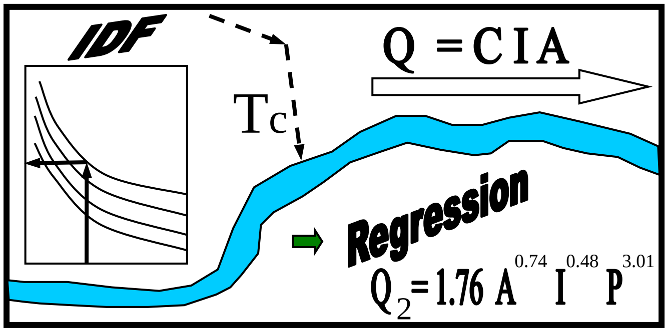
ACTIVITY: Other Hydrologic Computations

ST – 13



CITY OF KNOXVILLE

Description

The purpose of this stormwater treatment BMP is to provide formulas and data for other types of miscellaneous hydrologic computations. For instance, oil/water separators are often sized on the basis of a 6-month or 1-year design storm. Drainage structures are generally sized to handle the peak flow of a required design storm, for which it is recommended that more than one type of peak flow computation should be used. Types of miscellaneous or preliminary hydrologic computations (not connected with stormwater detention routing) may include:

- Rational method for computing peak flow
- Regression equations for computing peak flow
- Intensity-duration-frequency (IDF) curves for design storms
- Water balance analysis for wet detention basin or wetlands

Approach

The following table shows types of hydrologic computations for computing peak flows in the Knoxville area. The NRCS Unit Hydrograph method is specifically cited for drainage computations within the Knoxville Stormwater and Street Ordinance (Sections 22.5-21 and 22.5-33) using 24-hour Type II rainfall distribution and AMC II soil conditions. The NRCS method is capable of generating a hydrograph for the purpose of detention routing or for combining hydrographs.

Hydrology Design Method	Drainage Area	Time of Concentration	Impervious	Design Storms
Rational	< 50 acres	-- any --	0% to 100%	2 to 500 years
NRCS Unit Hydrograph	-- any --	-- any --	CN 40 to 98	1 to 500 years
TVA Regression Equations	> 230 acres	N / A	< 75%	2 to 500 years
USGS Regression Equations	> 135 acres	N / A	< 75%	2 to 100 years

Required by city ordinance →

Stormwater detention, routing and hydrograph generation are described in ST-10, Detention Computations. The Knoxville Stormwater and Street Ordinance requires a certain level of stormwater design and stormwater detention; it also contains provisions for fees, bonds, penalties, permits, definitions and easements which are not discussed in the BMP Manual. Also see these related BMPs for other hydrology topics:

ES-19	Design of temporary sediment basins, buoyancy of CMP risers
ES-22	Manning's open-channel equation, critical flow, grass retardance
ST-10	NRCS hydrographs and peak flow computation, weirs, orifices
ST-11	NRCS detention example worked out by customized Excel spreadsheets
ST-12	NRCS detention example worked out by HEC-1 and HEC-HMS

Culvert design is described in FHWA Hydraulic Design Series No. 5, "Hydraulic Design of Highway Culverts" (reference 158), and can be downloaded from:
http://www.fhwa.dot.gov/bridge/hydpub.htm

Time of Concentration

The Rational Method of determining peak flows (as does the NRCS Unit Hydrograph method) relies on accurately determining the time of concentration. Peak runoff for a small drainage area is almost always assumed to occur at the time when all of the area is contributing. This is called the time of concentration (Tc) and can be computed by several equations based on empirical formulas and research. In general, Tc should be computed with at least two different formulas. The minimum value for Tc is generally 5 minutes using the Rational Method, or at least 0.1 hours using NRCS methodology.

NRCS

The time of concentration can be computed using the formulas presented in the NRCS TR-55 publication (also ST-11 and ST-12, kinematic solution by Overton/Meadows). Travel time for channels is computed by estimating velocity using Manning's equation or some reasonable assumption. The sheet flow portion of Tc is represented by:

$$Tc = \frac{0.007\ (nL)^{0.8}}{(P_2)^{0.5}\ S^{0.4}} \qquad \text{(hours)}$$

n = Manning's roughness coefficient for surface (see ST-11 Worksheet #2)
L = Flow length for sheet flow over the surface (feet)
P_2 = Depth of 2-year, 24-hour storm for Knoxville = 3.3" (inches)
S = Average land slope for sheet flow over the surface (feet / foot)

Kerby

A second commonly used formula for overland flow component of Tc is Kerby's equation, which is valid up to a flow length of 1000 feet. It uses the terms defined previously except for a new retardance coefficient, R_K:

$$Tc = 0.83\ (R_K\ L)^{0.467}\ /\ (S)^{0.2335} \qquad \text{(minutes)}$$

With R_K = 0.02 (smooth pavement) 0.40 (average grass)
0.30 (poor grass, bare sod) 0.80 (dense grass)

Izzard

A third formula for the overland flow component of Tc is Izzard's formula, which is valid for values of IL < 500. The terms L and S have been previously defined.

$$Tc = \frac{41\ (0.007\, I\ + R)\ L^{1/3}}{(IS)^{2/3}} \qquad \text{(minutes)}$$

I = Rainfall intensity: estimate and then check with computed Tc (inches / hour)
R = Retardance coefficient: 0.007 (very smooth asphalt)
0.008 (slate roof)
0.012 (concrete surfaces)
0.017 (tar and gravel pavement)
0.046 (closely trimmed sod or grass)
0.060 (dense bluegrass)

Kinematic wave

A fourth formula for the overland flow component of Tc is the kinematic wave formula, which is valid for overland flow lengths up to 300 feet. All of the terms have been previously defined:

$$Tc = \frac{0.93\ L^{0.6}\ n^{0.6}}{I^{0.4}\ S^{0.3}} \qquad \text{(minutes)}$$

NRCS Lag

A fifth formula for overland flow Tc can also be determined from watershed lag time (T_L), which is the time between the center of mass of excess rainfall to the time of peak runoff (similar to an average overland flow time for small homogeneous areas).

$$Tc = 1.67\ T_L \qquad \text{(hours)}$$

$$T_L = \frac{L^{0.8}\ (S' + 1)^{0.7}}{1900\ W_S^{0.5}} \qquad \text{(hours)}$$

T_L = NRCS lag time (time Δ from center of rainfall excess to peak runoff) (hours)
S' = Potential rainfall storage for a particular ground use = 1000/CN - 10 (inches)
W_S = Average ground surface slope as a percentage (percent)

Rational Method

Compared to the NRCS Unit Hydrograph, the Rational Method is the older and more traditional method for computing peak flows for small drainage areas. In actuality, the units are such that 1 cfs is equal to 1.008 acre-inches per hour. However, the term "1.008" is traditionally ignored and the Rational Method equation is expressed as:

$$Q = C\ I\ A$$

Q = Peak flow for a given recurrence interval of x years (cfs)
C = Runoff coefficient: the fraction of rainfall which runs off (---)
I = The rainfall intensity for the design storm of x years (inches / hour)
A = Contributing drainage area for a given location (acres)

The runoff coefficient is initially selected from the range of values that are given in Table ST-13-1. Typically the value of C is adjusted upwards for larger design storms, to account for antecedent rainfall and more saturated conditions. When adjusting the C value, do not exceed the maximum value of 1.00, which represents the entire design storm rainfall being converted into runoff.

Multiply C by 1.00 for 10-year storms or any smaller return period.
Multiply C by 1.10 for 25-year storms.
Multiply C by 1.20 for 50-year storms.
Multiply C by 1.25 for 100-year storms or greater.

The rainfall intensities from the intensity-duration-frequency (IDF) curve for the Knoxville area are listed in Table ST-13-2. The time of concentration is used to select the average rainfall intensity that occurs over that time period for the selected design storm. In some instances, where the contributing drainage area is irregularly shaped or has very different land uses, a higher peak flow may occur when only part of the drainage area contributes at a much shorter time of concentration. Typical values for Tc (for illustrative purposes only) are shown in Figures ST-13-1 and ST-13-2, showing that land development will shorten the time of concentration.

TVA Regression Equations

These equations were originally developed by W.H. Espey Jr. and D.E. Winslow and published in the Proceedings of the American Society of Civil Engineers, Journal of the Hydraulics Division, Volume 100, No. HY-2, pages 279-293, 1974. The article was entitled "Urban Flood Frequency Characteristics". These equations were used by TVA to generate flow data in the FEMA Flood Insurance Studies for Knoxville and Knox County. A primary use of these equations is the preliminary design of culverts across streams that are depicted as blue lines (Waters of the State) on USGS quadrangle maps.

$$Q_2 = 107\ A^{0.804}\ I^{0.30}$$
$$Q_{10} = 217\ A^{0.802}\ I^{0.26}$$
$$Q_{50} = 344\ A^{0.796}\ I^{0.22}$$
$$Q_{100} = 402\ A^{0.796}\ I^{0.20}$$
$$Q_{500} = 556\ A^{0.795}\ I^{0.16}$$

Q_X = Peak flow for a given recurrence interval of x years (cfs)
A = Contributing drainage area for a given location (square miles)
I = Percent of the contributing drainage area that is impervious (%)

USGS Regression Equations

These equations were developed by Clarence Robbins and outlined in USGS Water Resources Investigations Report 84-4182, entitled "Synthesized Flood Frequency for Small Urban Streams in Tennessee". The equations are intended for streams with drainage areas between 0.21 and 24.3 square miles. A primary use of these equations is the preliminary design of culverts across streams that are depicted as blue lines (Waters of the State) on USGS quadrangle maps.

$$Q_2 = 1.76\ A^{0.74}\ I^{0.48}\ P^{3.01}$$
$$Q_5 = 5.55\ A^{0.75}\ I^{0.44}\ P^{2.53}$$
$$Q_{10} = 11.8\ A^{0.75}\ I^{0.43}\ P^{2.12}$$
$$Q_{25} = 21.9\ A^{0.75}\ I^{0.39}\ P^{1.89}$$
$$Q_{50} = 44.9\ A^{0.75}\ I^{0.40}\ P^{1.42}$$
$$Q_{100} = 77.0\ A^{0.75}\ I^{0.40}\ P^{1.10}$$

Q_X = Peak flow for a given recurrence interval of x years (cfs)
A = Contributing drainage area for a given location (square miles)
I = Percent of the contributing drainage area that is impervious (%)
P = The 2-year, 24-hour rainfall amount = 3.3" in Knoxville (inches)

Design Events Smaller Than 2-Year Storm

For some types of stormwater quality BMPs (such as sand filtration units or oil/water separators), there is usually a need to estimate design storms that occur annually or even more frequent. Stormwater quality BMPs, unless equipped with bypass units, are of course also required to safely handle larger design storms. The most efficient treatment flow rates for stormwater quality BMPs should usually correspond to 1-year or 2-year design storms. The following relationships are estimated for short-duration storms of less than 30 minutes:

2-month storm = 45% of the 2-year design storm rainfall intensity
3-month storm = 50% of the 2-year design storm rainfall intensity
4-month storm = 55% of the 2-year design storm rainfall intensity
6-month storm = 65% of the 2-year design storm rainfall intensity
1-year storm = 80% of the 2-year design storm rainfall intensity

Typical Rainfall Amounts for HEC-1 and HEC-HMS Models

The U.S. Army Corps of Engineers developed the HEC-1 hydrograph software over 30 years ago for use on mainframe computers, and then HEC-1 was adapted to run on personal computers during the mid-1980s. HEC-HMS is a recent program that is a successor to HEC-1, having windows-based graphics and other useful features.

The program user can input several values of rainfall (on the PH card if using HEC-1) and then the program will develop a hypothetical storm. This method of developing a 24-hour storm is not the same as a NRCS Type II rainfall distribution, and should not be used for detention basin routing. It will generally yield a smaller peak flow amount, typically 5% less, and does not constitute NRCS methods. Rainfall amounts to generate non-NRCS hypothetical storms in HEC-1 or HEC-HMS are shown in Table ST-13-3, generally using data in Weather Bureau Technical Paper No. 40 (1961).

Depth-duration-frequency information contained in Table ST-13-3 is for small watersheds less than 10 square miles in size. The average rainfall depth for watersheds greater than 10 square miles can be reduced by the following equations (which the USACE programs can handle internally):

Adjusted depth = Point rainfall depth x F_D x F_A → <u>*Use only if A > 10 sq.mi.*</u>

$$F_A = 1 - e^{(-0.015)(A)}$$

Point rainfall depth = rainfall depths taken from Table ST-13-3
F_D = rainfall duration factor (taken from Table ST-13-4)
F_A = rainfall area factor (areal reduction for watersheds > 10 sq.mi.)
A = area of contributing watershed (square miles)

Explanation of Hydrology Statistics

Phrases such as “25-year storm” or “100-year flood” are common terms for drainage design, floodplain management, etc. This section will help explain a few hydrology terms as well as clear up some misunderstandings. First, a 25-year storm does not necessarily produce a 25-year flood. The return period of the *precipitation event* (storm) is usually assumed to be the same as the return period of *measured streamflow* (flood), but this is not necessarily the case. Daily precipitation records have been kept at cities and airports for many decades in a standardized format, so that precipitation records and statistics are fairly reliable. However, streamflow records have usually been collected in a hit-or-miss fashion, are more expensive to gather, or may be rendered meaningless as a watershed is developed. Oftentimes, a stream gaging station is destroyed by a major flood (the very event it seeks to measure).

The return period of a storm, T_P, is the best available estimate of the recurrence interval. The probability of the T_P storm in any given year is $1/T_P$. For instance, the 100-year storm has a 1% chance (computed as 1/100) of occurring in any given year. The following formula can be used to estimate the probability of a T_P-year event over a period of N years. The results are listed in Table ST-13-5 for various storm events.

$$J = 1 - (1 - P)^N$$

J = Probability that a T_P-year event will occur 1 or more times over N years.
P = Probability of an event in any given year = $1 / T_P$
N = Number of years being analyzed

Water Balance

Wet detention basins and constructed wetlands must be analyzed to determine if stormwater runoff (with available contributions from groundwater flow or natural springs) will maintain an adequate water level during summer and autumn months. A major factor is how much contributing drainage area lies upstream. Water balance analysis depends on several factors that are very hard to quantify. Infiltration of water into the ground depends upon soil type, permeability, construction methods, or the presence of silt or organic fine materials. Evaporation depends on the amount of sunlight that reaches the water surface, nearby trees or buildings, and whether the project is on the south side of a slope or the north side. Air movement can be affected by topography, nearby traffic, and amount of sheltering vegetation. Wet detention basins and constructed wetlands should be constructed with a means to adjust water levels to improve operating conditions. Seasonal patterns can be incorporated into operation and maintenance of the BMP facility.

Tables ST-13-6 through ST-13-8 have monthly climate data at two NOAA stations in the Knoxville area. Information is taken from NOAA Climatography of the United States No. 81, containing monthly data for 30-year averages for Tennessee stations.

References **152, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 194**
(see BMP Manual Chapter 10 for list)

Table ST-13-1
Runoff Coefficients for Rational Method

	Hydrologic Soils Group											
	A			**B**			**C**			**D**		
Land Use	**<2%**	**(2-6)**	**>6%**	**<2%**	**(2-6)**	**>6%**	**<2%**	**(2-6)**	**>6%**	**<2%**	**(2-6)**	**>6%**
Forest	0.08	0.11	0.14	0.10	0.14	0.18	0.12	0.16	0.20	0.15	0.20	0.25
Meadow	0.14	0.22	0.30	0.20	0.28	0.37	0.26	0.35	0.44	0.30	0.40	0.50
Pasture	0.15	0.25	0.37	0.23	0.34	0.45	0.30	0.42	0.52	0.37	0.50	0.62
Farmland	0.14	0.18	0.22	0.16	0.21	0.28	0.20	0.25	0.34	0.24	0.29	0.41
Res. 1 acre	0.22	0.26	0.29	0.24	0.28	0.34	0.28	0.32	0.40	0.31	0.35	0.46
Res. 1/2 acre	0.25	0.29	0.32	0.28	0.32	0.36	0.31	0.35	0.42	0.34	0.38	0.46
Res. 1/3 acre	0.28	0.32	0.35	0.30	0.35	0.39	0.33	0.38	0.45	0.36	0.40	0.50
Res. 1/4 acre	0.30	0.34	0.37	0.33	0.37	0.42	0.36	0.40	0.47	0.38	0.42	0.52
Res. 1/8 acre	0.33	0.37	0.40	0.35	0.39	0.44	0.38	0.42	0.49	0.41	0.45	0.54
Industrial	0.85	0.85	0.86	0.85	0.86	0.86	0.86	0.86	0.87	0.86	0.86	0.88
Commercial	0.88	0.88	0.89	0.89	0.89	0.89	0.89	0.89	0.90	0.89	0.89	0.90
Streets: ROW	0.76	0.77	0.79	0.80	0.82	0.84	0.84	0.85	0.89	0.89	0.91	0.95
Parking	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97	0.95	0.96	0.97
Disturbed area	0.65	0.67	0.69	0.66	0.68	0.70	0.68	0.70	0.72	0.69	0.72	0.75

Note 1: Residential lot sizes are for single-family structures without including streets and right-of-way. Multi-family structures (townhouses, rowhouses) typically have higher runoff coefficients and should be computed using Note 2 below.

Note 2: Runoff coefficients may also be computed by proportioning land use as grass/landscaped/open (0.30) and as impervious/pavement/roof/sidewalk (0.95).

Table ST-13-2
Intensity Values for Various Durations (inches per hour)

Tc	**Return Period of Storm**					
minutes	**2-Year**	**5-Year**	**10-Year**	**25-Year**	**50-Year**	**100-Year**
5	4.60	5.55	6.25	7.30	7.90	8.60
10	3.70	4.60	5.25	6.20	6.80	7.49
15	3.19	3.98	4.60	5.45	6.00	6.60
20	2.82	3.50	4.10	4.90	5.45	6.02
25	2.48	3.12	3.70	4.45	4.95	5.50
30	2.22	2.80	3.34	4.03	4.53	5.03
35	2.02	2.55	3.06	3.67	4.14	4.62
40	1.86	2.35	2.82	3.38	3.80	4.24
45	1.73	2.18	2.62	3.14	3.53	3.93
50	1.62	2.04	2.46	2.94	3.30	3.67
55	1.53	1.92	2.32	2.77	3.10	3.45
60	1.45	1.82	2.20	2.62	2.93	3.26
90	1.06	1.36	1.64	1.95	2.18	2.45
120	0.86	1.09	1.31	1.55	1.71	1.95
180	0.66	0.80	0.97	1.13	1.23	1.38
360	0.41	0.50	0.58	0.66	0.75	0.83
720	0.24	0.30	0.34	0.39	0.43	0.48
1440	0.14	0.17	0.20	0.23	0.25	0.27

Table ST-13-3
Rainfall Depths for a HEC-1 (Non-NRCS) Hypothetical Storm

	Duration of storm							
STORM	**Minutes**		**Hours**					
EVENT	**5**	**15**	**1**	**2**	**3**	**6**	**12**	**24**
2-Year	0.45”	0.85”	1.50”	1.80”	2.00”	2.50”	2.90”	3.30”
5-Year	0.52”	1.03”	1.90”	2.35”	2.50”	3.00”	3.55”	4.10”
10-Year	0.56”	1.16”	2.18”	2.70”	2.90”	3.50”	4.10”	4.80”
25-Year	0.64”	1.35”	2.50”	3.10”	3.40”	4.00”	4.70”	5.50”
100-Year	0.77”	1.65”	3.15”	3.80”	4.10”	4.80”	5.80”	6.50”

See http://www.srh.noaa.gov/lub/wx/precip_freq/precip_index.htm for NOAA rainfall frequency maps from TP-40.

Table ST-13-4
Rainfall Area-Depth Factors for HEC-1 / HEC-HMS

Duration	F_D	F_A				
		10 sq.mi.	20 sq.mi.	30 sq.mi.	50 sq.mi.	100 sq.mi.
0.5 hour	0.48	0.933	0.876	0.826	0.747	0.627
1 hour	0.35	0.951	0.909	0.873	0.815	0.728
3 hours	0.22	0.969	0.943	0.920	0.901	0.804
6 hours	0.17	0.976	0.956	0.938	0.910	0.868
24 hours	0.09	0.987	0.977	0.967	0.953	0.930

Table ST-13-5
Probability Of Storm Event Occurring Over Specified Time Period

T	**N = specified time period (years)**								
(recurrence interval)	**1**	**5**	**10**	**25**	**50**	**100**	**200**	**500**	**1000**
2-year event	0.500	0.969	0.999	1.000	1.000	1.000	1.000	1.000	1.000
5-year event	0.200	0.672	0.893	0.996	1.000	1.000	1.000	1.000	1.000
10-year event	0.100	0.410	0.651	0.928	0.995	1.000	1.000	1.000	1.000
25-year event	0.040	0.185	0.335	0.640	0.870	0.983	1.000	1.000	1.000
50-year event	0.020	0.096	0.183	0.397	0.636	0.867	0.982	1.000	1.000
100-year event	0.010	0.049	0.096	0.222	0.395	0.634	0.866	0.993	1.000
500-year event	0.002	0.010	0.020	0.049	0.095	0.181	0.330	0.632	0.865

Table ST-13-6
30-Year Climate Data from 1961-1990 (UT Campus)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Rainfall												
Normal	4.27”	4.01”	4.91”	3.62”	4.42”	4.11”	4.49”	3.74”	3.23”	3.04”	3.97”	4.54”
Median	4.55”	3.78”	4.47”	3.36”	3.94”	3.85”	4.17”	3.21”	3.03”	3.24”	3.92”	4.13”
Temperature									……….	.(in degrees Fahrenheit)		
Normal	37.2	40.8	50.6	59.5	67.2	74.3	77.8	77.2	71.6	59.9	50.6	41.4
Median	**37.2**	**40.5**	**50.7**	**59.7**	**66.6**	**74.3**	**77.6**	**76.7**	**71.6**	**59.4**	**50.6**	**41.5**
Normal max	45.9	50.2	61.0	70.6	77.5	84.4	87.2	86.4	81.0	70.5	60.3	50.0
Normal min	**28.5**	**31.5**	**40.1**	**48.4**	**56.8**	**64.2**	**68.4**	**68.0**	**62.2**	**49.2**	**40.9**	**32.7**

Table ST-13-7
30-Year Climate Data from 1971-2000

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Normal Rainfall												
UT Campus	4.75”	3.91”	5.04”	3.52”	4.33”	4.77”	3.97”	3.40”	3.03”	3.03”	4.10”	4.37”
Airport	4.57”	4.01”	5.17”	3.99”	4.68”	4.04”	4.71”	2.89”	3.04”	2.65”	3.98”	4.49”
Temperature at UT Campus									……….	.(in degrees Fahrenheit)		
Normal max	46.6	51.6	61.1	70.5	77.8	84.7	88.2	87.0	81.2	70.9	60.1	50.3
Normal mean		**38.5**	**42.1**	**50.6**	**59.3**	**67.3**	**74.7**	**78.7**	**77.7**	**71.7**	**60.2**	**50.7**
42.0												
Normal min	**30.3**	**32.6**	**40.1**	**48.0**	**56.8**	**64.6**	**69.1**	**68.3**	**62.1**	**49.5**	**41.3**	**33.6**
Temperature at McGhee-Tyson Airport	Blount County								……….	.(in degrees Fahrenheit)		
Normal max	46.3	51.7	60.3	69.0	76.3	83.6	86.9	86.4	80.7	69.9	59.0	49.8
Normal mean		**37.6**	**41.8**	**49.7**	**57.8**	**66.0**	**73.8**	**77.7**	**76.9**	**70.8**	**58.8**	**49.0**

Table ST-13-8
30-Year Annual Climate Averages

Period	**Location**	**Normal Rainfall**	**Normal Max T**	**Normal Mean**	**Normal Min T**
1961-1990	UT Campus	48.35 inches/year	68.8º	59.0º	49.2º
1971-2000	UT Campus	48.22 inches/year	69.2º	59.5º	49.7º
1961-1990	McGhee-Tyson	47.14 inches/year	68.9º	57.6º	46.3º
1971-2000	McGhee-Tyson	48.55 inches/year	68.3º	58.4º	48.4º

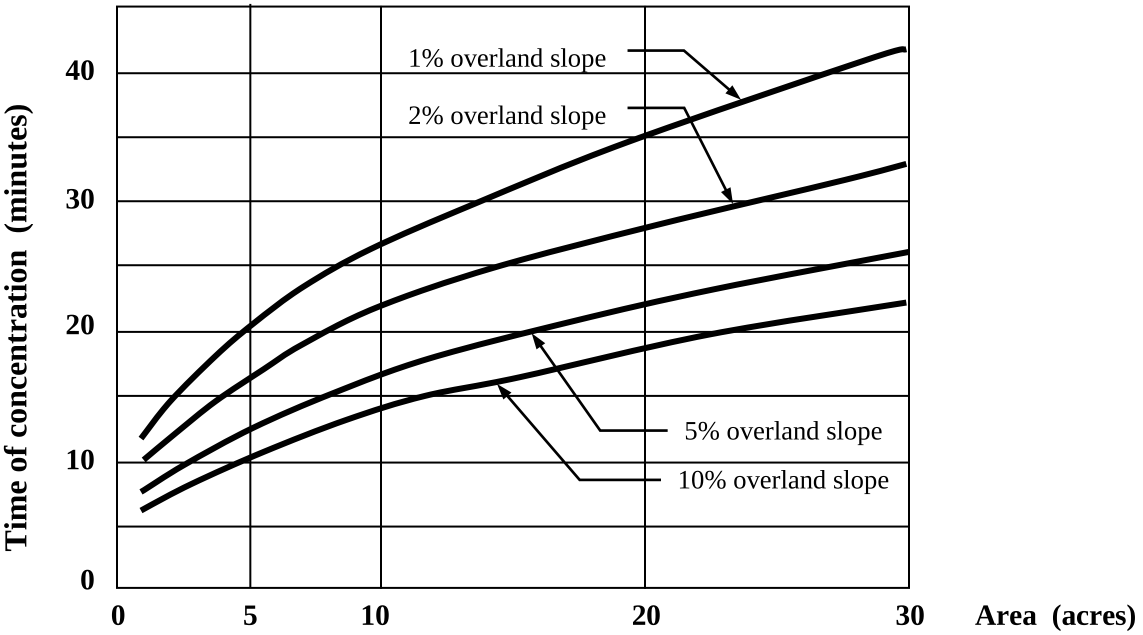


Figure ST-13-1
Typical Tc for Undeveloped Lands with Good Surface Cover

Note: Both Figures ST-13-1 and ST-13-2 were developed by CDM (reference 152) using assumptions to demonstrate typical times of concentration:

A. Areas are assumed to be approximately square in shape.
B. Overland flow length is equal to one-half length for square side.
C. Channel flow length is equal to length for square side.
D. Average impervious & surface roughness is used.
E. Overland flow time from kinematic wave & Kerby's equation.

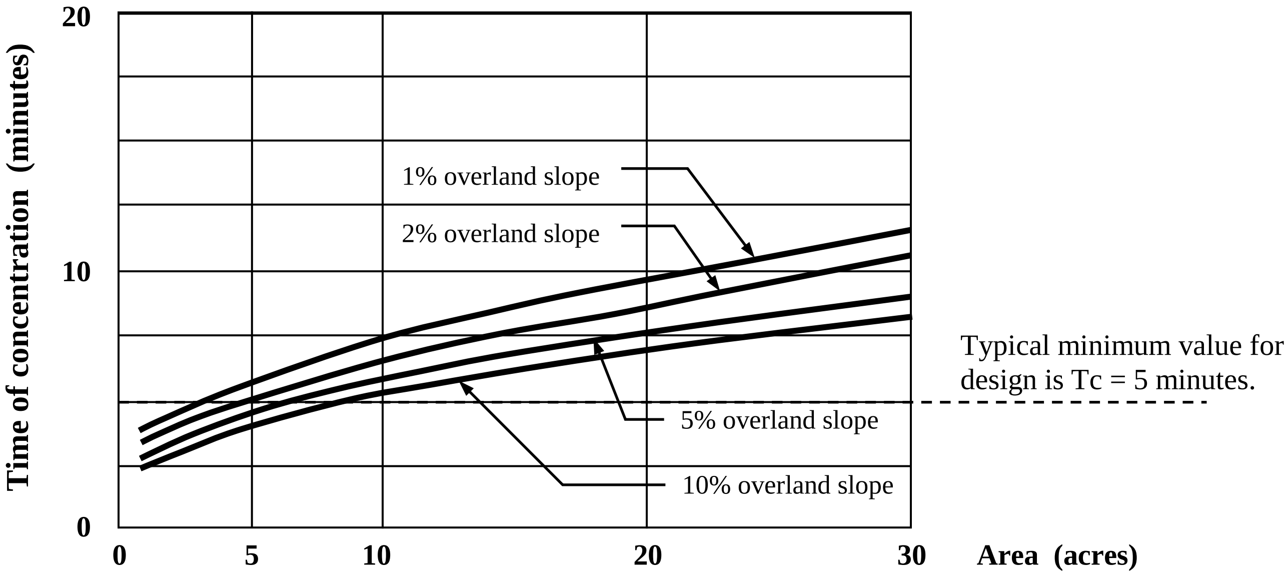


Figure ST-13-2
Typical Tc for Commercial and Industrial Development