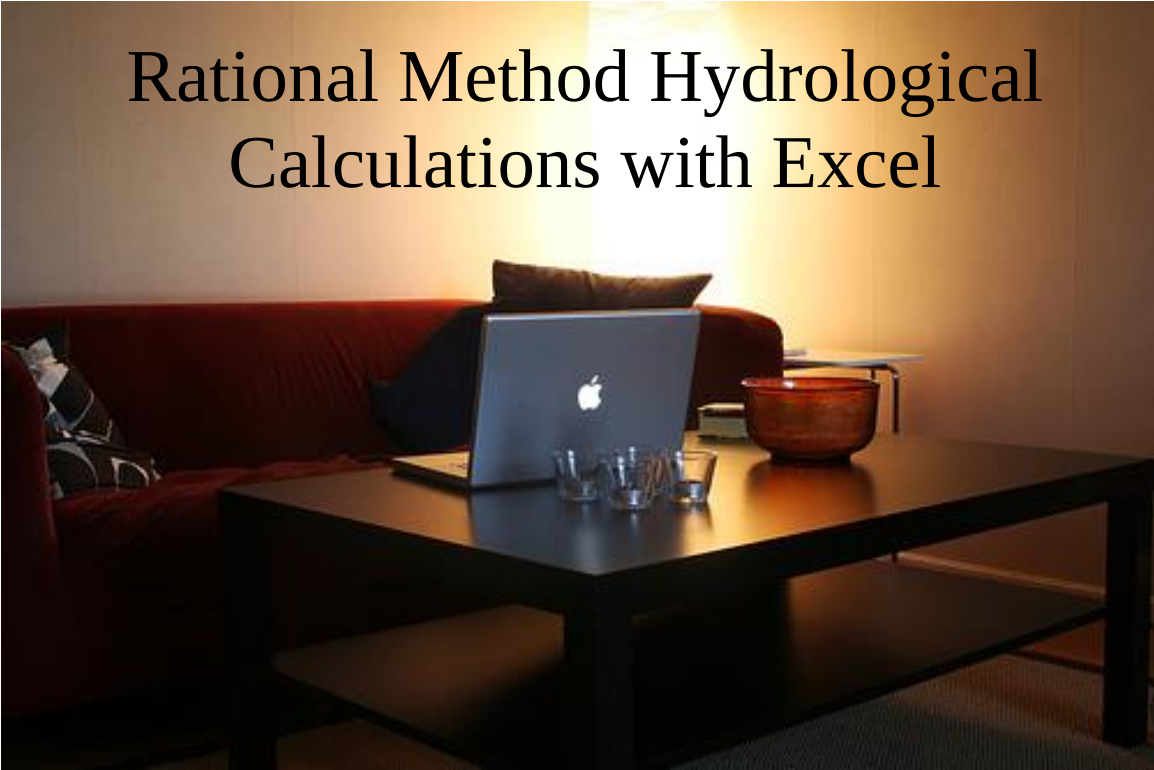




Rational Method Hydrological Calculations with Excel

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By

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RATIONAL METHOD HYDROLOGICAL CALCULATIONS WITH EXCEL

1. Introduction

Calculation of peak storm water runoff rate from a drainage area is often done with the Rational Method equation ($Q = CiA$). Calculations with the Rational Method equation often involve determination of the design rainfall intensity and the time of concentration of the watershed as well. This course includes discussion of the equations and the variables for these types of calculations. Example calculations, including the use of a spreadsheet, for Rational Method equation calculations and for determination of the design rainfall intensity and the time of concentration of the drainage area, are presented and discussed in this course. The parameters in the equations are defined with typical units for both U.S. and S.I. units.



Image Source: U.S. Forest Service; Air, Water & Aquatic Environments
Science Program website at:

www.fs.fed.us/rm/boise/research/techtrans/projects/scienceforkids/watersheds.shtml

2. Learning Objectives

At the conclusion of this course, the student will

- a) Know the parameters and their U.S. and S.I. units to be used in the Rational Method equation
- b) Be able to calculate peak storm water runoff rate with the Rational Method equation, using either U.S. or S.I. units
- c) Be able to place a given soil into one of the four SCS soil groups based on its measured minimum infiltration rate
- d) Be able to place a given soil into one of the four SCS soil groups based on its description
- e) Be able to determine a value of the Rational Method runoff coefficient based on land use, soil group, and slope of the watershed
- f) Be able to calculate the watershed time of concentration using the Kirpich equation, the Kerby-Hathaway equation, the FAA equation, and the SCS Lag equation.
- g) Be able to calculate the watershed time of concentration using more than one equation, with the Kerby-Kirpich method and with the NRCS method.
- h) Be able to calculate the overland sheet flow travel time for a watershed using the Manning Kinematic equation.
- i) Be able to calculate the shallow concentrated flow travel time for a watershed using the NRCS method.
- j) Be able to calculate the open channel flow travel time for a watershed using the Manning equation.
- k) Know the form of the equation used for rainfall intensity as a function of storm duration for a specified return period.
- l) Be familiar with methods for using Excel spreadsheets to make the types of calculations discussed in this course.

3. Topics Covered in this Course

- I. The Rational Method Equation
- II. Runoff Coefficients
- III. Watershed Time of Concentration
 - A. Single equation methods
 - B. Multiple equation methods
- IV. Design Rainfall Intensity
- V. Peak Storm Water Runoff Rate Calculations
- VI. The Steel Equation for Design Rainfall Intensity
- VII. Summary
- VIII. References

4. The Rational Method Equation

The Rational Method equation actually used to calculate peak storm water runoff rate is: $Q = CiA$ (U.S. units), or $Q = 0.0028 CiA$ (S.I. units) where:

- 1. **A** = the area of the watershed (drainage area) that drains to the point for which the peak runoff rate is needed (**acres** for U.S. units) (**ha** for S.I. units)
- 2. **C** = runoff coefficient for drainage area A. A physical interpretation is the fraction of rainfall landing on the drainage area that becomes storm water runoff. (dimensionless for both U.S. and S.I. units)
- 3. **i** = the intensity of the design storm for peak runoff calculation (**in/hr** for U.S. units) (**mm/hr** for S.I. units)
- 4. **Q** = the peak storm water runoff rate from the drainage area, A, due to the design storm of intensity, i. (**cfs** for U.S. units) (**m³/s** for S.I. units).

Explanation of Units: For the SI version of the equation ($Q = 0.0028 CiA$), the 0.0028 factor is needed to convert ha to m, mm to m, and hr to sec as follows:

$$Q = (\text{mm/hr})(\text{ha})(10,000 \text{ m}^2/\text{ha})(1 \text{ m}/1000 \text{ mm})(1 \text{ hr}/3600 \text{ sec}), \text{ or}$$

$$Q = 0.0028 CiA, \text{ with } i \text{ in mm/hr, } A \text{ in ha, and } Q \text{ in m}^3/\text{s}$$

At first glance the units don't appear to be correct for the specified U.S. units. The equation actually gives Q in acre-in/hr. The conversion factor, however, is 1.008 cfs/(acre-in/hr), and based on the precision with which the runoff coefficient can be determined, this conversion is typically taken to be 1, thus giving Q in cfs for rainfall intensity in in/hr and drainage area in acres.

The calculation of peak storm water runoff rate from the equation, $Q = CiA$, is quite straightforward if values are known for C , i , and A . Values for the drainage area, A , and the runoff coefficient, C , can typically be obtained without much trouble. Determination of the design rainfall intensity, i , usually requires the most effort.

Example #1: Calculate the peak storm water runoff rate from a watershed of 15 acres, with a runoff coefficient of 0.35, from a storm of intensity 2.4 in/hr.

Solution: This requires simply substituting into the equation ($Q = CiA$), thus:
 $Q = (0.35)(2.4)(15) = \underline{12.6 \text{ cfs}}$

5. Rational Method Runoff Coefficients

Since the physical interpretation of the runoff coefficient is the fraction of the rainfall on the watershed that becomes surface runoff, its value must be between one and zero. The value of the runoff coefficient for a given drainage area depends primarily on three factors: i) the soil type, ii) the land use, and iii) the slope of the watershed. Each of those factors will now be discussed briefly.

Soil Type: Sandy soils allow a high infiltration rate, so they have a relatively low storm water runoff rate and a relatively low runoff coefficient. Soils with a

large clay content, however, have a low infiltration rate. As a result, they have a relatively high storm water runoff rate and a relatively high runoff coefficient.

The United States Soil Conservation Service (SCS) has identified four soil group classifications (A, B, C, or D) that can be used to help in determining values for drainage area runoff coefficients. Determination of which SCS soil group fits a particular soil may be on the basis of a measured minimum infiltration rate for the soil or on the basis of a description of the soil.

The minimum infiltration rates (from ref #1) for each of the SCS soil groups are as follows:

- | | |
|------------|-------------------|
| a. Group A | 0.30 – 0.45 in/hr |
| b. Group B | 0.15 – 0.30 in/hr |
| c. Group C | 0.05 – 0.15 in/hr |
| d. Group D | 0 – 0.05 in/hr |

Descriptions of the four SCS soil groups (from ref #1) are as follows:

- | | |
|-----------|--|
| 3 Group A | Deep sand; deep loess; aggregated soils |
| 4 Group B | Shallow loess; sandy loam |
| 5 Group C | Clay loams; shallow sandy loam; soils low in organic content; soils usually high in clay |
| ➤ Group D | Soils that swell significantly when wet; heavy plastic clays; certain saline soils |

Land Use: Factors related to land use that affect the runoff coefficient are the fraction of the area with impervious cover, like streets, parking lots, or buildings and the extent of vegetative cover, which intercepts surface runoff.

Slope: In general, a watershed with a greater slope will have a higher runoff coefficient than one with a lesser slope.

The two tables below provide runoff coefficient values in terms of land use and watershed slope for each of the four SCS soil groups. As indicated below, the source for the information in the table is the Knox County Tennessee Stormwater Management Manual (Ref #2 at the end of the course).

Example #2: What is the value of the runoff coefficient to be used in Rational Method equation calculations, for a residential area with $\frac{1}{4}$ acre lots, soil group B, and slope of approximately 1.4% ?

Solution: From Part I of the Runoff Coefficient Table on the next two pages:

$$\underline{C = 0.33}$$

Slope :	Runoff Coefficient, C					
	Soil Group A			Soil Group B		
	< 2%	2-6%	> 6%	< 2%	2-6%	> 6%
Forest	0.08	0.11	0.14	0.10	0.14	0.18
Meadow	0.14	0.22	0.30	0.20	0.28	0.37
Pasture	0.15	0.25	0.37	0.23	0.34	0.45
Farmland	0.14	0.18	0.22	0.16	0.21	0.28
Res. 1 acre	0.22	0.26	0.29	0.24	0.28	0.34
Res. 1/2 acre	0.25	0.29	0.32	0.28	0.32	0.36
Res. 1/3 acre	0.28	0.32	0.35	0.30	0.35	0.39
Res. 1/4 acre	0.30	0.34	0.37	0.33	0.37	0.42
Res. 1/8 acre	0.33	0.37	0.40	0.35	0.39	0.44
Industrial	0.85	0.85	0.86	0.85	0.86	0.86
Commercial	0.88	0.88	0.89	0.89	0.89	0.89
Streets: ROW	0.76	0.77	0.79	0.80	0.82	0.84
Parking	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

Rational Method Runoff Coefficients - Part I

Source: Knox County Tennessee, Stormwater Management Manual,
<http://www.knoxcounty.org/stormwater/pdfs/vol2/3-1-3%20Rational>

Slope :	Runoff Coefficient, C					
	Soil Group C			Soil Group D		
	< 2%	2-6%	> 6%	< 2%	2-6%	> 6%
Forest	0.12	0.16	0.20	0.15	0.20	0.25
Meadow	0.26	0.35	0.44	0.30	0.40	0.50
Pasture	0.30	0.42	0.52	0.37	0.50	0.62
Farmland	0.20	0.25	0.34	0.24	0.29	0.41
Res. 1 acre	0.28	0.32	0.40	0.31	0.35	0.46
Res. 1/2 acre	0.31	0.35	0.42	0.34	0.38	0.46
Res. 1/3 acre	0.33	0.38	0.45	0.36	0.40	0.50
Res. 1/4 acre	0.36	0.40	0.47	0.38	0.42	0.52
Res. 1/8 acre	0.38	0.42	0.49	0.41	0.45	0.54
Industrial	0.86	0.86	0.87	0.86	0.86	0.88
Commercial	0.89	0.89	0.90	0.89	0.89	0.90
Streets: ROW	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
Disturbed Area	0.68	0.70	0.72	0.69	0.72	0.75

Rational Method Runoff Coefficients - Part II

Source: Knox County Tennessee, Stormwater Management Manual,
<http://www.knoxcounty.org/stormwater/pdfs/vol2/3-1-3%20Rational>

6. Watershed Time of Concentration

Background: The time of concentration doesn't appear directly in the Rational Method equation. It is needed, however, for determination of the design rainfall intensity to use in the Rational Method equation. For a given watershed, the time of concentration is the time required for rainfall landing on the farthest point of the watershed to reach the watershed outlet.

The time of concentration should be used as the duration of the design storm for calculating peak storm water runoff rate with the Rational Method equation. The reasoning for this is as follows: A storm of duration less than the time of concentration will never have the entire watershed contributing runoff flow to the outlet at the same time during the storm. A storm with duration equal to the time of concentration will have the full watershed contributing to the runoff at the outlet, (and thus reach peak flow rate) just before the storm ends. A storm of duration greater than the time of concentration, and having the same recurrence interval, will be less intense.

A. Estimating Time of Concentration with a Single Equation for Entire Watershed: Four equations of this type will be discussed here, the Kirpich equation, the Kerby-Hathaway equation, the FAA equation and the SCS Lag equation.

The **Kirpich equation** is based on data from seven rural watersheds with well-defined channels, steep slopes of 3% to 10%, and areas of 1 to 112 acres. It is used for urban areas for both overland flow and channel flow and for agricultural watersheds of up to 200 acres. The Kirpich equation is shown below for both U.S. and S.I. units:

For U.S. units: $t = 0.0078(L^{0.77})(S^{-0.385})$

Where: **L** = length of flow path in ft
 S = surface slope in ft/ft
 t = travel time (time of concentration) in min

For S.I. units: $t = 0.0195(L^{0.77})(S^{-0.385})$

Where: L = length of flow path in m
 S = surface slope in m/m
 t = travel time (time of concentration) in min

Reference: Texas DOT, Hydraulic Design Manual,
http://onlinemanuals.txdot.gov/txdotmanuals/hyd/time_of_concentration.htm

Example #3: What would be the time of concentration for a watershed with a path length for overland sheet flow of 2000 ft and ground slope of 4% ?

Solution: Substituting values into the Kirpich Equation gives:

$$t = 0.0078(2000^{0.77})(0.04^{-0.385}) = \underline{\underline{9.3 \text{ min}}}$$

The **Kerby-Hathaway equation** is based on data from watersheds having watercourses less than 1200 feet, slopes less than 1%, and areas less than 10 acres. The Kerby-Hathaway equation is shown below for both U.S. and S.I. units.

For U.S. units: $t = [0.67nL/(S^{1/2})]^{0.467}$

Where: L = length of flow path in ft
 S = surface slope in ft/ft
 n = overland flow resistance factor
 t = travel time (time of concentration) in min

For S.I. units: $t = [2.19nL/(S^{1/2})]^{0.467}$

Where: L = length of flow path in m
 S = surface slope in m/m
 n = overland flow roughness coefficient
 t = travel time (time of concentration) in min

Example #4: Use the Kerby-Hathaway equation to estimate the time of concentration for a watershed with a path length for overland sheet flow of 1000 ft, ground slope of 0.6%, and overland flow roughness factor equal to 0.2.

Solution: Substituting values into the Kerby-Hathaway Equation gives:

$$t = [(0.67)(0.2)(1000)/(0.04^{1/2})]^{0.467} = \underline{\underline{20.9 \text{ min}}}$$

The table below gives ranges of values for the overland flow roughness coefficient for various types of surfaces.

Roughness Coefficients for Overland Flow	
Type of Surface	n
Dense Growth	0.40 to 0.50
Pasture	0.30 to 0.40
Lawns	0.20 to 0.30
Bluegrass Sod	0.20 to 0.50
Short-Grass Prairie	0.10 to 0.20
Spase Vegetation	0.05 to 0.13
Bare Clay-Loam Soil (Eroded)	0.01 to 0.13
Concrete - Asphalt	
Very Shallow Depths (< 1/4")	0.10 to 0.15
Shallow Depths (> 1.4")	0.15 to 0.10
Deciduous Timberland	0.50 to 0.70
Conifer Timberland	0.60 to 0.80

Source: Missouri DOT, Engineering Policy Guide, Category 749, Hydrologic Analysis,
[http://epg.modot.org/index.php?title=Category:749_Hydrologic_Analysis#749.5.3.2 Kerby-Hathaway Equation for Overland Flow](http://epg.modot.org/index.php?title=Category:749_Hydrologic_Analysis#749.5.3.2_Kerby-Hathaway_Equation_for_Overland_Flow)

The **FAA equation** was developed by the Federal Aviation Authority. It is based on data from airfield drainage and is most valid for small watersheds where sheet flow and overland flow predominate. The FAA equation is shown below for both U.S. and S.I. units.

For U.S. units: $t = 1.8(1.1 - C)L^{0.5}/S^{0.33}$

Where: **L** = length of flow path in ft
 S = surface slope in ft/ft
 C = Rational Method runoff coefficient
 t = travel time (time of concentration) in min

For S.I. units: $t = 3.26(1.1 - C)L^{0.5}/S^{0.33}$

Where: **L** = length of flow path in m
 S = surface slope in m/m
 C = Rational Method runoff coefficient
 t = travel time (time of concentration) in min

Reference: NRCS (National Resources Conservation Service), National Engineering Handbook, Part 630 Hydrology, Ch. 15, Time of Concentration, <ftp://ftp.wcc.nrcs.usda.gov/wntsc/H&H/NEHhydrology/ch15.pdf>

Example #5: Use the FAA equation to estimate the time of concentration for a watershed with a path length for overland sheet flow of 40 m, ground slope of 0.6%, and Rational Method runoff coefficient equal to 0.25.

Solution: Substituting values into the FAA Equation gives:

$$t = 3.26(1.1 - 0.25)40^{0.5}/0.006^{0.33} = \underline{\underline{94.8 \text{ min}}}$$

The **SCS Lag equation** was developed by the Soil Conservation Service. It is based on data from agricultural watersheds and is most valid for rural watersheds. The SCS Lag equation is shown below for both U.S. and S.I. units.

For U.S. units: $t = 0.00526[(1000/CN) - 9]^{0.7} L^{0.8} / S^{0.5}$

Where: **L** = length of flow path in ft
 S = surface slope in ft/ft
 CN = runoff curve number
 t = travel time (time of concentration) in min

For S.I. units: $t = 0.00136[(1000/CN) - 9]^{0.7} L^{0.8} / S^{0.5}$

Where: **L** = length of flow path in m
 S = surface slope in m/m
 CN = runoff curve number
 t = travel time (time of concentration) in min

Example #6: Use the SCS Lag equation to estimate the time of concentration for a watershed with a path length for overland sheet flow of 120 ft, ground slope of 0.6%, and runoff curve number equal to 60.

Solution: Substituting values into the SCS Lag Equation gives:

$$t = 0.00526 \{ [(1000/75) - 9]^{0.7} \} (120^{0.8}) / 0.006^{0.5} = \underline{\underline{94.8 \text{ min}}}$$

Reference: NRCS (National Resources Conservation Service), National Engineering Handbook, Part 630 Hydrology, Ch. 15, Time of Concentration, <ftp://ftp.wcc.nrcs.usda.gov/wntsc/H&H/NEHhydrology/ch15.pdf>

The table below gives runoff curve number (CN) values for a few example types of agricultural land. There are much more extensive table of runoff curve number tables in the source which is given below the table. the hydrologic soil groups, A, B, C, & D are described above in Section 5, Rational Method Runoff Coefficients.

Runoff Curve Numbers for Cultivated Agricultural Lands						
Cover Type	Treatment	Hydrologic	Curve Number for Hydrologic Soil Group			
		Condition	A	B	C	D
Fallow	Bare Soil	----	77	86	91	94
	Crop Residue Cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row Crops	Straight Row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	Contoured and Terraced (C & T)	Poor	66	74	80	82
		Good	62	71	78	81
	C & T and CR	Poor	65	73	79	81
		Good	61	70	77	80

Source: USDA, Natural Resources Conservation Service, Conservation Engineering Division, Technical Release 55, Urban Hydrology for Small Watersheds, TR-55, June 1986,
http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf

B. Estimating Time of Concentration with more than one Equation: Two methods of this type will be discussed here, the Kerby-Kirpich method and the NRCS method.

The **Kerby-Kirpich method** uses the Kerby-Hathaway equation, described above, to calculate the overland sheet flow travel time in the upper portion of the watershed and it uses the Kirpich equation, described above, to calculate the channel flow time in the lower part of the watershed. Note that the watershed

must be divided into two portions, a sheet flow portion and a channel flow portion.

The parameters needed for this calculation are the length of the flow path, the surface slope, and the overland flow roughness coefficient for the overland sheet flow portion of the watershed, and the length of the flow path and surface slope for the channel flow portion of the watershed.

The **NRCS method** subdivides the watershed into three portions, an overland flow portion, a concentrated flow portion, and a channel flow portion. This method uses the Manning Kinematic equation to calculate the overland sheet flow travel time in the upper portion of the watershed. It uses the NRCS velocity method to calculate shallow concentrated flow travel time in the middle part of the watershed and it uses the Manning equation to calculate the channel flow travel time in the lower portion of the watershed. Those three equations will now each be presented and discussed briefly.

The U.S. and S.I. versions of the **Manning Kinematic equation** are shown below:

$$t_{ov} = \frac{0.42 (nL)^{0.8}}{P^{0.5} S^{0.4}}$$

Manning Kinematic
Equation - U.S. units

$$t_{ov} = \frac{5.48 (nL)^{0.8}}{P^{0.5} S^{0.4}}$$

Manning Kinematic
Equation - S.I. units

The parameters and their units in this equation are as follows:

- **t_{ov}** is the travel time for overland sheet flow (minutes for both U.S. & S.I. systems)
- **n** is the Manning roughness coefficient, which is dimensionless (see the table below for Manning Roughness Coefficient values for a variety of surfaces.)

- **L** is the length of the flow path (ft. for U.S. & m for S.I.)
- **P** is the 2 year, 24 hour rainfall depth (in. for U.S. & mm for S.I.)
- **S** is the ground slope, which is dimensionless (or ft/ft for U.S. & m/m for S.I.)

Manning Roughness Coefficient (n) for Overland Sheet Flow

Surface Description	n
Smooth surfaces (concrete, asphalt, gravel or bare soil)	0.011
Fallow (no residue)	0.05
Cultivated Soils:	
Residue cover < 20%	0.06
Residue cover > 20%	0.17
Grass:	
Short grass prairie	0.15
Dense grasses	0.24
Bermuda grass	0.41
Range (natural)	0.13
Woods:	
Light underbrush	0.4
Dense underbrush	0.8

Source: Iowa Stormwater Management Manual, Section on Time of Concentration, at: <http://www.intrans.iastate.edu/pubs/stormwater/Design/2C/2C-3%20Time%20of%20Concentration.pdf>

Example #7: Using the Manning Kinematic Equation, calculate the overland sheet flow travel time for a watershed with a path length for overland sheet flow of 75 ft; ground slope of 0.0004; Manning roughness coefficient for the flow path of 0.15; and 2yr/24hr rainfall of 5 inches?

Solution: Substituting values into the Manning Kinematic Equation for U.S. units gives: $t_{ov} = [0.42(0.15*75)^{0.8}]/[5^{0.5}*0.0004^{0.4}] = \underline{\underline{29.8 \text{ min}}}$

The **NRCS Velocity Method** is recommended by and described in references #3 and #4 (Natural Resources Conservation Service and the Iowa Stormwater Management Manual) for the shallow concentrated flow that normally develops within 100 to 300 feet into the watershed, after overland sheet flow. The NRCS velocity method involves calculation of the velocity of the shallow concentrated flow based on information about the slope and the type of surface. The travel time is then calculated as the travel length divided by the flow velocity. The equations used in NRCS velocity method calculations are as follows for U.S. units:

- $V = 16.1345 S^{0.5}$ for an unpaved surface
- $V = 20.3282 S^{0.5}$ for a paved surface
- $t_{sc} = L/(60V)$

For S.I. units, the NRCS Method equations are:

- $V = 4.9178 S^{0.5}$ for an unpaved surface
- $V = 6.1960 S^{0.5}$ for a paved surface
- $t_{sc} = L/(60V)$

The parameters and their units for these equations are as follow:

- t_{sc} = travel time for shallow concentrated flow (in minutes for U.S. or S.I. units)
- L = length of the flow path (ft for U.S. or m for S.I. units)
- V is the shallow concentrated flow velocity (ft/sec for U.S. or m/s for S.I. units)
- S is the slope of the flow path (dimensionless, i.e. ft/ft or m/m)

Example #8: Using the NRCS Velocity Method, what would be the travel time for an unpaved, concentrated shallow flow path of 105 ft, with a slope of 0.0004?

Solution: Substituting the slope into the U.S. equation for an unpaved surface gives: $V = 16.135 (0.0004)^{0.5} = 0.3227 \text{ ft/sec}$. Then:
 $t_{sc} = L/(60V) = 105/(60*0.3227) = \underline{\underline{5.4 \text{ min}}}$

Example #9: Set up an Excel spreadsheet to solve Example #7 and Example #8.

Solution: The image on the next page show an Excel spreadsheet set up to calculate the travel time for overland sheet flow with the Manning Kinematic Equation and the travel time for shallow concentrated flow using the NCRS method.

The given information is shown entered into the blue cells. For Example #3, the inputs are: $n = 0.15$, $L = 75 \text{ ft}$, $P = 5 \text{ in}$, and $S = 0.0004$. The spreadsheet then calculates the overland sheet flow travel time with the Manning Kinematic Formula in the yellow cell. The result is the same as the result shown above for Example #7:

$$\underline{\underline{t_1 = 29.8 \text{ min}}}$$

For Example #8, the inputs are $L = 105 \text{ ft}$ and $S = 0.0004$. Entering these two values in the blue cells leads to values for V and t_2 for an unpaved surface and for a paved surface through equations entered in the yellow cells. Since the surface described in Example #4 is unpaved, the answer for the shallow concentrated flow is the same as that calculated above:

$$\underline{\underline{t_2 = 5.4 \text{ min}}}$$

Calculation of Overland Sheet Flow Travel Time			
Using the Manning Kinematic Equation - U.S. units			
Instructions: Enter values in blue boxes. Spreadsheet calculates values in yellow boxes			
Inputs			
Manning Roughness		Ground Slope, S =	0.0004
Coefficient, n =	0.15		
Calculations			
Length of Flow Path, L =	75	ft	
2 yr, 24 hr rainfall, P =	5	in	
		Overland Flow Time	
		Travel, t₁ =	30.7 min
Calculation of Shallow Concentrated Flow Travel Time			
Using the NCRS Method - U.S. units			
Inputs		Calculations	
Length of Flow Path, L =	105	ft	
Ground Slope, S =	0.0004		
		For unpaved surface:	
		Flow Velocity, V =	0.32269 ft/sec
		Travel time, t₂ =	5.4 min
		For paved surface:	
		Flow Velocity, V =	0.406564 ft/sec
		Travel time, t₂ =	4.3 min
Find more Excel spreadsheets for stormwater at: EngineeringExcelTemplates.com			

The **Manning equation** can be used for the open channel flow portion of the storm water runoff that typically occurs at the end of the runoff path. This equation is recommended by both ref #3 and ref #4 for calculating open channel flow travel time. You may well be familiar with the Manning equation as follow:

- U.S. units: $Q = (1.49/n)A(R^{2/3})(S^{1/2})$
- S.I. units: $Q = (1.0/n)A(R^{2/3})(S^{1/2})$

Other equations (in addition to the Manning equation) that are used in calculating travel time for the open channel flow portion of the storm water runoff are:

- Velocity of flow = $V = Q/A$ for either U.S. or S.I. units
- Travel time = $t_{ch} = L/(60V)$ for either U.S. or S.I. units

The definitions and units for the parameters in these equations are:

- t_{ch} is the open channel flow travel time (min for either U.S. or S.I. units)
- L is the length of the open channel flow path (ft – U.S. or m – S.I.)
- V is the average open channel flow velocity (ft/sec – U.S. or m/s – S.I.)
- Q is the flow rate in the open channel (cfs – U.S. or m^3/s – S.I.)
- R is the hydraulic radius of the open channel flow ($R = A/P$ with A and P as defined below) (ft – U.S. or m – S.I.)
- A is the cross-sectional area of the open channel flow (ft^2 – U.S. or m^2 – S.I.)
- P is the wetted perimeter of the open channel flow (ft – U.S. or m – S.I.)
- n = Manning roughness coefficient for the channel surface (dimensionless)

Example #10: What would be the travel time for the open channel flow portion of storm water runoff in a channel with bottom width = 2 ft; depth of flow = 1.2 ft; side slope = 3; Manning roughness = 0.022; channel bottom slope = 0.0003; and flow path length = 75 ft?

Solution: The solution proceeds by calculation of A, P, R, Q, V, and t_3 as follows:

$$\text{For the trapezoidal channel: } A = by + zy^2 = 2*1.2 + 3*1.2^2 = 6.7 \text{ ft}^2$$

$$P = b + 2y(1 + z^2)^{1/2} = 2 + 2*1.2(1 + 3^2)^{1/2} = 9.6 \text{ ft}$$

$$R = A/P = 6.7/9.6 \text{ ft} = 0.70 \text{ ft}$$

$$Q = (1.49/n)A(R^{2/3})(S^{1/2}) = (1.49/0.022)(6.7)(0.70^{2/3})(0.0003^{1/2}) = 6.22 \text{ cfs}$$

$$V = Q/A = 6.22/6.7 \text{ ft/sec} = 0.925 \text{ ft/sec}$$

$$\text{Finally: } t_3 = L/(60V) = 75/(60*0.925) = \underline{\underline{1.4 \text{ min}}}$$

Example #11: Set up an Excel spreadsheet to solve Example #10.

Solution: The image below shows an Excel spreadsheet set up to calculate the travel time for open channel flow with the Manning Equation .

The given information for Example #11 is shown entered into the blue cells. For this example, the inputs are: **b** = 2 ft, **y** = 1.2 ft, **z** = 3, **n** = 0.022, **S** = 0.0003, and **L** = 75. The spreadsheet then calculates the parameters shown in the yellow cells, including the channel travel time. The result is the same as the result shown above for Example #6:

$$\underline{\underline{t_3 = 1.4 \text{ min}}}$$

Calculation of Channel Flow Travel Time					
Using the Manning Equation - U.S. units					
For a Trapezoidal Channel Cross-section					
Inputs			Calculations		
Bottom width, b =	2	ft	Cross-Sect. Area, A =	6.7	ft ²
Depth of flow, y =	1.2	ft	Wetted Perimeter, P =	9.6	ft
Side Slope, z =	3		Hydraulic Radius, R =	0.70	ft
(H:V = z:1)					
			Discharge, Q =	6.22	cfs
Manning roughness, n =	0.022				
			Ave. Velocity, V =	0.925	ft/sec
Channel bottom slope, S =	0.0003	ft/ft			
			Channel travel time, t₃ =	1.4	min
Length of Flow Path, L =	75	ft			
Find more Excel spreadsheets for stormwater at: EngineeringExcelTemplates.com					

Example #12: Calculate the time of concentration for a watershed that has the overland sheet flow travel time, concentrated shallow flow travel time, and channel flow travel time as calculated above in the previous several examples.

Solution: The time of concentration, which is the total travel time from the periphery of the watershed to the outlet, is simply the sum of the overland sheet flow travel time (**t₁**), the shallow concentrated flow travel time (**t₂**), and the channel flow travel time (**t₃**).

Time of Concentration = 29.8 + 5.4 + 1.4 min = **36.6 min**

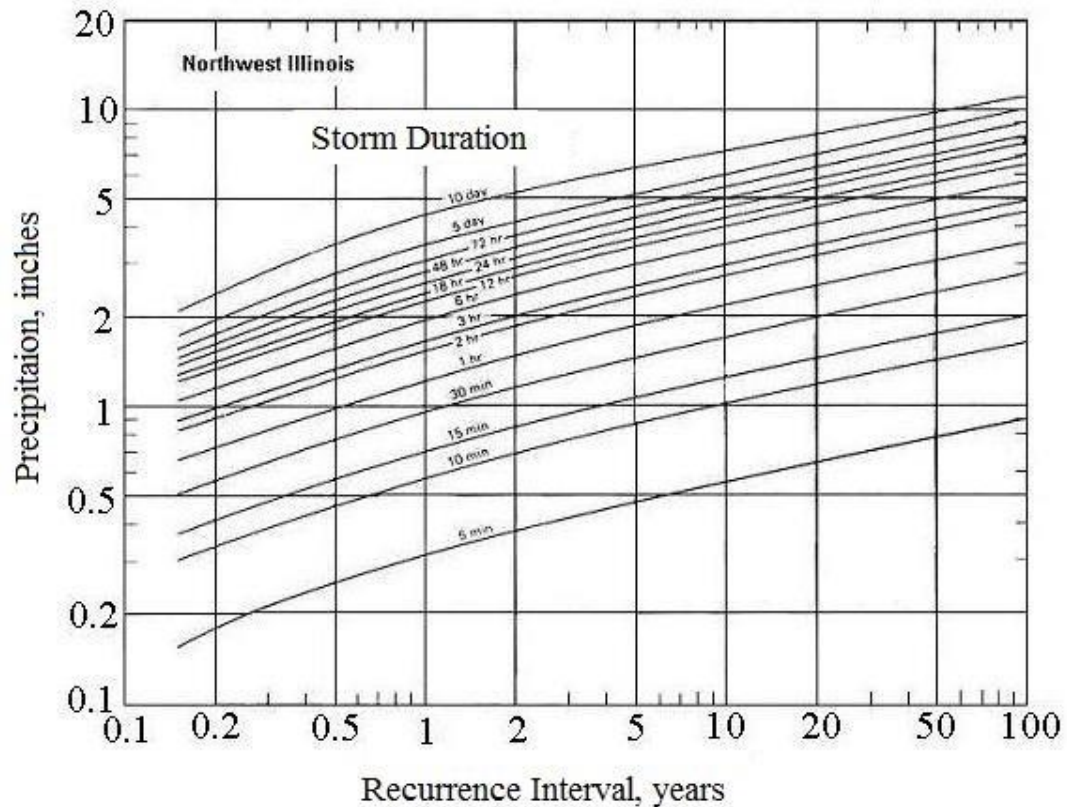
7. Design Rainfall Intensity

The design rainfall intensity, i , for use in the Rational Method equation is the intensity of a constant intensity design storm with return period equal to a specified value for the purpose of the peak runoff rate being calculated, and duration equal to the time of concentration of the watershed. The return period to be used is typically specified by a state or local government agency.

In order to determine the design storm intensity for known duration and return period, some type of intensity-duration-frequency (IDF) data for the location of interest is needed. In general, for a given return period, a shorter duration storm will be of greater intensity than a longer duration storm. IDF data is available from state agencies in many U.S. states. It may be in the form of graphs, tables, and/or equations. The figure below (adapted from Illinois State Water Survey *Bulletin 70* (ref #5) shows an example IDF graph for northwest Illinois.

Depending on the type of IDF data available, the design rainfall intensity, i , can typically be obtained for a given return period and storm duration by reading from a graph or interpolating from a table. When using an Excel spreadsheet for calculations, however, it is more convenient to have the IDF data in the form of an equation. When the data is fit to an equation, the typical form for the equation is: $i = a/(d + b)$ for each return period of interest, where i is the storm intensity, d is the storm duration, and a & b are constants. The equation $i = a/(d + b)$ can be rearranged into the form:

$$1/i = (1/a)d + b/a, \text{ which is a linear equation for } 1/i \text{ vs } d.$$



Example #13: Calculate the design rainfall intensity for a drainage area in northwest Illinois with a design return period of 25 years, and a time of concentration of 36.6 minutes.

Solution: From the IDF diagram for northwest Illinois on the previous page, the precipitation for a storm of duration 36.6 minutes and return period 25 years can be estimated as 2.2 inches. The intensity of the design storm (duration = 36.6 minutes, return period = 25 years) can be calculated as follows:

$$i = [(2.2 \text{ inches}) / (36.6 \text{ minutes})] (60 \text{ min/hr}) = \underline{\underline{3.61 \text{ in/hr} = i}}$$

8. Peak Storm Water Runoff Rate Calculation

When the design rainfall intensity, **i**, has been determined and specified watershed drainage area, **A**, and runoff coefficient, **C**, are available, these values can be substituted into the Rational Method equation: $Q = CiA$, to calculate the peak runoff rate, **Q**.

Example #14: Determine the peak flow rate if the design storm described in Example #9 falls upon a 25 acre watershed with runoff coefficient equal to 0.33.

Solution: The drainage area (**A**) is given as 25 acres, the runoff coefficient (**C**) is given as 0.33, and the design rainfall intensity was determined to be 3.61 in/hr, so the design peak storm water runoff rate can be calculated from the Rational Method equation; $Q = CiA$. Thus:

$$Q = (0.33)(3.61)(25) = \underline{29.7 \text{ cfs}} = Q$$

Example #15: Set up an Excel spreadsheet to determine the design rainfall intensity and the peak stormwater runoff rate for the design storm and watershed described in Example #13 and Example #14. (**A** = 25 acre, located in northwest Illinois, a design return period of 25 years, and a time of concentration of 36.6 minutes.)

Solution: The image on the next page shows an Excel spreadsheet set up to calculate the design rainfall intensity of Example #13, and the peak stormwater runoff rate of Example #14.

The blue cells near the top of the sheet are for user entry of the drainage area, design return period, runoff coefficient, and design storm duration (time of concentration).

Rational Method Calculation of Design Rainfall Intensity and Peak Storm Water Runoff Rate - U.S. units (for specified return period and storm duration)					
Instructions: Enter values in blue boxes. Spreadsheet calculates values in yellow boxes					
Inputs					
Drainage Area, A =		25	acres	Runoff Coefficient, C = 0.33	
Design Return Period =		25	years	Design Storm Duration, d = 36.6 min (= time of concentration)	
Data from IDF (intensity-duration-frequency) graph or table for the design location:				Calculation of equation constants (a & b) using linear regression of 1/i vs d: (1/i = (1/a)d + b/a)	
Input	Calculated	Input	Calculated		
Precip, in	i, in/hr	d, min	1/i, hr/in	slope = 0.005099 = 1/a	
1.6	6.40	15	0.16	a = 1/slope = 196	
2.2	4.40	30	0.23		
2.6	2.60	60	0.38	intercept = 0.0776 = b/a	
				b = a*intercept = 15.2	
Calculation of Design Rainfall Intensity, i, using the equation: $i = a/(d + b)$: (using the value for storm duration, d, specified above)					
Design Rainfall Intensity, i =				3.78	in/hr
Calculation of Design Peak Storm Water Runoff Rate, Q, using the equation: $Q = CiA$					
Design Peak Storm Water Runoff Rate, Q =				31.2	cfs
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Then it is also necessary to enter three pairs of values for storm duration and precipitation depth in inches, from the IDF data for the design location, into the blue cells near the center of the sheet. For this example, the following pairs of values were read from the IDF diagram for northwest Illinois above:

D, min	15	30	60
Precip, in	1.6	2.2	2.6

Note that the rainfall duration values were chosen so that the design rainfall duration (36.6 min) falls within the range of those data points.

After entry of the above three pairs of values in the blue cells, the spreadsheet will calculate rainfall intensity, i , and $1/i$ for each storm duration, with fairly simple calculations. Also the spreadsheet carries out the linear regression, using the Excel “Intercept” function and the Excel “Slope” function to find the values for the constants a and b in the equation $i = a/(d + b)$.

The resulting equation for rainfall intensity, i , as a function of storm duration, d , (for a 25 year storm) for this example is: **$i = 196/(d + 15.2)$**

The spreadsheet calculates the design rainfall intensity by substituting the specified design storm duration (36.6 min) into the equation, giving:

$$\mathbf{i = 3.78 \text{ in/hr}}$$

Note that this is close to the value of $i = 3.61 \text{ in/hr}$ that was obtained in the Example #9 calculation. Both methods are limited by the accuracy to which the values can be read from the IDF diagram.

At the bottom of the spreadsheet, the peak stormwater discharge rate is calculated from $Q = CiA$, with the user entered values for C and A and the calculated value of i . This results in:

$$Q = (0.33)(3.78)(25) = \mathbf{31.2 \text{ cfs} = Q}$$

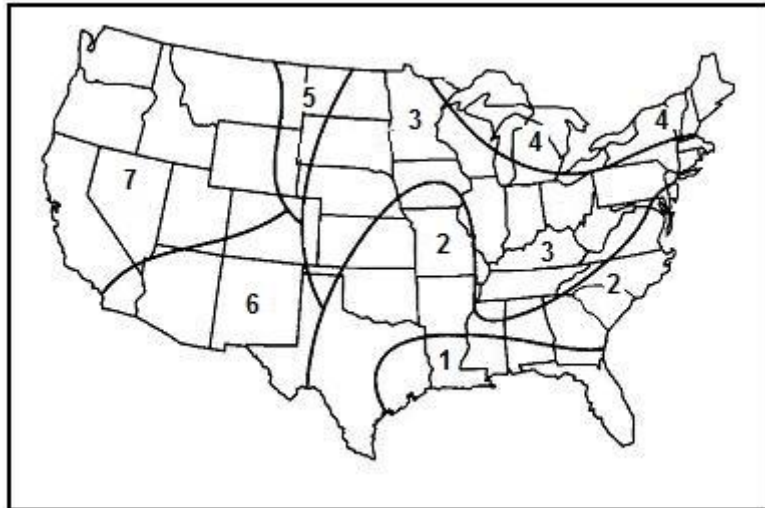
9. The Steel Equation for Design Rainfall Intensity

The Steel equation is an alternative for calculating design rainfall intensity for a location where good IDF data is not available. The Steel equation is:

$$i = a/(d + b)$$

Values for the constants a and b for seven regions of the United States for return periods of 2, 5, 10, 25, 50, and 100 years are given in the table below. The seven U.S. regions are shown on the following map.

Steel Equation Constants for U.S. Regions (i = in/hr)								
return	Equation	U.S. Region						
period	Constants	1	2	3	4	5	6	7
2	a	209	140	102	70	70	68	32
	b	30	21	17	13	16	14	11
5	a	247	190	131	97	81	75	48
	b	29	25	19	16	13	12	12
10	a	300	230	170	111	111	122	60
	b	36	29	23	16	17	23	13
25	a	327	260	230	170	130	155	67
	b	33	32	30	27	17	26	10
50	a	315	350	250	187	187	160	65
	b	28	38	27	24	25	21	8
100	a	367	375	290	240	240	210	77
	b	33	36	31	28	29	26	10



The particular Steel equation to use for a specified location in the United States and specified return period can be obtained by getting the values of the constants, **a** and **b**, from the map and table above.

Example #16: Use the Steel equation to find the design rainfall intensity and peak storm water runoff rate for a 25 acre drainage area in northwest Illinois with a runoff coefficient of 0.33, a design return period of 25 years, and a time of concentration of 36.6 minutes.

Solution: The map above shows northwest Illinois to be in region 3 of the United States. The table shows the following values of the constants **a** and **b** for a 25 year return period in region 3: **a** = 230, **b** = 30. The equation for rainfall intensity as a function of storm duration is thus:

$$i = 230/(d + 30)$$

Substituting $d = 36.6$ minutes gives:

$$i = 230/(36.6 + 30) = \underline{\underline{3.45 \text{ in/hr}}}$$

The peak storm water runoff rate can now be calculated using the Rational Method equation:

$$Q = CiA = (0.33)(3.45)(25) = \underline{\underline{28.5 \text{ cfs}}}$$

Example #17: Set up an Excel spreadsheet to solve Example #16.

Solution The image on the next page shows an Excel spreadsheet set up to solve this Example. The drainage area, design return period, runoff coefficient, and design storm duration (time of concentration) values are entered into the blue cells near the top of the spreadsheet. Then the Steel equation constants need to be identified using the map and table. Those constants (**a** and **b**) are then entered into the appropriate blue cells. The spreadsheet then calculates the design storm intensity and the design peak storm water runoff rate.

The results are: **$i = 3.45 \text{ in/hr}$** and **$Q = 28.5 \text{ cfs}$**

Note that these values are similar to, but not exactly the same as the values of **i** and **Q** obtained by the other two procedures. For comparison the **i** and **Q** values obtained by three different procedures are shown below.

Example #14 (i calculated from storm precipitation read from IDF graph):

$$i = 3.61 \text{ in/hr} \quad Q = 29.7 \text{ cfs}$$

Examples #15 & 16 (i calculated using linear regression equation with course spreadsheet)

$$i = 3.78 \text{ in/hr} \quad Q = 31.2 \text{ cfs}$$

Example #17 (i calculated using the Steel equation):

$$i = 3.45 \text{ in/hr} \quad Q = 28.5 \text{ cfs}$$

Calculation of Design Rainfall Intensity and Peak Storm Water Runoff Rate - U.S. units			
Using the STEEL equation ($i = a/(d + b)$)			
Instructions: Enter values in blue boxes. Spreadsheet calculates values in yellow boxes			
Inputs			
Drainage Area, A =	25	acres	Runoff Coefficient, C = 0.33
Design Return Period =	25	years	Design Storm Duration, d = 36.6 min (= time of concentration)
Enter the Steel Equation constants (a & b) for your region of the U.S. (or a location with comparable rainfall characteristics) and the design return period - from the table on the facing page:			
Steel constant, a =	230		
Steel constant, b =	30		
Calculations			
Design Intensity, i =	3.45	in/hr	[$i = a/(d + b)$]
Calculation of Design Peak Storm Water Runoff Rate, Q, using the equation: $Q = CiA$			
Design Peak Storm Water Runoff Rate, Q =	28.5	cfs	

10. Summary

The Rational Method equation, $Q = CiA$, is widely used to calculate peak storm water runoff rate for a variety of storm water management applications. As described in this course, Excel spreadsheets can be useful for calculation of the watershed time of concentration (used as duration of design storm); to prepare an equation for design storm intensity as a function of storm duration by linear regression, and to calculate the peak storm water runoff rate. Calculation of the design storm intensity with the Steel equation can also be conveniently done with a spreadsheet. Numerous example calculations and solutions using the spreadsheet included with the course were presented and discussed.

11. References

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Rational Method Hydrological Calculations with Excel - Quiz

Updated: 3/13/2018

1. What are the units for the peak storm water runoff rate, as calculated with the Rational Method equation using the normal U.S. units for A & i ?

- a. gpm
- b. gph
- acre-ft/hr
- cfs

2. Calculate the peak storm water runoff rate from a watershed of 20 ha, with a runoff coefficient of 0.42, due to a storm of intensity 85 mm/hr

- 5. 714 cfs
- 6. 4.5 m³/s
- 7. 2.0 m³/s
- 8. 0.88 m³/s

3. A soil with a measured minimum infiltration rate of 0.25 in/hr is in which of the four SCS soil groups?

- Group A
- Group B
- Group C
- Group D

4. A shallow sandy loam soil that is low in organic content is in which of the four SCS soil groups?

- Group A
- Group B
- Group C
- Group D

5. The time of concentration for a watershed is the time required for rainfall landing on the farthest point in the watershed to reach the watershed outlet.

- True
- False

6. What is the value of the runoff coefficient to be used in Rational Method calculations for a meadow, soil group B, 1.6% slope?

- e. 0.20
- f. 0.28
- g. 0.23
- h. 0.10

7. Which of the following is most suitable for calculating travel time for overland sheet flow?

- m) The NRCS Method
- n) The Manning Equation
- o) The Hazen Williams Equation
- p) The Manning Kinematic Equation

8. What value of the Manning roughness coefficient should be used for overland sheet flow on natural range?

- 6 0.13
- 7 0.41
- 8 0.40
- 9 0.15

9. Calculate the shallow concentrated flow velocity in ft/sec by the NRCS method, for a paved surface with a slope of 0.00074

- i. 0.17
- j. 0.44
- k. 0.55
- l. 0.66

10. The duration of the design storm for determining rainfall intensity to use in the Rational Method should always be the travel time for overland sheet flow.

- True
- False

11. What is the value of the runoff curve number to be used in the SCS Lag Equation for cultivated agricultural land with straight row crops, good hydrologic condition, and soil group B?

- a. 86
- b. 81
- c. 78
- d. 74

12. Calculate the peak storm water runoff rate from a watershed with an area of 25 acres, with a runoff coefficient of 0.42, from a design storm of intensity 1.9 in/hr.

- a. 18 cfs
- b. 21 cfs
- c. 19 cfs
- d. 20 cfs

13. The FAA equation is most suitable for calculating the time of concentration for which of the following?

- a. small watersheds where sheet flow and overland flow predominate
- b. large agricultural watersheds
- c. watersheds having watercourses less than 12 feet, slopes less than 1%, and areas less than 10 acres
- d. small agricultural watersheds with channel flow

14. The SCS Lag equation is most suitable for calculating the time of concentration for which of the following?

- a. small urban watersheds
- b. airfields
- c. large urban watersheds
- d. rural watersheds

15. The NRCS method for estimating watershed time of concentration subdivides the watershed into three portions, an overland flow portion, a concentrated flow portion, and a channel flow portion.

- a. True
- b. False