Hydraulic Design of Storm Sewers Using Excel

Course No: C04-014

Credit: 4 PDH

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COURSE CONTENT

1.   Introduction

Storm sewers are widely used to carry away runoff from storms, primarily in urban areas. The hydraulic design begins after the location of the manholes for the system has been determined. Between each pair of manholes the storm sewer will have a constant slope and diameter. The hydraulic design process results in determination of an appropriate diameter and slope for each length of storm sewer and determines the depth of the bottom of the pipe at each manhole. The overall procedure and each step will be presented and discussed. Example calculations for a single length of storm sewer between two manholes will be performed and an example of calculations between successive manholes will be done using Excel.

This course is intended for civil engineers, hydraulic engineers, highway engineers, environmental engineers, and hydrologists. After completing this course you will be able to carry out hydraulic design of storm sewers to determine diameter, slope and depth of invert at each manhole for the length of storm sewer between two successive manholes. Also, after completing this course, you will also be able to set up an Excel program to carry out hydraulic design for successive lengths of storm sewer.

2.   Learning Objectives

At the conclusion of this course, the student will

- Be able to determine the value for runoff coefficient for a drainage area with known land use, SCS soil group, and approximate surface slope.

- Be able to find the rainfall intensity for specified storm duration and return period at a specified location if given an I-D-F table or graph for that location.

- Be able to estimate the overland flow travel time for a drainage area using the Manning Kinetic Equation.

- Be able to estimate channel flow travel time using Manning's Open Channel Flow Equation.

- Be able to estimate peak runoff rate from a drainage area using the Rational Method.

- Be able to use Method I and Method II as outlined in this course to calculate design diameter and slope for a length of storm sewer between two successive manholes.

- Be able to determine the velocity and flow rate in a circular pipe flowing partially full if enough information is available to calculate the full pipe velocity and flow rate.

- Be able to put together the above skills to carry out the overall hydraulic design of a length of storm sewer between two successive manholes.

- Be able to use Excel to make storm sewer hydraulic design calculations for lengths of storm sewer between successive manholes.
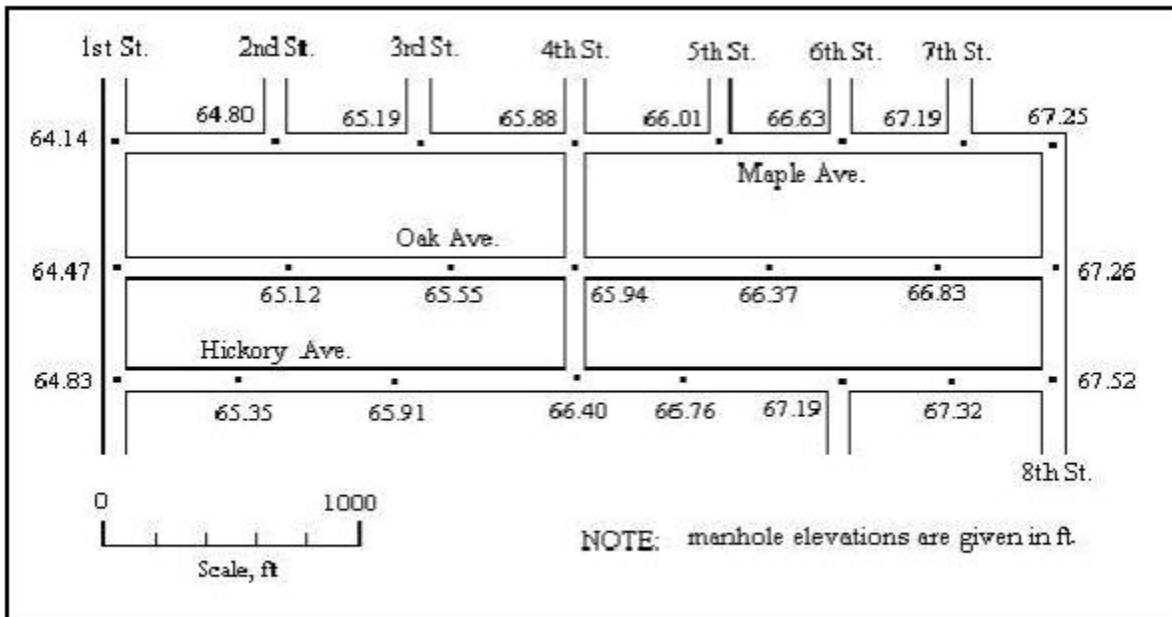
3.   Course Outline

1.   Example Manhole Layout and Sectional View

2. Overview of Hydraulic Design for Storm Sewers

3. Determination of Q_{des}, the Design Flow Rate – the Rational Method

    a) Drainage Area, A
    b) Runoff Coefficient, C

4.   Example Manhole Layout and Sectional View

As mentioned above, the hydraulic design begins after the locations of the manholes have been determined. Also the surface elevation at each manhole will be needed. Figure 1 shows an example street map with manhole locations and surface elevation at each manhole. This is the type of starting information that will be assumed for the hydraulic design, as discussed in this course. Figure 1 will be used as the manhole layout for the examples worked in this course.

Figure 2 shows a sectional view of a storm sewer line between two manholes. The parameters to be determined by the hydraulic design are shown in the figure: i) the diameter of the pipe, D, ii) the slope of the pipe, S, and iii) the depth needed for the trench at each manhole location, depth #1 and depth #2. The design flow rate for this length of pipe, Q_{des}, shown in the diagram, plays an important role in the calculations.

	1st St.	2nd St.	3rd St.	4th St.	5th St.	6th St.	7th St.	

64.14

64.80   65.19   65.88   66.01   66.63   67.19   67.25

Maple Ave.

Oak Ave.

64.47

65.12   65.55   65.94   66.37   66.83   67.26

Hickory Ave.

64.83

65.35   65.91   66.40   66.76   67.19   67.32   67.52

8th St.

0 ——— 1000

Scale, ft

NOTE: manhole elevations are given in ft.

drawn by H. Bengtson

Figure 1. Example Storm Sewer Manhole Layout Map

manhole #1

manhole #2

Ground Surface

depth #1

depth #2
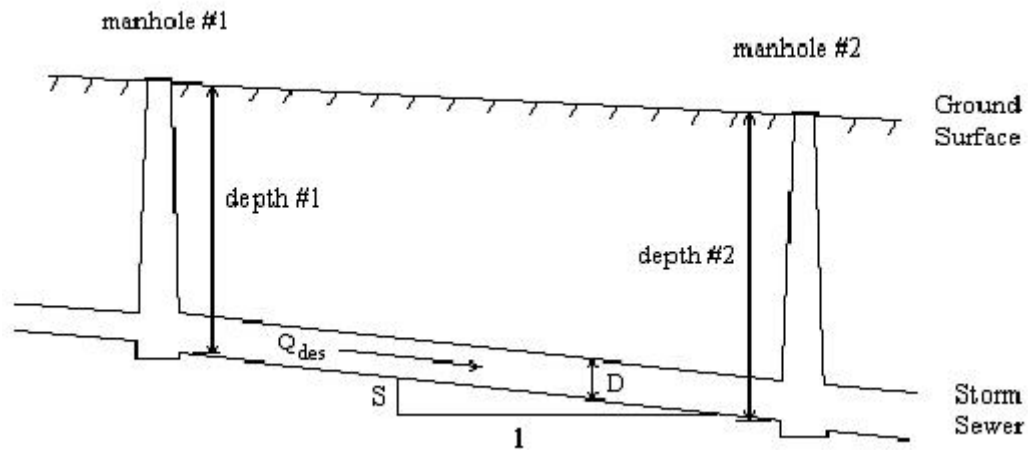
Q_{des}

S

D

1

Storm Sewer

Figure 2. Sectional View of Storm Sewer between Two Manholes

4

5. Overview of Hydraulic Design for Storm Sewers

The first step in the hydraulic design of a length of storm sewer is typically determination of a design flowrate for that length of pipe. This is the main area of difference between storm sewer design and sanitary sewer design. For sanitary sewers the design flow rate is based on the number and types of connections to the sewer line (residential, commercial, industrial, etc.) For storm sewers the design flow rate is based on the runoff from a design storm for the site of the storm sewer system. Determination of Q_{des}, will be covered in the next section of this course. Once Q_{des}, is known, specified design criteria will be used to find a diameter and slope for the pipe and depth below the surface that will give i) adequate cover for freeze protection and structural stability, ii) adequate velocity to avoid sediment collecting in the line and iii) adequate capacity to carry the flow rate, Q_{des}, with out backing up storm water in the manholes. The determination of the diameter, slope, and depth of the pipe will be covered in section 5 of this course.

6. Determination of Q_{des}, the Design Flow Rate – The Rational Method

The Rational Method is widely used for determining design flow rate in storm sewer design. The Rational Equation, and estimation of its parameters to calculate Q, will be covered here because of its key role in hydraulic design of storm sewers. The Rational Method is used for other purposes also, especially with relatively small drainage areas.

The equation for the Rational Method is: $\mathbf{Q = C\,i\,A}$ (1)

Where: Q is the peak runoff rate for a specified return period, cfs*

C is the runoff coefficient that is the fraction of rainfall which becomes runoff. The value of C is dependent upon the land use of the drainage area. It is dimensionless

i is the design rainfall intensity, in/hr

A is the drainage area, acres

*The units for Q are actually acre-in/hr, but the conversion factor from acre-in/hr to cfs is very nearly one.

The Rational Method is most suitable for relatively impervious area without surface storage, such as ponds or swamps. The recommended maximum drainage area is 100 acres. These criteria are typically met for storm sewer drainage areas.

Drainage Area, A: In order to calculate the peak runoff rate for hydraulic design of the storm sewer pipe from equation (1), values are needed for C, i, and A. The easiest of the three is usually the drainage area, A. This area can be determined from a scale map such as Figure 1. For a developed area, such as that depicted in Figure 1, the lots are typically landscaped to allow surface runoff from the back of the lot to the street. Determination of drainage area for each inlet, using this assumption, will be illustrated in examples, in sections 6 and 7. For a less developed area, it may be necessary to use a map with surface elevation contours on it, to identify the drainage area for each inlet to the storm sewer system.

Runoff Coefficient, C: There are many tables available for runoff coefficient, C, as a function of the land use of the drainage area. Many state and local agencies have stormwater management manuals with such tables in them. Table 3 and Table 4, given below, are an example from the Knox County Tennessee *Stormwater Management Manual*.   The section of the manual containing information on the Rational Method, including Tables 3 and 4, is available on the internet at:

http://www.knoxcounty.org/stormwater/pdfs/vol2/3-1-3%20Rational%20Method.pdf.

Soil Conservation Service (SCS) has identified four soil groups, A, B, C, & D, which are often used in determination of a value for runoff coefficient, C. There are three ways to determine the soil group present in a particular drainage area:

i)   from the soil characteristics (see Table 1, below),

ii)   from measured minimum infiltration rate (see Table 2, below),

iii)   from county soil surveys available from the appropriate SCS district.

Table 1. Characteristics of SCS Soil Groups

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**

Table 2. Minimum Infiltration Rates for SCS Soil Groups

SCS Soil Group	Min. Infiltration Rate, in/hr
A	0.30 - 0.45
B	0.15 - 0.30
C	0.05 - 0.15
D	0 - 0.05

Tables 3 and 4 give C as a function of land use, average slope, and Soil Conservation Service (SCS) soil group,

Table 3. Rational Method Runoff Coefficients – Part 1

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

Table 4. Rational Method Runoff Coefficients – Part 2

| | Runoff Coefficient (C) | | | | | |
| | Soil Group C | | | Soil Group D | | |
Slope:	<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

Example #1: Determine the runoff coefficient to use for an area with ½ acre residential lots with sandy loam soil and average surface slopes less than 2%.

Solution: From Table 1, sandy loam would be Soil Group B. From Table 3, the runoff coefficient for Soil Group B, slope < 2%, and Res. ½ acre is: **C = 0.28**

Design Rainfall Intensity, i: Design rainfall intensity, i, is the intensity of a **constant intensity design storm** with duration equal to the **time of concentration**

and with the **design return period**. The terms in bold will be reviewed briefly along with a review of **intensity-duration frequency** relationships for rainfall.
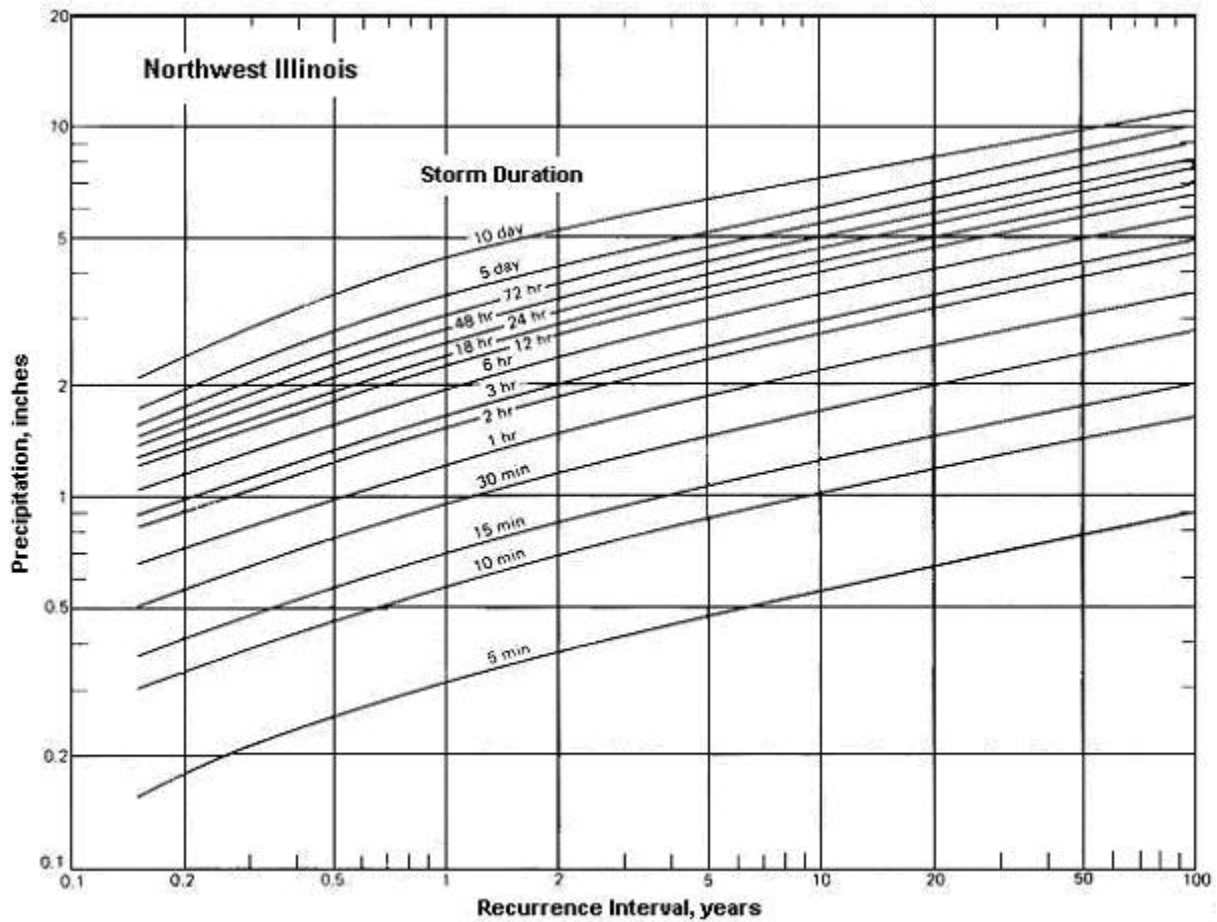

Design Return Period: The **return period** for a hydrological event of given magnitude at a given location, is the average length of time between occurrences of the hydrological event at the given magnitude or greater at that location. For example, if 2 inches of rainfall in a 30 minute period has a 20 year return period at a given location, then 2 inches or more of rainfall should occur within a 30 minute period once every 20 years on the average at the given location. Or, as another example, if the 50 year flow rate of a given river at a given location is 100 cfs, then that river should flow at 100 cfs or more only once every 50 years on the average at that location. The **design return period** to be used for storm sewer design is typically specified by a state or local agency. For example, Knox County Tennessee in its *Stormwater Management Manual*, specifies a return period of 25 years for storm sewer pipe design in section 2.5.

Intensity-Duration-Frequency (**I-D-F**) Relationship: Intensity, duration and frequency are interrelated for precipitation events at a given location. In general, for a given duration, longer return period storms will be of greater intensity than shorter return period storms. Also, for a given return period, shorter duration storms will have a greater intensity than longer duration storms. In particular, for example, the average intensity of a 50 year storm of 10 minutes duration will be greater than the average intensity of a 50 year, 30 minute duration storm. A typical pattern for the relationship among intensity, duration and frequency is shown in Figure 3, which is for northwest Illinois. It is one of ten such figures for ten sections of Illinois, from the Illinois State Water Survey, *Bulletin 70*, which is available on the internet at: http://www.isws.illinois.edu/atmos/statecli/RF/rf.htm.   A graph such as Figure 3 helps one to see the pattern of the relationships among the three parameters, intensity, duration, and frequency, but a table such as Table 5 is more useful for obtaining accurate values for one of the parameters if the other two are known or specified. Figure 3 and Table 5 both have IDF data for northwest Illinois, which will be used as the location for the examples worked in this course.

Illinois State Water Survey *Bulletin 70* is the prescribed source of I-D-F data for the state of Illinois. *Bulletin 71* and a link to the U.S. Weather Bureau site with

national I-D-F data are also available at the Illinois State Water Survey website given above.   I-D-F data is available for most states from some state agency.

Figure 3. Intensity-Duration-Frequency Graph for
Precipitation in Northwest Illinois

Example #2: What is the amount of rainfall in inches and the average intensity (in in/hr) of a 25 year storm of 10 minutes duration in northwest Illinois?

Solution: From Figure 3, one can see that the rainfall amount for the 10 minute, 25 year storm is between 1 inch and 2 inches, but it is difficult to read the graph

accurately. From Table 5 (section 01), the 10 minute duration, 25 year rainfall amount can be read directly as: **1.23 inches.** The average intensity can then be calculated as the rainfall amount divided by the duration of the storm:

$$i = 1.23 \text{ in}/(10/60) \text{ hr} = \textbf{7.38 in/hr} = \textbf{i}$$

Table 5. Example I-D-F Data (A Portion of Table 13 from Illinois State Water Survey *Bulletin 70*)

Mean Frequency Distribution of Rainfall Amount in inches for Storm Periods of 5 minutes to 10 days, and Recurrence Intervals of 6 months to 100 Years in Illinois by Sections

Sectional code

01 - Northwest	06 - West Southwest
02 - Northeast	07 - East Southeast
03 - West	08 - Southwest
04 - Central	09 - Southeast
05 - East	10 - South

Section	Duration	6-month	9-month	1-year	2-year	5-year	10-year	25-year	50-year	100-year
01	10-day	3.50	4.02	4.37	5.23	6.30	7.14	8.39	9.64	11.09
01	5-day	2.76	3.17	3.45	4.13	5.10	5.91	7.21	8.36	9.97
01	72-hr	2.45	2.82	3.06	3.73	4.67	5.42	6.59	7.64	8.87
01	48-hr	2.24	2.58	2.80	3.42	4.28	4.96	6.07	7.02	8.07
01	24-hr	2.08	2.36	2.57	3.11	3.95	4.63	5.60	6.53	7.36
01	18-hr	1.92	2.18	2.37	2.86	3.63	4.26	5.15	6.01	6.92
01	12-hr	1.81	2.06	2.24	2.71	3.43	4.00	4.86	5.66	6.51
01	6-hr	1.56	1.77	1.93	2.33	2.96	3.48	4.20	4.90	5.69
01	3-hr	1.33	1.52	1.65	1.99	2.53	2.97	3.59	4.18	4.90
01	2-hr	1.23	1.40	1.52	1.83	2.33	2.74	3.31	3.86	4.47
01	1-hr	0.98	1.11	1.21	1.46	1.86	2.18	2.63	3.07	3.51
01	30-min	0.77	0.87	0.95	1.15	1.46	1.71	2.07	2.42	2.77
01	15-min	0.57	0.64	0.70	0.84	1.07	1.25	1.51	1.76	1.99
01	10-min	0.46	0.52	0.57	0.66	0.87	1.02	1.23	1.44	1.62
01	5-min	0.25	0.29	0.31	0.37	0.47	0.56	0.67	0.78	0.89
02	10-day	3.30	3.79	4.12	4.95	6.04	6.89	8.18	9.38	11.14
02	5-day	2.60	2.99	3.25	3.93	4.91	5.70	6.93	8.04	9.96
02	72-hr	2.34	2.70	2.93	3.55	4.44	5.18	6.32	7.41	8.78
02	48-hr	2.18	2.49	2.70	3.30	4.09	4.81	5.88	6.84	8.16
02	24-hr	2.03	2.31	2.51	3.04	3.80	4.47	5.51	6.46	7.56
02	18-hr	1.86	2.12	2.30	2.79	3.50	4.11	5.06	5.95	6.97
02	12-hr	1.77	2.01	2.18	2.64	3.31	3.89	4.79	5.62	6.59
02	6-hr	1.52	1.74	1.88	2.28	2.85	3.35	4.13	4.85	5.68
02	3-hr	1.30	1.47	1.60	1.94	2.43	2.86	3.53	4.14	4.85
02	2-hr	1.20	1.36	1.48	1.79	2.24	2.64	3.25	3.82	4.47
02	1-hr	0.96	1.09	1.18	1.43	1.79	2.10	2.59	3.04	3.56
02	30-min	0.75	0.86	0.93	1.12	1.41	1.65	2.04	2.39	2.80
02	15-min	0.55	0.63	0.68	0.82	1.03	1.21	1.49	1.75	2.05
02	10-min	0.45	0.51	0.55	0.67	0.84	0.98	1.21	1.42	1.67
02	5-min	0.24	0.28	0.30	0.36	0.46	0.54	0.66	0.78	0.91

Time of Concentration, t_c: The **time of concentration** (t_c) for a drainage area is the time required for runoff from the hydrologically farthest point of the drainage area to reach its outlet. First, the rationale for using t_c as the storm duration for calculating peak runoff rate will be discussed, then methods for estimating t_c for a given drainage area will be considered.

For the short duration storms being considered here, they are typically assumed to be constant intensity for the entire storm duration. Hence the term, **constant intensity design storm** is derived. Consider the case of a storm with duration less than t_c. In this case, runoff will never come from the entire drainage area. By the time the runoff from the farthest points of the drainage area reaches the outlet, rain will no longer be falling, and the land closest to the outlet will no longer be contributing runoff.

If the storm duration is longer than t_c, then runoff from then entire drainage area will reach the outlet before the storm ends, but the intensity of the storm will be less than that for a storm of lesser duration (e.g. t_c) with the same return period. Hence the maximum peak runoff rate (for a specified return period) will be from a storm of duration t_c, for which the entire drainage area will be draining to the outlet (and the peak runoff rate will occur) just before the storm ends.

Estimation of Time of Concentration: There are many methods available for estimating time of concentration for a drainage area. Many state and local agencies specify the method(s) to be used in their jurisdiction. Two of the methods will be discussed and illustrated with examples here. They are the Manning's Equation for channel flow and the Manning Kinematic Equation for overland flow.

The Manning Kinematic Equation is presented in Soil Conservation Service, *Technical Note - Hydrology No N4*, which is available on the internet at: http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Tools_Models/WinTR55.html.

The equation is:

$$t = \frac{0.007\,(nL)^{0.8}}{P_2^{0.5}\,S^{0.4}} \tag{2}$$

Where: t = runoff travel time in hr

n = Manning roughness coefficient (empirical constant), dimensionless

L = length of the flow path in ft

P_2 = 2 year, 24 hour rainfall in inches

S = ground slope in ft/ft

Manning's Equation for open channel flow is widely used for many types of open channel flow. For determination of time of concentration, it is useful for portions of the flow such as gutter flow and gravity flow in the circular sewer pipes. Manning's Equation is:

$$V = \frac{1.49}{n}\,R_h^{2/3}\,S^{1/2} \tag{3}$$

Where: V = velocity of runoff flow, ft/sec

S = the constant bottom slope of the channel, ft/ft

n = Manning Roughness coefficient (empirical constant), dimensionless

R_h = hydraulic radius = A/P

Where: A = cross-sectional area normal to the flow direction, ft^2

P = wetted perimeter of the cross-sectional area of flow, ft

Equation (3) gives velocity for the runoff flow, not travel time. The travel time can then be calculated from equation (4) below:

$$t = \frac{L}{60V} \tag{4}$$

Where: L = length of flow path in ft

V = velocity of the runoff flow in ft/sec

t = runoff travel time in minutes

The time of concentration, t_c, is the total time for runoff to travel from the hydrologically farthest point of the drainage area to the outlet. It may be made up of several components of travel time calculated from equation (2) and/or equations (3) and (4). In that case t_c would be calculated by summing all of the component travel times as shown in equation (5) below:

$$t_c, = t_1 + t_2 + \ldots + t_n \tag{5}$$

Values for the Manning roughness coefficient, n, are widely available. Most state and local agencies include one or more tables of values for n in their stormwater guidelines. Table 6 below gives typical values of n for a variety of surfaces.

Table 6. Manning's Roughness Coefficient (n) for Overland Flow Surfaces

Surface	n
Plastic, glass	0.009
Bare sand	0.010
Graveled surface	0.012

Smooth concrete	0.011
Asphalt or bare clay	0.012
Ordinary concrete lining	0.013
Vitrified clay	0.015
Cast iron	0.015
Smooth earth	0.018
Corrugated metal pipe	0.023
Short grass	0.15
Dense grass	0.24
Bermudagrass	0.41
Woods, no underbrush	0.20
Woods, light underbrush	0.40
Woods, dense underbrush	0.80
Rangeland	0.13

Example #3:   The runoff flow path for an area draining to a particular storm sewer inlet, has 120 ft of overland flow over short grass with a surface slope of 0.009 and then 400 ft of gutter flow with a slope of 0.0008. Estimate the time of concentration for this drainage area if it is located in northwestern Illinois.

Solution: Manning's Kinematic Equation [equation (2)] will be used for the overland flow portion, where:

L = 120 ft   and   S = 0.009   (given)

P_2 = 3.11 inches, from Table 5

n = 0.15, from Table 6

Substituting values into equation (2) gives the following:

$$t_1 = \frac{0.007\,[(0.15)(120)]^{0.8}}{3.11^{0.5}\,0.009^{0.4}}$$

This calculation gives: t_1 = 0.2638 hr = 15.8 minutes

McCuen (reference #1 for this course) gives n = 0.011 and R_h = 0.2 for use in Manning's Equation for paved gutter flow.   Using these two values with S = 0.0008, in equation (3) gives the following:

$$V = \frac{1.49}{0.011}\,0.2^{2/3}0.0008^{1/2}$$

This calculation gives the gutter flow velocity: V = 1.310 ft/sec

The gutter travel time is then: t_2 = 400/[(60)(1.310) = 5.1 minutes

The time of concentration is then: t_1 + t_2 = 15.8 + 5.1 = **20.9 minutes = t_c**

Example #4: The drainage area in **Example #3** is 5.3 acres, made up of ½ acre residential lots. It is located in northwestern Illinois, has clay loam soil and has a surface slope less than 2%. What is the peak runoff rate from this drainage area for a 25 year return period?

Solution: Equation (1) [Q = C i A], will be used to calculate Q, the peak runoff rate, where the parameter values are:

A = **5.3** acres (given)

C = **0.31** from Table 4 (Soil Group C, < 2% slope, res. ½ acre)

i = the intensity for a 25 year storm of 20.9 minutes duration in northwestern Illinois

The value for i will be found from Table 5. The 25 year rainfall amounts for 15 minute and 30 minute storms can be found in the table. The intensity for each is then calculated by dividing rainfall amount by duration. Then the 20.9 minute intensity is found by interpolation. This is all summarized in the table below (all for 25 year return period, in northwestern Illinois:

duration, min	precipitation, in	intensity, in/hr
15	1.51	6.04
30	2.07	4.14
20.9		5.29

The intensity for a storm duration of 20.9 minutes was calculated as follows:

$$i = 6.04 - [(20.9 - 15)/(30 - 15)] (6.04 - 4.14) = \textbf{5.29 in/hr}$$

The values for C, i, and A can now be substituted into equation (1) to give:

$$Q = (0.31)(5.29)(5.3) = \textbf{\underline{8.69 cfs}} = \textbf{\underline{peak runoff rate}} \ (= Q_{des})$$

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7. Criteria and Procedure for Determining Diameter, Slope and Depth

Three general design criteria are typically used for the determination of diameter, slope and depth for a length of sewer pipe between two manholes. Those three criteria are:

i) $V_{full} \geq V_{min}$ with pipe diameter and slope at their design values

ii) $Q_{full} \geq Q_{des}$ with pipe diameter and slope at their design values

iii) depth from ground surface to top of pipe $\geq$ minimum cover

V_{full} and Q_{full} are the velocity and flow rate, respectively, when the sewer is flowing full with design diameter and slope for the pipe. V_{min} is the minimum velocity required in order to prevent accumulation of sediment in the pipe. This is prescribed by a state or local agency. A typical value for storm sewers is 3 ft/sec. $V_{min} = 3$ ft/sec will be used for the examples in this course. Q_{des} is the peak runoff rate calculated from the rational equation, as just illustrated in Example #4. Minimum cover, typically prescribed by a state or local agency, is set to keep the pipes below the frost line and to provide adequate structural stability for loads on the pipe. For the examples in this course, a minimum cover of 5 feet will be used.

The equations typically used for pipe slope and diameter are Manning's Equation for average velocity [equation (3)], Manning's Equation for flow rate, and a commonly used definition for average velocity. The latter two equations are:

$$Q = \frac{1.49}{n} A R_h^{2/3} S^{1/2} \qquad (6)$$

$$V = \frac{Q}{A} \qquad (7)$$

As indicated by the criteria, the sewer pipe is usually designed so that it will meet the design criteria when it is flowing full under gravity. For a circular pipe flowing full, the cross-sectional area normal to flow is: $A = \pi D^2/4$, and the wetted perimeter is: $P = \pi D$, so the hydraulic radius is:

$$R_h = A/P = (\pi D^2/4)/(\pi D) = D/4$$

Substituting for A & Rh in equations (3), (6), & (7) and solving equation (7) for Q, gives the following three design equations:

$$Q = \frac{\pi D^2}{4} V \tag{8}$$

$$V = \frac{1.49}{n} \left(\frac{D}{4}\right)^{2/3} S^{1/2} \tag{9}$$

$$Q = \frac{1.49}{n} \left(\frac{\pi D^2}{4}\right) \left(\frac{D}{4}\right)^{2/3} S^{1/2} \tag{10}$$

The calculations to determine diameter and slope for the sewer pipe can proceed in one of two ways, depending upon the slope of the ground surface. These two approaches will be called Method I and Method II.

Method I is used when the ground surface slope is shallow. In particular it is used when the surface slope is less than the pipe slope needed to give velocity in the pipe equal to V_{min}. In this case the calculations should proceed as follows:

i) calculate the pipe diameter, D, using equation (8) with $V = V_{min}$, and $Q = Q_{des}$

ii) calculate the pipe slope, S, for the next larger standard pipe size, using equation (9) with $V = V_{min}$

iii)   If the required slope from step ii) is too great, use a larger diameter pipe, and repeat step ii). If the required slope is too small to maintain minimum cover, use the Method II calculation procedure.

Method II is used for a steep ground surface slope. In particular it is used when the surface slope is greater than the pipe slope needed to give velocity in the pipe equal to V_{min}. In this case the calculations should proceed as follows:

i)   Set the pipe slope, S, equal to the ground surface slope.

ii)   calculate the pipe diameter, D, using equation (10), with $Q = Q_{des}$, and S = the slope just chosen in step i).

iii)   Choose the next larger standard pipe diameter.

vi)   Calculate V_{full}, using equation (9), and check to be sure that $V_{full} \geq V_{min}$. If not adjust the slope and repeat.

Standard pipe diameters are mentioned above for both Method I and Method II. Those standard diameters for most types of pipe used for storm sewers are:

4, 6, 8, 10, 12, 15, 18, 21, 24, 27, 30, 33, 36, 39, 42, 48, 54, 60 inches,

with 6" increments up to 180 inches.

These are nominal pipe sizes, but for the degree of accuracy in these calculations, it is typical to use the nominal size as the inside diameter for pipe sizing and for the outside diameter for calculating trench depth.

Example #5: For a sewer line between two manholes, $Q_{des} = 8.69$ cfs, $V_{min} = 3$ ft/sec, minimum cover = 5 ft, and ground surface slope = 0.0005. The Manning roughness coefficient for the pipe is 0.012. Determine an appropriate diameter and slope for that sewer pipe.

Solution: Try Method I first. i) Substituting 8.69 cfs and 3 ft/sec into equation (8), gives:

$$8.69 = (\pi D^2/4)(3)$$

Solving for D: $D = [(8.69)(4)/(3\pi)]^{1/2} = 1.9 \text{ ft} = 23.0 \text{ in}$

Choose the next larger standard pipe size: **D = 24 inches**

ii)   Substituting known values into equation (9), gives:

$$3 = (1.49/0.012)[(24/12)/4]^{2/3}(S^{1/2})$$

Solving for S: $S = \{[(3)(0.012)]/[(1.49)(0.5^{2/3})]\}^2 =$ **0.00147 = S**

Since the pipe slope is greater than the ground surface slope, minimum cover will be maintained if the upstream end of the pipe has at least the 5 ft required minimum cover. Thus the D and S values calculated will be ok.

Example #6: Consider all of the data in **Example #5** to remain the same, except that the ground surface slope is 0.0028. Determine an appropriate diameter and slope for that sewer pipe.

Solution: Assume that Method I was tried first, leading to the results above. It would then be noted that the required, pipe slope is less than the ground surface slope, so minimum cover would not be maintained if the upstream end of the pipe has only 5 ft of cover. Thus the Method II calculation procedure should be used as follows:

i) Set the pipe slope equal to the ground slope: **S = 0.0028**

ii) Substituting values for Q (8.69), n (0.012) and S (0.0028) into equation (10) gives the following:

$$8.69 = (1.49/0.012)(\pi/4)(D^2)(D/4)^{2/3}(0.0028^{1/2})$$

Solving for D: $D^{8/3} = [(8.69)(0.012)(4)(4^{2/3})]/[(1.49)(\pi)(0.0028^{1/2}) = 4.24$

$$D = 4.24^{3/8} = 1.72 \text{ ft} = 20.6 \text{ inches}$$

The next larger standard pipe size is **D = 21 inches**

Calculate $V_{full} = (1.49/0.012)[(21/12)/4]^{2/3}(0.0028^{1/2}) = 3.79$ ft/sec

Thus $V_{full} \geq V_{min}$, so the diameter and slope calculated above will be ok.

8.   Flow in Partially Full Circular Sewers

As illustrated in the previous section, calculations for the hydraulic design of storm sewers are typically made on the basis of the circular pipe flowing full. The storm sewer pipe will actually flow less than full much of the time, however, with storms of lesser intensity than the design storm. **The primary purpose of this section is to present a method for calculating flow rate and velocity for a circular pipe flowing partially full when the flow rate and velocity for full pipe flow are known, and to briefly discuss the implications of storm sewers flowing partially full with respect to the design criterion of maintaining a minimum velocity to prevent sediment accumulating in the pipes.** (Note comment at end of section)

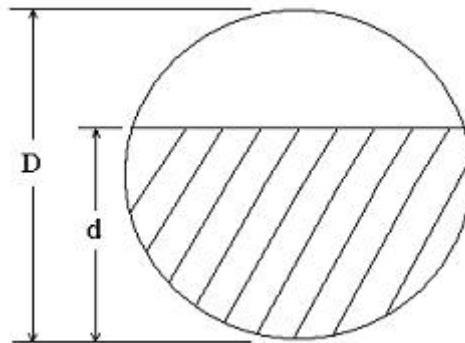Figure 4 below, shows the depth of flow, d, and the diameter, D, for a circular pipe flowing partially full.

Figure 4. Depth of Flow, d, and Diameter, D, for Partially Full Pipe Flow

Figure 5 below can be used to estimate the velocity of flow, V, and flow rate, Q, for a circular pipe flowing partially full, with known values for d, D, V_{full} and Q_{full}. For a length of storm sewer pipe with known D and S, V_{full} and Q_{full} can be calculated from equations (9) and (10).

The original source for Figure 5 is ref #4 in the list at the end of this course (Camp, 1946). Readings from a similar figure in Steel & McGhee (ref #5) were used to construct Figure 5.

A few comments about Figure 5 are in order. Note the graph at the top of the figure that shows variation in n/n_{full} as a function of d/D. This variation of Manning roughness, n, with depth of flow would not be intuitively expected, and is not, in fact, based on measurement of the roughness, n, itself. Rather it is a calculation mechanism devised by Camp and published in his 1946 Sewage Works Journal article, in order to obtain better agreement with measured results for partially full pipe flow than that obtainable using the Manning equation with constant n.

There is considerable room for confusion, however, because graphs very similar to Figure 5, but based on constant n, are also 'out there' on websites and in books. The Camp version (like Figure 5 in this course), however is used in the ASCE 1969, *Design and Construction of Sanitary and Storm Sewers* Handbook, and in subsequent WPCF and joint ASCE WEF handbooks, so it is being used here.
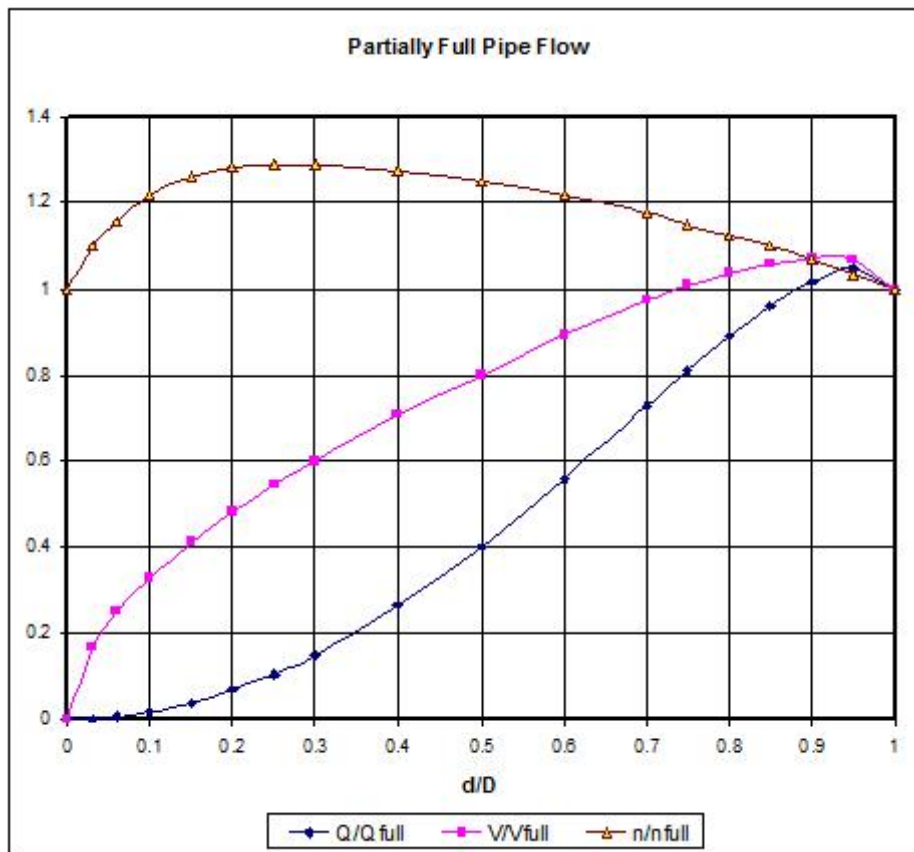

Figure 5. Flow Rate and Velocity Ratios in Pipes Flowing Partially Full

Example #7: Consider the section of storm sewer pipe from **Example #6** with D
= 21 inches and S = 0.0028. The velocity flowing full was calculated as
V_{full} = 3.79 ft/sec.

    a)   Estimate the velocity and flow rate in this pipe when it is flowing
                with water 10 inches deep in the pipe.

    b)   Estimate the velocity and flow rate in this pipe when it is flowing
                with water 15 inches deep in the pipe.

Solution: Calculate Q_{full} from eqn (8): Q_{full} = $(\pi/4)(21/12)^2(3.79)$ = 9.12 cfs

a) d/D = 10/21 = 0.476   From Fig 5: Q/Q_{full} = 0.37 and V/V_{full} = 0.776

Thus: Q = 0.37 Q_{full} = (0.37)(9.12) = **3.4 cfs = Q**

and: V = 0.776 V_{full} = (0.776)(3.79) = **2.9 ft/sec = V**

b) d/D = 15/21 = 0.71   From Fig 5: Q/Q_{full} = 0.72 and V/V_{full} = 0.96

Thus: Q = 0.72 Q_{full} = (0.72)(9.12) = **6.6 cfs = Q**

and: V = 0.96 V_{full} = (0.96)(3.79) = **3.6 ft/sec = V**

Comments on Solution: These results show that the velocity remains near or
above 3 ft/sec for flow rates down to about 40% of Q_{des}. Thus storms of
considerably lesser intensity than the design storm will keep the pipes flushed out.

9. A Worked Example Between Two Manholes

Example #8: Carry out the hydraulic design for the storm sewer along maple Ave., between 8th St. and 7th St., as shown on the storm sewer layout map in Figure 1. The results of the hydraulic design should be the diameter and slope for the sewer pipe and the elevation of the bottom of the pipe (pipe invert elevation*) at each manhole.

* The pipe invert is actually the bottom of the inside of the pipe, however, the thickness of the pipe is usually not taken into account for storm sewer hydraulic calculations. Consistent with the precision to which other parameters can be determined, the nominal pipe diameter is typically used as the inside diameter of the pipe for flow rate and velocity calculations, and it is used as the outside diameter for trench depth calculations.

Following is additional information for **Example #8**:

Location: Northwestern Illinois

State Policies: $V_{min} = 3$ ft/sec

                  Minimum cover $= 5$ feet

                  Return period for design $= 25$ years

Drainage Area: $A = 4.5$ acres

                  $t_c = 18$ minutes to the manhole inlet

                  surface slope ≤ 2 %

                  soil is sandy loam

                  land use is 1/3 acre residential lots

Storm Sewer Pipe: concrete pipe with $n = 0.013$

Solution: First the design rainfall intensity, i, will be determined for a return period of 25 years and storm duration of 18 minutes. For determination of a single value of i, for known return period and duration, interpolation from a table such as Table 5 works fine. If, however, this process must be repeated for several values of i, and/or a spreadsheet will be used to make calculations, it is useful to derive an equation for rainfall intensity as a function of storm duration. This can be done for a specified return period. To illustrate this process, an equation will be derived for use in Example #8, for a return period of 25 years and storm duration from 10 to 30 minutes.

The typical form for an equation of intensity as a function of duration is:

$$i = \frac{a}{b + \delta} \tag{11}$$

Where: δ is storm duration and a & b are empirical constants.

Taking the inverse of each side of the equation gives: $1/i = (b + \delta)/a$

Rearranging gives an equation of a straight line for $1/i$ vs δ :

$$\frac{1}{i} = \frac{1}{a}\delta + \frac{b}{a} \tag{12}$$

A plot of $1/i$ vs δ, for a given return period, should give a straight line with slope equal to $1/a$ and $1/i$ intercept equal to b/a. Instead of plotting the data, however, the SLOPE and INTERCEPT functions in Excel can be used to calculate the slope and intercept directly from the data, as shown in Figure 6 below.

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	A	B	C	D	E	F	G
1	**δ, min.**	**1/i, hr/in**		**P, in.**	**i, in/hr**		**i (calc'd)**
2	10	0.1355		1.23	7.38		7.29
3	15	0.1656		1.51	6.04		6.12
4	30	0.2415		2.07	4.14		4.13
5	**18**						**5.58**
6	slope = SLOPE(B2:B4,A2:A4) =			0.005248	= 1/a		
7							
8	intercept = INTERCEPT(B2:B4,A2:A4) =				0.08466	= b/a	
9							
10	**a** = 1/0.005248 =		**190.6**				
11							
12	**b** = (0.08466)(190.6) =		**16.13**				
13							
14	The equation is thus:		**i = 190.6/(16.13 + δ)**				

Figure 6. Calculation of Slope and Intercept Using Excel

The data for rainfall depth in inches (P), for storm durations of 10, 15, & 30 minutes in northwestern Illinois came from Table 5. The intensity for each storm duration, and then the inverse of each was calculated. The format for the SLOPE and INTERCEPT functions are shown in Figure 6, where B2:B4 is the range for the y data (1/i in this case) and A2:A4 is the range for the x data (δ in this case). After obtaining values for **1/a** and **b/a**, values for **a** and **b** can be calculated as shown. The equation for i as a function of δ, for the duration range, 10 min $\le$ δ $\le$ 30 min, with a return period of 25 years is:

$$i = \frac{190.6}{16.13 + \delta} \tag{13}$$

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The intensity for a duration equal to t_c (18 minutes) calculated from equation (13) is **5.58 in/hr**.

From Table 3, for Soil Group B, slope ≤ 2 %, and res. 1/3 acre: C = **0.30**

The design peak runoff rate can then be calculated as:

$$Q = C \, i \, A = (0.30)(5.58)(4.5) \text{ cfs} = \textbf{7.53 cfs} = \textbf{Q}_{\textbf{des}}$$

The distance from the manhole at 8th St. to the manhole at 7th St., is **343 ft**, as measured on the map, using the scale at the bottom of the map. The ground surface slope between the two manholes is thus equal to: $(67.25 - 67.19)/343 =$ **0.000175 = surface slope.** Since the surface slope is not very large, use Method #1 to calculate D and S.

i)   Substituting 7.53 cfs and 3 ft/sec into equation (8), gives:

$$7.53 = (\pi \, D^2/4)(3)$$

Solving for D: $D = [(7.53)(4)/(3\pi)]^{1/2} = 1.79 \text{ ft} = 21.5 \text{ in}$

Choose the next larger standard pipe size: <u>**D = 24 inches**</u>

ii)   Substituting known values into equation (9), gives:

$$3 = (1.49/0.013)[(24/12)/4]^{2/3}(S^{1/2})$$

Solving for S: $S = \{[(3)(0.013)]/[(1.49)(0.5^{2/3})]\}^2 = $ <u>**0.00173 = S**</u>

Since the pipe slope is greater than the ground surface slope, minimum cover will be maintained if the upstream end of the pipe has at least the 5 ft required minimum cover. Thus the D and S values calculated will be ok.

With 5 ft of cover at the 8th St. manhole, the invert elevation will be equal to surface elevation minus 5 ft minus pipe diameter:

$$\textbf{8}^{\textbf{th}} \textbf{ St. invert elevation} = 67.25 - [5 + (24/12)] = \underline{\textbf{60.25 ft}}$$

The invert elevation at the 7th St. manhole can be calculated from the pipe slope, the distance between the manholes, and the 8th St. invert elevation:

$$\textbf{7}^{\textbf{th}} \textbf{ St. invert elevation} = 60.25 - (0.00173)(346) = \underline{\textbf{59.65 ft}}$$

As a check, the ground cover at the 7th St. manhole is (67.19 – 59.65) – (24/12), which is 5.54 ft. This is indeed more than the required 5 ft minimum.

10. Use of Excel for Calculations between Successive Manholes

Example #9: Set up an Excel spreadsheet to do the hydraulic design of the storm sewer line along Maple Ave. from 8th St. to 4th St., as shown on the storm sewer manhole layout in Figure 1. All of the information given for **Example #8** applies to this example as well. Start out with the calculations already made for the section between 8th St. and 7th St. Then continue with the other three sections of storm sewer.
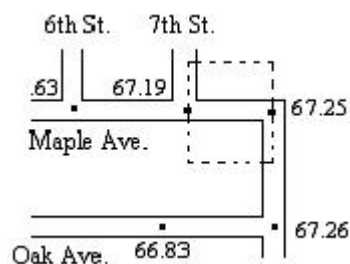
Solution: A printout of the spreadsheet calculations is given on page 28. The derivation of the intensity-duration equation [$i = 191/(\delta + 16.1)$] for a 25 year return period, is included at the bottom of the sheet, because the values of a and b

(191 and 16.1) are used for calculation of design rainfall intensity, i, in the spreadsheet. A brief discussion of each column in the spreadsheet follows.

Column 1 (line): This is simply an identifier for the section of storm sewer being designed in each row of the spreadsheet. The first row is the line between 8th St. and 7th St., which was designed in **Example #8**.

Column 2 (length, ft): This is the length of the line as measured on the map using the map scale.

Column 3 (area increment, acres): This is the drainage area for the section of storm sewer being designed. For the line from 8th to 7th Streets, the drainage area was given in **Example #8**, as 4.5 acres. For the line from 7th to 6th Streets, the area increment is the area draining to the manhole at 7th Street, as shown by the dashed line in the diagram below. It was assumed that the residential lots are landscaped so that runoff drains from the back of each lot to the street.

The back of the lots was taken to be half-way between Maple Ave. and Oak Ave. It was assumed that the lot sizes on the other side of Maple Ave. are the same size as those between Maple and Oak Avenues. The area in square feet was found by measuring and using the map scale. (The conversion factor for square feet to acres is 43,560 ft^2/acre.)

Column 4 (cumul. area, acres): This is the total drainage area contributing to the flow in the section of sewer line being designed. It is calculated by adding the new incremental area to the previous cumulative area.

Column 5 (C): This is the runoff coefficient, as determined in **Example #8.**

Column 6 (inlet time, min): This is the inlet time to the first manhole for this storm sewer line. In this case it is the 18 minute time of concentration for the drainage area feeding the inlet at 8th St. as given in **Example #8.**

Column 7 (t_c, min): The time of concentration for each line after the first one, is the inlet time to the first manhole plus the pipe flow time from the first manhole to the upstream manhole of the line being designed. The pipe flow to be added to the inlet time for the line from 7th to 6th St. is the pipe flow time from 8th to 7th St. This is calculated as 1.9 minutes in column 17. Thus t_c for the second line (from 7th to 6th St.) is 18 + 1.9 = 19.9 minutes.

Column 8 (i, in/hr): The design rainfall intensity is calculated from the equation derived for i as a function of δ: [i = 191/(δ + 16.1)], using the value of t_c from column 7 as δ.

Column 9 (Q_{des}, cfs): Q_{des} is calculated from Q = C i A, using C from column 5, A from column 4, and i from column 8.

Column 10 (D_{pipe}, in): D_{pipe} is calculated from the equation (8): $Q = (\pi D^2/4)V$, with Q = Q_{des} from column 9, and V = 3 ft/sec.

Column 11 (D_{std}, in): D_{std} is the next larger standard pipe size, entered into the spreadsheet by hand.

Column 12 (pipe slope (V_{full} = 3), ft/ft): The pipe slope, S, is calculated from equation (9) [$V = (1.49/n)(D/4)^{2/3}S^{1/2}$], with V = 3 ft/sec, n = 0.013, as specified for this problem, and $D = D_{std}$, from column 11.

Column 13 (surface slope, ft/ft): The surface slope is calculated from the two manhole elevations (entered in column 18 &19) and the line length (entered in column 2).

Column 14 (V_{full}, ft/sec): The full pipe velocity is calculated using equation (9) with n = 0.013, $D = D_{std}$ from column 11 and S from column 24 (see explanation of column 24 below). This is a check to be sure that V_{full} is greater than or equal to V_{min} (3 ft/sec in this case).
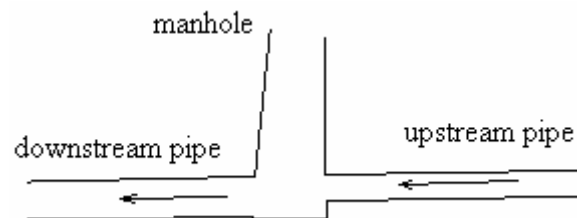
Column 15 (Q_{full}, cfs): The full pipe flow rate is calculated using equation (10) with n = 0.013, $D = D_{std}$ from column 11 and S from column 24 (see explanation of column 24 below). This is a check to be sure that Q_{full} is greater or equal to Q_{des}.

Column 16 (length, ft): This column is simply a copy of column 2, because the length of the line is used for the calculation in the next column.

Column 17 (t_{pipe}, min): The pipe flow time, t_{pipe} is calculated as length, from column 16, divided by V_{full}, from column 14, divided by 60 to convert seconds to minutes.

Columns 18 & 19 (ground elev., ft): These elevations are entered from the information on the manhole layout map, Figure 1.

Column 20 (invert elevation [upper], ft): For the first manhole in this length of storm sewer (from 8th to 7th St), the upper invert elevation is calculated as upper surface elevation minus (5 ft + pipe diam in ft). For subsequent lines, the upper invert elevation is calculated as the lower invert elevation for the previous line minus the difference between the current and previous pipe diameters in ft. This is because the top of the two pipes that meet at a manhole should be aligned, as shown in the figure below.

Column 21 (invert elevation [lower], ft): The lower invert elevation is calculated using the upper invert elevation from column 20, the pipe slope from column 12, and the pipe length from column 16.

Columns 22 and 23 (ground cover, ft) The ground cover at both manholes is calculated as surface elevation from column 18 or 19 minus (invert elevation from column 20 or 21 minus pipe diameter in ft). This is calculated as a check to make sure that minimum cover is maintained.

Column 24 (pipe slope for design, ft/ft) The slope from column 12 (calculated from eqn (9) or from column 13 (surface slope) is entered by hand into column 24 depending on whether calculations should proceed according to Method I or Method II. The value of pipe slope in column 24 is used for column 14 and column 15 calculations.

This spreadsheet works directly as outlined above for Method I calculations. (For cases in which the ground surface slope is relatively small.) For steep surface slope, where Method II calculations are needed in order to maintain minimum cover, the ground surface slope from column 13 should be entered into column 24. Then standard diameters can be entered into column (11) by trial and error, to find the smallest standard diameter which will give $V_{full} > 3$ ft/sec and $Q_{full} > Q_{des}$.

Storm sewer design for   Maple Avenue from 8th Street to 4th Street

col. 1	col. 2	col. 3	col. 4	col. 5	col. 6	col. 7	col. 8	col. 9
		area	cumul.		inlet			
	Length	increment	area		time	t_C	i	Q_{des}
Line	ft	acres	acres	C	min	min	in/hr	cfs
8th - 7th	343	4.5	4.5	0.3	18	18	5.58	7.54
7th - 6th	470	3.70	8.20	0.3	18	19.9	5.29	13.01
6th - 5th	478	5.07	13.27	0.3	18	22.5	4.93	19.63
5th - 4th	560	5.16	18.43	0.3	18	25.2	4.61	25.51

col. 10	col. 11	col. 12	col. 13	col. 14	col. 15	col. 16	col. 17
		pipe slope	surface				
D_{pipe}	D_{std}	(V_{full} = 3)	slope	V_{full}	Q_{full}	Length	t_{pipe}
in	in	ft/ft	ft/ft	ft/sec	cfs	ft	min
21.5	24	0.001726	0.000175	3	9.42	343	1.9
28.2	30	0.001282	0.001191	3	14.73	470	2.6
34.6	36	0.001005	0.001297	3	21.21	478	2.7
39.5	42	0.000819	0.000232	3	28.86	560	3.1

col. 18	col. 19		col. 20	col. 21		col. 22	col. 23	col. 24
								pipe slope
Ground Elev, ft			Invert Elev, ft			Cover Depth, ft		for design
upper	lower		upper	lower		upper	lower	ft/ft
67.25	67.19		60.250	59.658		5	5.5	0.001726
67.19	66.63		59.158	58.555		5.5	5.6	0.001282
66.63	66.01		58.055	57.575		5.6	5.4	0.001005
66.01	65.88		57.075	56.616		5.4	5.8	0.000819

derivation of IDF equation [i = a/(b + δ)] for T = 25 years, 10 min < δ < 30 min:

δ, min	1/i, hr/in	i, in/hr			
10	0.14	7.38	slope =	0.00525	= 1/a
15	0.17	6.04			
30	0.24	4.14		a = 1/slope =	191
			intercept =	0.0847	= b/a
				b = a*intercept =	16.1

The IDF equation is thus: i = 191/(δ + 16.1)

11.   Summary

A major part of hydraulic design of storm sewers is determination of the design peak runoff rate, usually with the Rational Method. The parameters needed for the Rational Method calculation are runoff coefficient, C, design rainfall intensity, i, and drainage area, A. Discussion of these parameters and examples of their determination were included in this course. With known design flow rate, minimum required velocity and minimum cover, methods of calculating design pipe diameter and slope and invert elevation at each manhole were presented and illustrated with examples. A spreadsheet such as Excel works very well for hydraulic design of storm sewers. An example was included illustrating the use of Excel.

12.   References

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(The rest of their Stormwater Management Manual is available at:
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3.   Illinois State Water Survey, *Bulletin 70*, available on the internet at:
http://www.isws.illinois.edu/atmos/statecli/RF/rf.htm

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