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Rational Method Hydrologic Calculations with Excel 2

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Rational Method Hydrologic Calculations with Excel

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COURSE CONTENT

1. Introduction

Calculation of peak storm water runoff rate from a drainage area is often done with the Rational Method equation ($Q = CiA$). Use of Excel spreadsheets for calculations with this equation and for determination of the design rainfall intensity and the time of concentration of the drainage area, are included in this course. The parameters in the equations are defined with typical units for both U.S. and S.I. units.



Drainage Areas and Surface Runoff

Image Credit: [Virginia Cooperative Extension](#)

2. Learning Objectives

At the conclusion of this course, the student will

- Know the parameters and their U.S. and S.I. units to be used in the Rational Method equation
- Be able to calculate peak storm water runoff rate with the Rational Method equation, using either U.S. or S.I. units
- Be able to place a given soil into one of the four SCS soil groups based on its measured minimum infiltration rate
- Be able to place a given soil into one of the four SCS soil groups based on its description
- Be able to determine a value of the Rational Method runoff coefficient based on land use, soil group, and slope of the watershed
- Be able to calculate the overland sheet flow travel time for a watershed using the Manning Kinematic equation
- Be able to calculate the shallow concentrated flow travel time for a watershed using the NRCS method
- Be able to calculate the open channel flow travel time for a watershed using the Manning equation
- Know the form of the equation used for rainfall intensity as a function of storm duration for a specified return period.
- 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
- IV. Design Rainfall Intensity
- V. Peak Storm Water Runoff Rate Calculations
- VI. Summary
- VII. 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:

- **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)
- **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)
- **i** = the intensity of the design storm for peak runoff calculation (**in/hr** for U.S. units) (**mm/hr** for S.I. units)
- **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 stormwater 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: $Q = (0.35)(2.4)(15) = \underline{\underline{12.6 \text{ cfs}}}$

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, it must have a value 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:

- Group A 0.30 – 0.45 in/hr
- Group B 0.15 – 0.30 in/hr
- Group C 0.05 – 0.15 in/hr
- Group D 0 – 0.05 in/hr

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

- Group A Deep sand; deep loess; aggregated soils
- Group B Shallow loess; sandy loam
- 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).

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>

Example #2: What is the value of the runoff coefficient to be used in Rational Method equation calculations, for a residential area with ¼ acre lots, soil group B, and slope of approximately 1.4% ?

Solution: From Part I of the Runoff Coefficient Table above, **C = 0.33**

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. This is because a storm of duration less than the time of concentration will never have all of the watershed contributing flow 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 the same recurrence interval, will be less intense.

Estimating Time of Concentration: Many empirical equations are available for calculating time of concentration for a watershed. Three that are in widespread use will be discussed in this course. The **Manning Kinematic equation** will be discussed for overland sheet flow. The **NRCS method** will be used for shallow concentrated flow. Finally, the **Manning equation** will be discussed for flow in a channel.

The **Manning Kinematic equation** is shown below for both U.S. and S.I. units:

$$t_1 = \frac{0.42 (nL)^{0.8}}{P^{0.5} S^{0.4}}$$

Manning Kinematic
Equation - U.S. units

$$t_1 = \frac{5.48 (nL)^{0.8}}{P^{0.5} S^{0.4}}$$

Manning Kinematic
Equation - S.I. units

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

- t_1 is the travel time for overland sheet flow (min 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 #3: What would be 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 $t_1 = [0.42(0.15*75)^{0.8}]/[5^{0.5}*0.0004^{0.4}] = \underline{\underline{30.7 \text{ min}}}$

The **NRCS 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 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 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
- $t_2 = L/(60V)$

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
- $t_2 = L/(60V)$

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

- t_2 = 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 #4: 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: $V = 16.135 (0.0004)^{0.5} = 0.3227$ ft/sec. Then:
 $t_2 = L/(60V) = 105/(60*0.3227) = \underline{\underline{5.4 \text{ min}}}$

The image on the next page shows part of an Excel spreadsheet that will calculate the overland sheet flow travel time with the Manning Kinematic Equation and the shallow concentrated flow time with the NRCS Method based on input information about the watershed. A spreadsheet to make this type of calculation is available for low cost download at www.engineeringexceltemplates.com. You don't need to download the spreadsheet, however, to complete this course and take the exam.

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 Coefficient, n =	0.15	Ground Slope, S =	0.0004
Calculations			
Length of Flow Path, L =	75 ft	Overland Flow Time	
2 yr, 24 hr rainfall, P =	5 in	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	For unpaved surface:	
Ground Slope, S =	0.0004	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

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 method 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 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 = $t_3 = L/(60V)$ for either U.S. or S.I. units

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

- t_3 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 (ft² – U.S. or m² – 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 #5: 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 t₃ as follows:

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

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

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

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

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

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

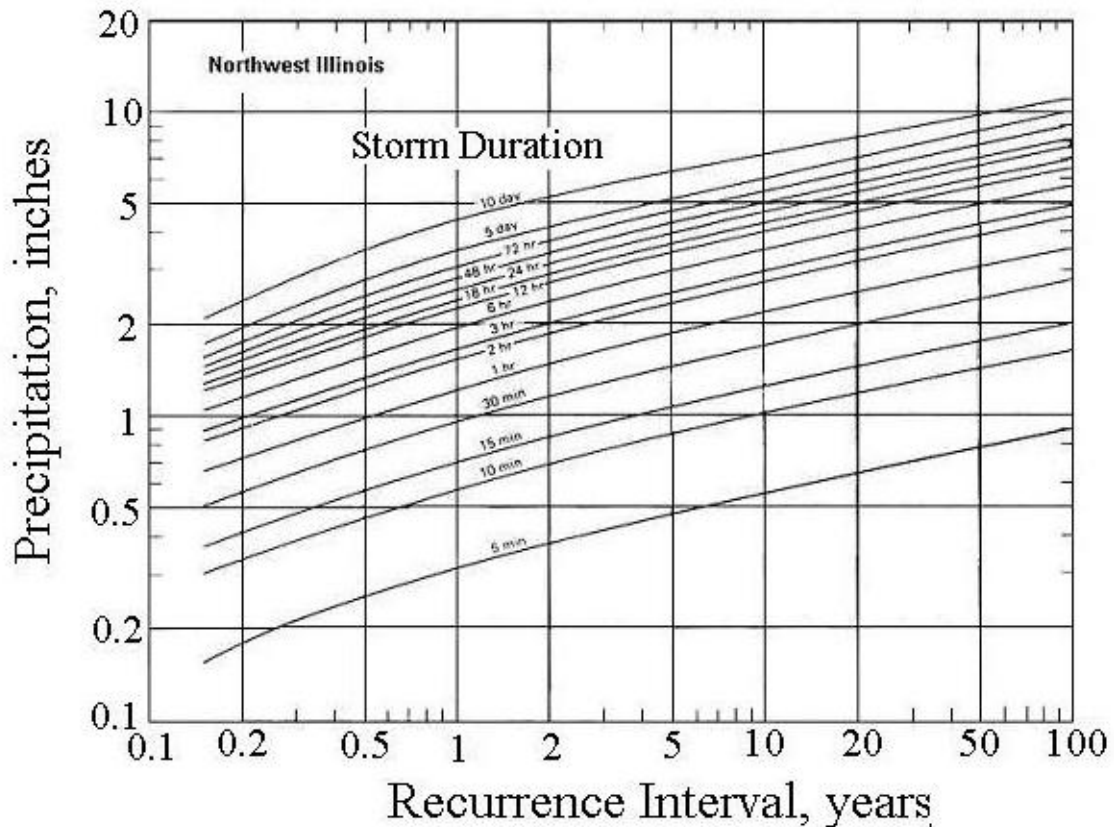
These calculations can be conveniently done with an Excel spreadsheet as shown in the image on the next page. It shows another part of the Excel spreadsheet above. This part calculates the travel time for the open channel flow part of the storm water runoff using the Manning equation. Calculation of the overall time of concentration is also shown on this part of the spreadsheet. This overall spreadsheet for calculation of time of concentration is available at the [link mentioned above](#). As stated before, you don't need to download the spreadsheet to complete this course and take the exam.

Calculation of Channel Flow Travel Time			
Using the Manning Equation - U.S. units			
For a Trapezoidal Channel Cross-section			
<u>Inputs</u>		<u>Calculations</u>	
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 = (H:V = z:1)	3		Hydraulic Radius, R = 0.70 ft
Manning roughness, n =	0.022		Discharge, Q = 6.22 cfs
Channel bottom slope, S =	0.0003	ft/ft	Ave. Velocity, V = 0.925 ft/sec
Length of Flow Path, L =	75	ft	Channel travel time, t₃ = 1.4 min
Calculation of Time of Concentration			
(t _c = t ₁ + t ₂ + t ₃)			
<u>Inputs (values from above)</u>		<u>Calculations</u>	
t ₁ =	30.7	min	t _c = 37.5 min
t ₂ =	5.4	min	
t ₃ =	1.4	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 some 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 an 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, one of the form: $i = a/(d + b)$ 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:

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

The image below shows an Excel spreadsheet set up to carry out a linear regression of $1/i$ vs d , using input values for i vs d from available IDF data. The slope and intercept from the linear regression are used to calculate the constants a and b . Then the equation $i = a/(d + b)$ can be used to calculate design rainfall intensity, i , for any desired storm duration, d , at the same return period as that used to obtain the values for a and b .

8. Peak Storm Water Runoff Rate Calculation

The spreadsheet shown on the next page (available from the [link mentioned above](#)) will also calculate the peak storm water runoff rate, using the calculated design rainfall intensity, i , and specified watershed drainage area, A , and runoff coefficient, C , in the Rational Method equation: $Q = CiA$.

	A	B	C	D	E	F	G	H	I	J	
1	Calculation of Design Rainfall Intensity										
2	and Peak Storm Water Runoff Rate - U.S. units										
3	(for specified return period and storm duration)										
4	Inputs										
5											
6	Drainage Area, A =		25		acres		Runoff Coefficient, C =		0.35		
7											
8	Design Return Period =		15		years		Design Storm Duration, d =		22 min		
9	(= time of concentration)										
10											
11	Data from IDF (intensity-duration-frequency)					Calculation of equation constants (a & b)					
12	graph or table for the design location:					using linear regression:					
13											
14	Input		Input		Calculated						
15	i, in/hr		d, min		1/i, hr/in		slope =		0.005248 = 1/a		
16											
17	7.38		10		0.14		a = 1/slope =		191		
18	6.04		15		0.17						
19	4.14		30		0.24		intercept =		0.0847 = b/a		
20											
21									b = a*intercept =		16.1
22											
23	Calculation of Design Rainfall Intensity, i, using the equation: $i = a/(d + b)$:										
24	(using the value for storm duration, d, specified above)										
25											
26	Design Rainfall Intensity, i =								5.00		in/hr
27											
28	Calculation of Design Peak Storm Water Runoff Rate, Q, using the equation: $Q = CiA$										
29											
30	Design Peak Storm Water Runoff Rate, Q =								43.7		cfs
31											

9. 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.

10. References

1. McCuen, Richard H., *Hydrologic Analysis and Design, 2nd Ed*, Upper Saddle River, NJ, 1998.
2. Knox County Tennessee, [Stormwater Management Manual, section on the Rational Method](#)
3. U.S. [Soil](#) Conservation Service, [Technical Note - Hydrology No N4](#), June 17, 1986.
4. Iowa Stormwater Management Manual, [Section on Time of Concentration](#).
5. Illinois State Water Survey, [Bulletin 70](#).