(2F - K\Delta t)^2 + 8K\Delta t(\Psi\theta + F)\right]^{1/2} \quad (4.2)$$

where:

Δt	=	the computation interval, and
F	=	accumulated depth of infiltration at the start of rainfall.

The average filtration rate is:

$$f = \frac{\Delta F}{\Delta t} \quad (4.3)$$

Use of the Green and Ampt equation as coded in HEC-1, HEC-HMS, and FLO-2D involves the simulation of rainfall loss as a two phase process, as illustrated in Figure 4.2. As of version 6.2, HEC-RAS 2D does not yet include the first phase but does include the second. The first phase is the simulation of the surface retention loss as previously described; this loss is called the initial abstraction (IA) in HEC-1 and initial loss in HEC-HMS. During this first phase, all rainfall is lost (zero rainfall excess generated) during the period from the start of rainfall up to the time that the accumulated rainfall equals the value of IA. It is assumed, for modeling purposes, that no infiltration of rainfall occurs during the first phase. IA is primarily a function of land-use and surface cover, and recommended values of IA for use with the Green and Ampt equation are presented in Table 4.6. For example, about 0.35 inches of rainfall will not become runoff due to surface retention for desert and rangelands on relatively flat slopes in Maricopa County.

The second phase of the rainfall loss process is the infiltration of rainfall into the soil matrix. For modeling purposes, the infiltration begins immediately after the surface retention loss (IA) is completely satisfied, as illustrated in Figure 4.2. The three Green and Ampt equation infiltration parameters as coded in HEC-1 are:

- hydraulic conductivity at natural saturation (XKSAT) equal to K in Equation (4.1);
- wetting front capillary suction (PSIF) equal to ψ in Equation (4.1); and
- volumetric soil moisture deficit at the start of rainfall (DTHETA) equal to θ in Equation (4.1).

The three infiltration parameters are functions of soil characteristics, ground surface characteristics, and land management practices. The soil characteristics of interest are particle size distribution (soil texture) including gravel content, organic matter, and bulk density. The primary soil surface characteristics are vegetation canopy cover, ground cover, and soil crusting. The land management practices are identified as various land development and agricultural tillages as they result in changes in soil porosity.

The soil moisture deficit (DTHETA) is a volumetric measure of the soil moisture storage capacity that is available at the start of the rainfall. DTHETA is a function of the effective porosity of the soil. The range of DTHETA is zero to the effective porosity. If the soil is effectively saturated at the start of rainfall then DTHETA equals zero; if the soil is devoid of moisture at the start of rainfall then DTHETA equals the effective porosity of the soil.

Under natural conditions, soil seldom reaches a state of soil moisture less than the wilting point of vegetation. Due to the rapid drainage capacity of most soils in Maricopa County, at the start of a design storm, the soil would not be expected to be in a state of soil moisture greater than the field capacity, where the field capacity is the amount of soil moisture retained after excess water has drained away.

However, Maricopa County also has a large segment of its land area under irrigated agriculture, and it is reasonable to assume that the design frequency storm could occur during or shortly after certain lands have been irrigated. Therefore, soil moisture for irrigated lands could be at or near effective saturation during the start of the design rainfall.

Three conditions for DTHETA have been defined for use in Maricopa County based on antecedent soil moisture conditions that could be expected to exist at the start of the design rainfall. These three conditions are:

- "Dry" for antecedent soil moisture near the vegetation wilting point
- "Normal" for antecedent soil moisture condition near field capacity due to previous rainfall or irrigation applications on nonagricultural lands; and
- "Saturated" for antecedent soil moisture near effective saturation due to recent irrigation of agricultural lands.

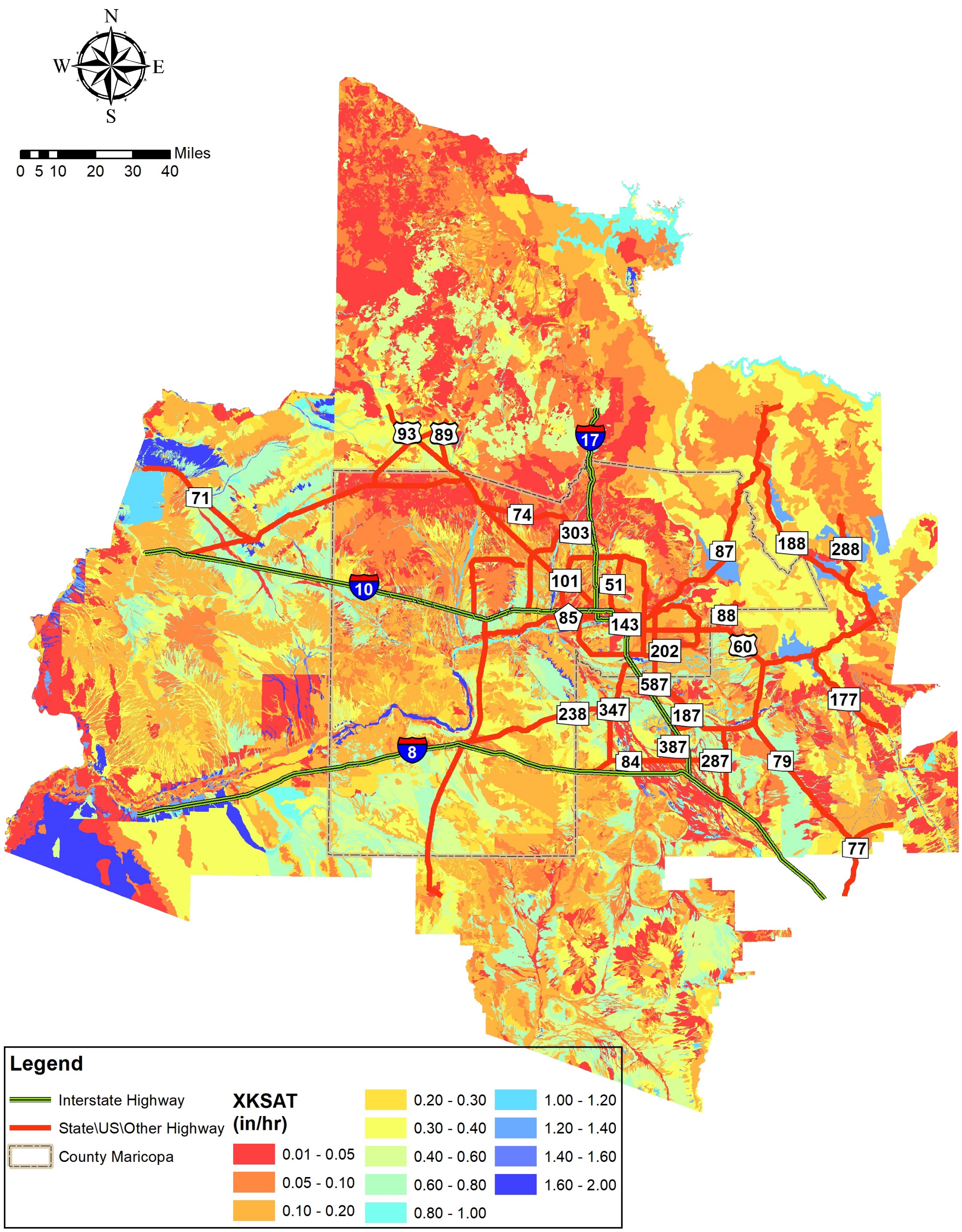
Values of DTHETA have been estimated by subtracting the initial volumetric soil moisture for each of the three conditions from the soil porosity.

Values of DTHETA for the three antecedent soil moisture conditions are shown in Table 4.5. DTHETA "Dry" should be used for soil that is usually in a state of low soil moisture such as would occur in the desert and rangelands of Maricopa County. DTHETA "Normal" should be used for soil that is usually in a state of moderate soil moisture such as would occur in irrigated lawns, golf courses, parks, and irrigated pastures, or immediately following a heavy rain. DTHETA "Saturated" should be used for soil that can be expected to be in a state of high soil moisture such as irrigated agricultural land. However, judgment should be exercised when using a "Saturated" condition, particularly for large areas of irrigated land as it is unlikely that the entire area is being irrigated at the same time.

Values of Green and Ampt equation parameters for Maricopa County and contributing watersheds are based on Saxton and Rawls (2006), which is a continuation of the work by Rawls et al. 1983b. Values of XKSAT are computed based on the percent by weight of sand and clay for a given matric soil. The XKSAT value is then corrected based on percent by weight of gravel content for the bulk soil and percent of organic matter in the matric soil (less than 2mm particle size), as well as its relative compaction. Refer to APPENDIX C for a complete description of how the Green and Ampt parameters for use in Maricopa County were derived and for tables of XKSAT, PSIF, and DTHETA values for each NRCS soil map unit (SMU). The spatial variation of XKSAT is shown on Figure 4.3 and is available for request from the District. A copy of the calculation tool, the XKSAT Program, that performs these computations can also be requested from the District for use.

FIGURE 4.3

Spatial variation of XKSAT



There is a large range of G&A parameter values within each soil texture class. The gravel and organic matter content affect the extent of those ranges. The data in Table 4.4 and Table 4.5 exemplify how these values can vary within each texture class. Table 4.4 contains the average, median, and 90 percent confidence interval bounding values of XKSAT and PSIF, for each texture class. These statistics were prepared using data from all NRCS soil horizons from every NRCS Soil Survey Geographic Database (SSURGO) soil survey in Arizona and Nevada. The number of soil horizons used in the analysis for each texture class is listed column (2). Table 4.5 lists the same information for DTHETA Dry and DTHETA Normal. Keep in mind that a sample of soil, for example a silty loam with a median value of XKSAT, will not also have a median value of PSIF and DTHETA. The data in these tables should be used as a reference to compare to, rather than as a source of values to use.

Table 4.4
RANGES OF XKSAT AND PSIF VALUES FOR ARIZONA AND NEVADA SOILS FOR BARE GROUND BASED ON ALL NRCS SOIL HORIZONS INCLUDING ORGANIC MATTER AND GRAVEL CORRECTIONS

Soil Texture Classification	Count	XKSAT (in/hr)				PSIF (in)			
		L[1]	Med[2]	Avg[3]	U[4]	L[1]	Med[2]	Avg[3]	U[4]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
sand	9429	0.96	1.80	2.03	4.32	0.01	0.01	0.18	5.89
loamy sand	9853	0.64	1.00	1.05	1.76	0.16	0.76	0.78	1.40
sandy loam	38824	0.25	0.45	0.46	0.84	2.58	4.57	4.50	6.43
loam	28813	0.08	0.18	0.18	0.42	8.06	12.99	12.57	17.08
silty loam	9841	0.04	0.13	0.13	0.41	10.76	24.45	25.48	40.20
silt	7	0.03	0.13	0.27	2.51	0.01	47.31	34.56	70.57
sandy clay loam	5713	0.04	0.10	0.10	0.21	6.88	9.25	8.95	11.02
clay loam	11206	0.03	0.05	0.05	0.09	13.89	16.65	16.59	19.29
silty clay loam	3625	0.03	0.05	0.06	0.12	15.12	24.24	24.50	33.88
sandy clay	314	0.00	0.01	0.01	0.04	10.50	11.09	11.20	11.90
silty clay	1925	0.02	0.03	0.04	0.07	10.03	16.73	16.30	22.57
clay	7678	0.01	0.02	0.02	0.03	10.86	15.06	14.56	18.27

1. Lower bound of 90 percent confidence interval
2. Median value
3. Average (mean) value
4. Upper bound of 90 percent confidence interval

Table 4.5
RANGES OF DTHETA VALUES FOR ARIZONA SOILS FOR BARE GROUND
BASED ON ALL NRCS SOIL HORIZONS INCLUDING ORGANIC MATTER AND GRAVEL CORRECTIONS

Soil Texture Classification	Count	DTHETA Dry				DTHETA Normal			
		L[1]	Med[2]	Avg[3]	U[4]	L[1]	Med[2]	Avg[3]	U[4]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
sand	9429	0.38	0.41	0.41	0.45	0.34	0.38	0.38	0.41
loamy sand	9853	0.35	0.37	0.37	0.40	0.30	0.32	0.32	0.34
sandy loam	38824	0.29	0.32	0.33	0.36	0.21	0.24	0.24	0.27
loam	28813	0.26	0.31	0.31	0.36	0.13	0.18	0.18	0.22
silty loam	9841	0.26	0.31	0.32	0.38	0.08	0.14	0.14	0.20
silt	7	0.18	0.33	0.42	0.65	0.01	0.10	0.17	0.35
sandy clay loam	5713	0.22	0.25	0.25	0.28	0.11	0.15	0.15	0.18
clay loam	11206	0.22	0.25	0.25	0.27	0.09	0.11	0.11	0.13
silty clay loam	3625	0.24	0.27	0.28	0.31	0.08	0.10	0.11	0.14
sandy clay	314	0.16	0.18	0.18	0.21	0.05	0.07	0.07	0.10
silty clay	1925	0.21	0.23	0.24	0.26	0.07	0.09	0.09	0.12
clay	7678	0.19	0.20	0.21	0.22	0.06	0.08	0.08	0.09

1. Lower bound of 90 percent confidence interval
2. Median value
3. Average (mean) value
4. Upper bound of 90 percent confidence interval

Because of the large range of values within a texture class, it is recommended that the SMU-specific G&A parameters based on the sand, clay, gravel and organic matter content within each component soil be used for hydrology studies within Maricopa County rather than those from a generalized texture class assignment. The SMU-specific G&A parameters are available in GIS format by Public Records Request from the District. Refer to APPENDIX C for more detail

In very few cases, only soil texture is known and the sand, clay, and gravel component fractions are unknown. These NRCS soil types are referred to as Miscellaneous Component Soils, as further described in APPENDIX C. For these cases, equations for the direct estimation of PSIF and DTHETA as a function of XKSAT alone (bare ground condition) have been created by non-linear regression analysis. The computed values of XKSAT, PSIF and DTHETA for every NRCS soil horizon within the soil surveys covering Maricopa County watersheds were used in the regression analysis. Refer to APPENDIX C for more detail. If only the soil texture is known, a value of XKSAT should be selected, using engineering judgment, from Table 4.4. Then, PSIF and DTHETA can be determined, as a function of XKSAT (bare ground condition) using the provided regression equations in APPENDIX C,or by requesting the XKSAT Calculator tool from the District.

Procedure for Areally Averaging Green and Ampt Parameter Values

Most drainage areas or modeling subbasins will be composed of several subareas containing soils of different textures. Therefore, a composite value for the Green and Ampt parameters that are to be applied to the drainage areas for modeling subbasins needs to be determined. The procedure for determining the composite value is to average the area-weighted logarithms (log-average) of the XKSAT, PSIF, and DTHETA values.

The Green & Ampt parameters and naturally occurring rock outcrop percentage for each map unit as determined from the NRCS is provided in APPENDIX C. The data contained in this appendix covers Maricopa County, and all watersheds that contribute to the County. The values for XKSAT, PSIF, and DTHETA listed in APPENDIX C are weighted based on the percentage of each unique soil texture present in the map unit. The weighted values take into consideration the horizon depth of the soil textures in regard to the expected depth of infiltration during the design storm duration. An example of the weighting procedure along with other assumptions and criteria used in developing the Green & Ampt parameters are provided in APPENDIX C. The composite XKSAT, PSIF, and DTHETA are calculated by Equation (4.4):

$$\overline{Var} = \text{alog}_{10}\left(\frac{\Sigma A_i \log_{10} Var_i}{A_T}\right) \quad (4.4)$$

where:

$\overline{Var}$	=	either composite subarea hydraulic conductivity at natural saturation (XKSAT) inches/hour; capillary suction (PSIF), inches; or antecedent soil moisture deficit (DTHETA)
Var_i	=	either subarea hydraulic conductivity at natural saturation (XKSAT) inches/hour; capillary suction (PSIF), inches; or antecedent soil moisture deficit (DTHETA)
A_i	=	size of subarea
A_T	=	size of the watershed or modeling subbasin

Procedures for Adjusting Hydraulic Conductivity for Vegetation Cover

The hydraulic conductivity (XKSAT) can be affected by several factors besides soil texture. For example, hydraulic conductivity is reduced by soil crusting, increased by tillage, and can be increased or decreased by the influence of ground cover and canopy cover. The values of XKSAT that are presented for bare ground as a function of soil texture alone should be adjusted under certain soil cover conditions in HEC-1 and HEC-HMS modeling.

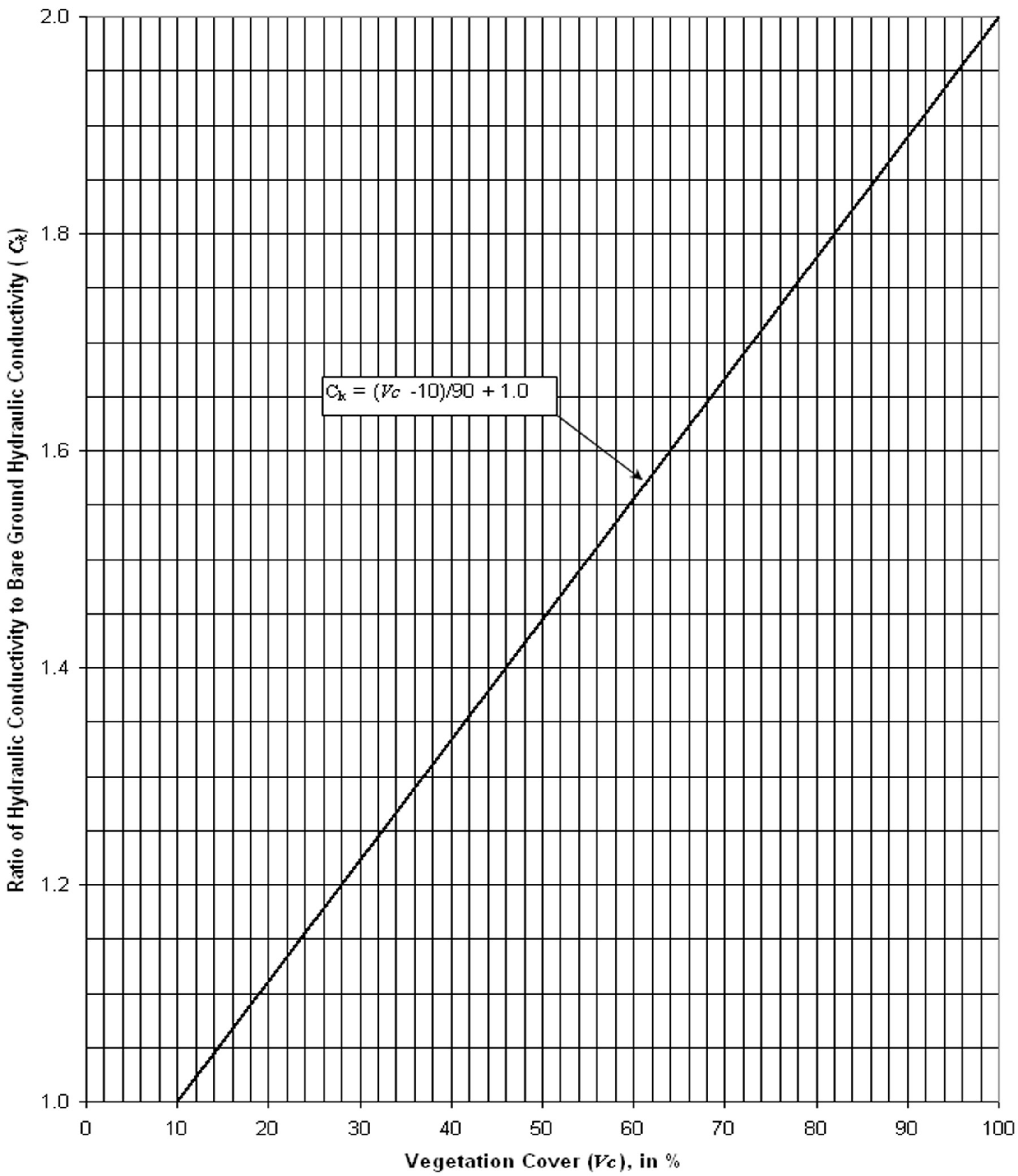
Ground cover, such as grass and litter, will generally increase the infiltration rate over that of bare ground conditions. Similarly, canopy cover – such as from trees, brush, and tall grasses – can also increase the bare ground infiltration rate. Desert species such as creosote bush and desert thorn can decrease the bare ground infiltration rate (Caldwell, Young, Zhu and McDonald, 2008). The procedures and data that are presented are for estimating the Green and Ampt parameters based solely on soil texture and would be applicable for bare ground conditions. Past research has shown that the wetting front capillary suction parameter (PSIF) is relatively insensitive in comparison with the hydraulic conductivity parameter (XKSAT); therefore only the hydraulic conductivity parameter is adjusted for the influences of cover over bare ground.

Procedures have been developed (Rawls et al. 1989) for incorporating the effects of soil crusting, ground cover, and canopy cover into the estimation of hydraulic conductivity for the Green and Ampt equation; however, those procedures are not recommended for use in Maricopa County at this time. A simplified procedure to adjust the bare ground hydraulic conductivity for vegetation cover is shown on Figure 4.4. This figure is based on the documented increase in hydraulic conductivity due to various soil covers as reported by investigators using rainfall simulators on native western rangelands (Kincaid et al. 1964; Sabol et al. 1982a; Sabol et al. 1982b; Bach, 1984; Ward, 1986; Lane et al. 1987; Ward and Bolin, 1989). This correction factor can be used based on an estimate of vegetation cover as used by the NRCS in soil surveys; that is, vegetation cover is evaluated on basal area for grass and forbs, and is evaluated on canopy cover for trees and shrubs. Note that this correction can be applied only to soils other than sand and loamy sand, with an XKSAT value equal or less than 1.2 in/hr. This correction should not be applied to canopy cover areas of creosote bush and desert thorn.

The influence of tillage results in a change in total porosity and therefore a need to modify the three Green and Ampt equation infiltration parameters. The effect of tillage systems on soil porosity and the corresponding changes to hydraulic conductivity, wetting front capillary suction, and water retention is available (Rawls and Brakensiek, 1983a). Although this information is available, it is not presented in this manual, nor is it recommended that these adjustments be made to the infiltration parameters for design purpose use in Maricopa County, because for most flood estimation purposes it cannot be assumed that the soil will be in any particular state of tillage at the time of storm occurrence and therefore the base condition infiltration parameters, as presented, should be used for flood estimation purposes. However, appropriate adjustment to the infiltration parameters can be made, as necessary, for special flood studies such as reconstitution of storm events.

FIGURE 4.4

Effect of Vegetation Cover on Hydraulic Conductivity
for Hydraulic Soil Groups B, C, and D, and for all Soil Textures *other than* Sand and Loamy Sand



Accounting for the Affects of Desert Pavement on Infiltration

Desert pavement surfaces may play an important role in watershed runoff response. The affect of desert pavement on infiltration has been a focus of study in various research efforts, which have resulted in contrasting conclusions. A portion of this research suggests that desert pavement may limit the rate of infiltration (Wood et al., 2004). Rainfall simulation tests in the Rainbow Wash watershed showed that the runoff rate slowed within 15-20 minutes after runoff collection began, although the initial runoff response was rapid (DRI, 2010). This may indicate that the subsurface had wetted through and the underlying soil began to control. In contrast, other research has shown that desert pavement may not have a significant effect on infiltration (Chen et al., 2009). Examples of desert pavement, in three levels of development, are shown on Figure 4.5.

Models including effects of desert pavement for the Daggs Wash Watershed were developed to test a potential application for calibration purposes (FCDMC, 2022). The effect of desert pavement cannot be directly addressed by an adjustment to the infiltration parameters since an adequate relationship has not been developed. Adjustments to the percentage of impervious area estimates (RTIMP) were used to simulate the effects of the degree of desert pavement, with the assumption that desert pavement decreases infiltration. These adjustments resulted in improved hydrologic model results when compared with gage-measured runoff hydrographs.

Due to the opposing research opinions, changes to infiltration due to desert pavement should be examined using engineering judgment based on the location of the study and the degree of desert pavement, and applied with prior approval from the District.

FIGURE 4.5

EXAMPLES OF DESERT PAVEMENT

<table>
<tr><td>Strongly Developed</td><td>Moderately Developed</td></tr>
<tr><td></td><td></td></tr>
<tr><td colspan="2">Poorly Developed</td></tr>
<tr><td colspan="2"></td></tr>
</table>

Selection of IA, RTIMP, and Percent Vegetation Cover

Table 4.6 contains suggested values for IA, RTIMP and percent vegetation cover for various natural conditions and urban land use types. The values in Table 4.6 are meant as guidelines and are not to be taken as prescribed values for these parameters. Note that the values for RTIMP reflect effective impervious areas not total impervious areas. Effective impervious area is composed of that portion of rock outcrop that is not fractured and fissured, and is hydraulically-connected. Estimation of the effective percentage of rock outcrop requires engineering judgment based on field visits to examine the rock outcrop areas.

Hydraulically connected areas are those that, in 1D models like HEC-1 and HEC-HMS, are directly connected by channel conveyance to the downstream end of a modeling subbasin. The hydraulically-connected area is assumed to not drain as sheet flow or small channel flow over pervious areas where it can be infiltrated before entering a main channel conveyance. Main channel conveyances include street gutters, urban channels, and significant natural channels that convey the runoff directly to the point of concentration. In 2D models such as FLO-2D and HEC-RAS 2D, infiltration occurring over pervious areas downstream of impervious areas is simulated and accounted for. Therefore, all impervious area is to be accounted for in FLO-2D and HEC-RAS, not just hydraulically connected areas.

Also, note that the values for percent vegetation cover are for pervious areas only. These three parameter values are used in the calculation of average input parameters for the Green and Ampt loss method as described above. Sound engineering judgment and experience should always be used when selecting rainfall loss parameters and assigning land use categories for any given watershed.

Table 4.6
***IA*, *RTIMP*, AND VEGETATIVE CANOPY COVER FOR REPRESENTATIVE LAND USES IN MARICOPA COUNTY**

Land Use[1] Code	Land Use Category	Description	IA[2] inches	RTIMP[2,3] %	Vegetation Cover[2,4] %
(1)	(2)	(3)	(4)	(5)	(6)
VLDR	Very Low Density Residential[3]	40,000 sq. feet and greater lot size	0.30	5	30
LDR	Low Density Residential[3]	12,000 – 40,000 sq. feet lot size	0.30	15	50
MDR	Medium Density Residential[3]	6,000 – 12,000 sq. feet lot size	0.25	30	50
MFR	Multiple Family Residential[3]	1,000 – 6,000 sq. feet lot size (# du/ac)	0.25	45	50
I1	Industrial 1[3]	Light and General	0.15	55	60
I2	Industrial 2[3]	General and Heavy	0.15	55	60
C1	Commercial 1[3]	Light, Neighborhood, Residential	0.10	80	75
C2	Commercial 2[3]	Central, General, Office, Intermediate	0.10	80	75
P	Pavement and Rooftops	Asphalt and Concrete, Sloped Rooftops	0.05	95	0
GR	Gravel Roadways & Shoulders	Graded and Compacted, Treated and Untreated	0.10	50	0
AG	Agricultural	Tilled Fields, Irrigated Pastures, slopes < 1%	0.50	0	85
LPC	Lawns/Parks/Cemeteries	Over 80% maintained lawn	0.20	Varies[5]	80
DL1	Desert Landscaping 1	Landscaping with impervious under treatment	0.10	95	30

Land Use[1] Code	Land Use Category	Description	IA[2] inches	RTIMP[2,3] %	Vegetation Cover[2,4] %
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
DL2	Desert Landscaping 2	Landscaping without impervious under treatment	0.20	0	30
NDR	Undeveloped Desert Rangeland	Little topographic relief, slopes < 5%	0.35	Varies[5]	Varies[6]
NHS	Hillslopes, Sonoran Desert	Moderate topographic relief, slopes > 5%	0.15	Varies[5]	Varies[6]
NMT	Mountain Terrain	High topographic relief, slopes > 10%	0.25	Varies[5]	Varies[6]

Notes:

1. Other land use or zoning classifications, such as Planned Area Development and Schools must be evaluated on a case by case basis. Additional land use classes are available in the Maricopa County Drainage Policies and Standards, Tables 6.5 and 6.6.
2. These values have been selected to fit many typical settings in Maricopa County; however, the engineer/hydrologist should always evaluate the specific circumstances in any particular watershed for hydrologic variations from these typical values.
3. RTIMP = Percent Effective Impervious Area, including right-of-way. Effective means that all impervious areas are assumed to be hydraulically connected. The RTIMP values may need to be adjusted based on an evaluation of hydraulic connectivity.
4. Vegetation Cover = Percent vegetation cover for pervious areas only. Not to be applied to areas of sand or loamy sand.
5. RTIMP values must be estimated on a case by case basis.
6. Vegetation Cover values must be estimated on a case by case basis.

4.4.2 Initial Loss Plus Uniform Loss Rate (IL+ULR)

This is a simplified rainfall loss method that is often used, and generally accepted, for flood hydrology. In using this simplified method it is assumed that the rainfall loss process can be simulated as a two-step procedure, as illustrated in Figure 4.6. Initially, all rainfall is prevented from becoming runoff until the accumulated rainfall is equal to the initial loss; and second, after the initial loss is satisfied, a portion of all future rainfall is lost at a uniform rate. All of the rainfall is lost if the rainfall intensity is less than the uniform loss rate.

According to HEC-1 nomenclature, two parameters are needed to use this method: the initial loss (STRTL), and the uniform loss rate (CNSTL).

Because this method is to be used for special cases where infiltration is not controlled by soil texture, or for drainage areas and subbasins that are predominantly sand, the estimation of the parameters will require model calibration, results of regional studies, or other valid techniques. It is not possible to provide complete guidance in the selection of these parameters; however, some general guidance is provided:

A. For special cases of anticipated application, the uniform loss rate (CNSTL) will either be very low for nearly impervious surfaces, or possibly quite high for exceptionally fast-draining (highly pervious) land surfaces. For land surfaces with very low infiltration rates, the value of CNSTL will probably be 0.05 inches per hour or less. For sand, a CNSTL of 0.5 to 1.0 inch per hour or larger may be reasonable. Higher values of CNSTL for sand and other surfaces are possible; however, use of high values of CNSTL would require special studies to substantiate the use of such values.

B. Although the IL+ULR method is not recommended for watersheds where the soil textures can be defined and where the Green and Ampt method is encouraged, some general guidance in the selection of the uniform loss rate is shown in Table 4.7 and Table 4.8. Table 4.8 was prepared based on the values in Table 4.7 and the hydraulic conductivities shown in Figure 4.4. In Table 4.8, the initial infiltration (II) is an estimate of the infiltration loss that can be expected prior to the generation of surface runoff. The value of initial loss (STRTL) is the sum of initial infiltration (II) of Table 4.8 and surface retention loss (IA) of Table 4.6; STRTL = II + IA.

C. The estimation of initial loss (STRTL) can be made on the basis of calibration or special studies at the same time that CNSTL is estimated. Alternatively, since STRTL is equivalent to initial abstraction, STRTL can be estimated by using the NRCS CN equations for estimated initial abstraction, written as:

$$STRTL = \frac{200}{CN} - 2 \qquad (4.5)$$

Estimates for CN for the drainage area or subbasin should be made referring to various publications of the NRCS, particularly TR-55 (NRCS, 1986). Equation (4.5) should provide a fairly good estimate of STRTL in many cases, however, its use should be judiciously applied and carefully considered in all cases.

FIGURE 4.6
REPRESENTATION OF RAINFALL LOSS
ACCORDING TO THE INITIAL LOSS PLUS UNIFORM LOSS RATE (IL + ULR)

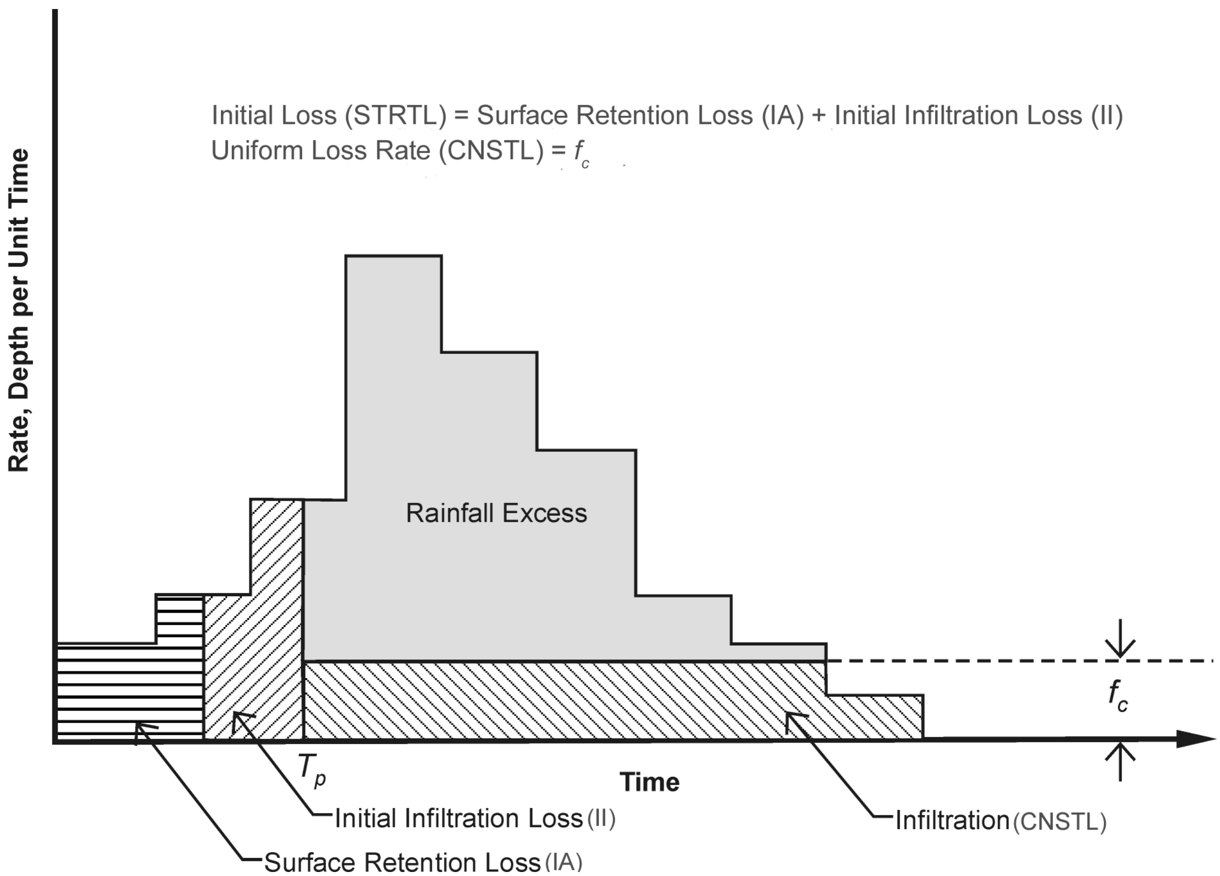


Table 4.7
PUBLISHED VALUES OF UNIFORM LOSS RATES

	Uniform Loss Rate, inches/hour		
Hydrologic Soil Group (1)	**Musgrave (1955) (2)**	**USBR (1973)[1] (3)**	**USBR (1987)[2] (4)**
A	0.30 – 0.45	0.40	0.30 – 0.50
B	0.15 – 0.30	0.24	0.15 – 0.30
C	0.05 – 0.15	0.12	0.05 – 0.15
D	0 – 0.05	0.08	0 – 0.05

Notes:
1. Design of Small Dams, Second Edition, 1973, Appendix A.
2. Design of Small Dams, Third Edition, 1987.

Table 4.8
INITIAL LOSS PLUS UNIFORM LOSS RATE PARAMETER VALUES FOR BARE GROUND ACCORDING TO HYDROLOGIC SOIL GROUP

Hydrologic Soil Group (1)	Uniform Loss Rate CNSTL (2)	Initial Infiltration, inches II[1]		
		Dry (3)	Normal (4)	Saturated (5)
A	0.4	0.6	0.5	0
B	0.25	0.5	0.3	0
C	0.15	0.5	0.3	0
D	0.05	0.4	0.2	0

Notes:
1. Selection of II:

Dry = Nonirrigated lands, such as desert and rangeland.
Normal = Irrigated lawn, turf, and permanent pasture.
Saturated = Irrigated agricultural land.

4.5 PROCEDURE FOR ESTIMATING LOSS RATES

Procedures for estimating rainfall loss rates are provided in the following sections. These procedures are written assuming manual methods are used. The basic process described also applies when using a GIS-based approach. Notes and general guidance on the application of these procedures are provided along with a detailed example using the Green and Ampt method in Section 9.3.

4.5.1 Green and Ampt Method

A. When soils data are available:

1. Prepare a base map of the drainage area with delineated subbasins, if used.
2. Determine the location of the study area in regard to the limits of the soil surveys provided in APPENDIX C, Figure C.1.
   a. If the study area is completely contained within these limits:
      i. Overlay the watershed limits on the soil survey maps from the appropriate soil survey report(s) and tabulate the map units present within the watershed. GIS coverages of the soil survey information are available via Public Records Request from the District.

ii. Cross reference the map units with the GIS coverage's associated attribute table, or those listed in APPENDIX C, Section C.4.3, and tabulate the weighted values of XKSAT, PSIF, RTIMP and dry and natural DTHETA for each map unit.

iii. Proceed to item (3) or (4).

b. If the study area is partly or entirely outside the limits of the soils surveys provided in APPENDIX C, Figure C.1:

i. Gather other relevant soil survey data. Relevant soil survey data includes soil particle size distribution, soil texture, gravel content, organic matter and bulk density. Possible sources of additional soils data are:

- General soils surveys by county prepared by the NRCS.
- Other detailed soil surveys.
- US Forest Service Terrestrial Ecosystem Reports.

ii. Using the data contained in the alternative source, follow the example procedure for determination of the weighted XKSAT, PSIF, and DTHETA values for each unique map unit that is included in APPENDIX C, Section C.3

iii. Proceed to item (3) or (4).

3. If the watershed or subbasin contains only one soil map unit, then use the selected parameters.

4. If the watershed or subbasin is composed of soils of different map units, then area-weighted parameter values will be calculated:

a. Calculate the area-weighted value of XKSAT, PSIF, and DTHETA by using Equation (4.4).

b. Calculate the arithmetically area-weighted value of naturally occurring rock outcrop to obtain $RTIMP_N$.

5. Cross reference the soil map unit(s) with land use information for the study area to determine the antecedent moisture condition, for selection of the DTHETA value for each map unit. See Section 4.4.1 for more information on determination of the antecedent moisture condition. If a single soil map unit intersects with more than one

land use, Equation (4.4) can be used to compute the area-weighted average DTHETA value.

6. Select values of IA for each land use and/or soil map unit using Table 4.6. Arithmetically area-weight the values of IA if the drainage area or subbasin is composed of subareas of different IA.

7. Select values of developed condition RTIMP ($RTIMP_D$) for each land use using Table 4.6. For natural land uses, set $RTIMP_D$ to zero. Arithmetically area-weight the values of $RTIMP_D$ if the drainage area or subbasin is composed of land use subareas of different $RTIMP_D$. Compute the area-weighted value of $RTIMP_D$ based on the total subbasin area and denote it by $RTIMP_L$. Arithmetically area-weight the percentage of rock outcrop for all soil map units to obtain subbasin wide $RTIMP_N$. If estimating the effective percentage of impervious area that is hydraulically connected, arithmetically area-weight the effective percentage impervious area for all soil map units to obtain subbasin effective impervious area (EFF) in percent, and calculate the final value of $RTIMP_N$ using Equation (4.6). Compute the final subbasin wide composite value of RTIMP using Equation (4.7).

$$RTIMP_N = RTIMP_N \times EFF \tag{4.6}$$

$$RTIMP = RTIMP_N + RTIMP_L - \frac{Min(RTIMP_N, RTIMP_L)}{2} \tag{4.7}$$

For a full derivation of Equation (4.7), please see APPENDIX C.

7. Estimate the vegetative cover (VC) for the natural portions of the drainage area or subbasin. Select values of VC for each land use using Table 4.6. Arithmetically area-weight the values of VC if the drainage area or subbasin is composed of land use subareas of different VC. Arithmetically average the natural VC and the area-weighted land use VC.

8. Adjust the XKSAT value for VC using Figure 4.4, if appropriate.

B. Alternative Methods:

As an alternative to the above procedures, Green and Ampt loss rate parameters can be estimated by reconstitution of recorded rainfall-runoff events on the drainage area or hydrologically similar watersheds, or parameters can be estimated by use of rainfall simulators in field experiments. Plans and procedures for estimating Green and Ampt loss rate parameters by either of these procedures should be approved by the Flood Control District and/or the local agency before initiating the procedures.

4.5.2 Initial Loss Plus Uniform Loss Rate Method

A. When soils data are available:

1. Prepare a base map of the drainage area delineating modeling subbasins, if used.

2. Delineate subareas of different infiltration rates (uniform loss rates) on the base map. Assign a land-use or surface cover to each subarea.

3. Determine the size of each subbasin and size of each subarea within each subbasin.

4. Estimate the impervious area (RTIMP) for the drainage area or each subarea.

5. Estimate the initial loss (STRTL) for the drainage area or each subarea by regional studies or calibration. Alternatively, Equation (4.5) or Table 4.6 and Table 4.8 can be used to estimate or to check the value of STRTL.

6. Estimate the uniform loss rate (CNSTL) for the drainage area or each subarea by regional studies or calibration. Table 4.7 can be used, in certain situations, to estimate or to check the values of CNSTL.

7. Calculate the area-weighted values of RTIMP, STRTL, and CNSTL for the drainage area or each subbasin.

8. Enter the area-weighted values of RTIMP, STRTL, and CNSTL for the drainage area or each subbasin on the LU record of the HEC-1 input file.

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