# CHAPTER 2

# HYDRAULICS OF SEWERS

The hydraulic design procedure for sewers requires:

1. Determination of Sewer System Type
2. Determination of Design Flow
3. Selection of Pipe Size
4. Determination of Flow Velocity

## SANITARY SEWERS

### DETERMINATION OF SEWER SYSTEM TYPE

Sanitary sewers are designed to carry domestic, commercial and industrial sewage with consideration given to possible infiltration of ground water. All types of flow are designed on the basis of having the flow characteristics of water.

### DETERMINATION OF DESIGN FLOW

In designing sanitary sewers, average, peak and minimum flows are considered. Average flow is determined or selected, and a factor applied to arrive at the peak flow which is used for selecting pipe size. Minimum flows are used to determine if specified velocities can be maintained to prevent deposition of solids.

**Average Flow.** The average flow, usually expressed in gallons per day, is a hypothetical quantity which is derived from past data and experience. With adequate local historical records, the average rate of water consumption can be related to the average sewage flow from domestic, commercial and industrial sources. Without such records, information on probable average flows can be obtained from other sources such as state or national agencies. Requirements for minimum average flows are usually specified by local or state sanitary authorities or local, state and national public health agencies. Table 1 lists design criteria for domestic sewage flows for various municipalities. Commercial and industrial sewage flows are listed in Table 2. These tables were adapted from the “Design and Construction of Sanitary and Storm Sewers,” published by American Society of Civil Engineers and Water Pollution Control Federation. To apply flow criteria in the design of a sewer system, it is necessary to determine present and future zoning, population densities and types of business and industry.

**Peak Flow.** The actual flow in a sanitary sewer is variable, and many studies have been made of hourly, daily and seasonal variations. Typical results of one study are shown in Figure I adapted from “Design and Construction of Sanitary and Storm Sewers,” published by the American Society of Civil Engineers and Water Pollution Control Federation. Maximum and minimum daily flows are used in the design of treatment plants, but the sanitary sewer must carry the peak flow that will occur during its design life. This peak flow is defined as the mean rate of the maximum flow occurring during a 15-minute period for any 12-month period and is determined by multiplying average daily flow by an appropriate factor. Estimates of this factor range from 4.0 to 5.5 for design populations of one thousand, to a factor of 1.5 to 2.0 for design population of one million. Tables 1 and 2 list minimum peak loads used by some municipalities as a basis for design.

**Minimum Flow.** A minimum velocity of 2 feet per second, when the pipe is flowing full or half full, will prevent deposition of solids. The design should be checked using the minimum flow to determine if this self-cleaning velocity is maintained.

## SELECTION OF PIPE SIZE

After the design flows have been calculated, pipe size is selected using Manning's formula. The formula can be solved by selecting a pipe roughness coefficient, and assuming a pipe size and slope. However, this trial and error method is not necessary since nomographs, tables, graphs and computer programs provide a direct solution.

**Manning's Formula.** Manning's formula for selecting pipe size is:

$$Q = \frac{1.486}{n} AR^{2/3} S^{1/2} \qquad (1)$$

A constant $C_1 = \frac{1.486}{n} AR^{2/3}$ which depends only on the geometry and characteristics of the pipe enables Manning's formula to be written as:

$$Q = C_1 S^{1/2} \qquad (2)$$

Tables 3, 4, 5 and 6 list full flow values of $C_1$ for circular pipe, elliptical pipe, arch pipe, and box sections. Table A-1 in the Appendix lists values of $S^{1/2}$.

**Manning's "*n*" Value.** The difference between laboratory test values of Manning's "*n*" and accepted design values is significant. Numerous tests by public and other agencies have established Manning's "*n*" laboratory values. However, these laboratory results were obtained utilizing clean water and straight pipe sections without bends, manholes, debris, or other obstructions. The laboratory results indicated the only differences were between smooth wall and rough wall pipes. Rough wall, or corrugated pipe, have relatively high "*n*" values which are approximately 2.5 to 3 times those of smooth wall pipe.

All smooth wall pipes, such as concrete and plastic, were found to have "*n*" values ranging between 0.009 and 0.010, but, historically, engineers familiar with sewers have used 0.012 and 0.013. This "design factor" of 20-30 percent takes into account the difference between laboratory testing and actual installed conditions. The use of such design factors is good engineering practice, and, to be consistent for all pipe materials, the applicable Manning's " " laboratory value should be increased a similar amount in order to arrive at design values.

**Full Flow Graphs.** Graphical solutions of Manning's formula are presented for circular pipe in Figures 2 through 5 and for horizontal elliptical pipe, vertical elliptical pipe, arch pipe and box sections in Figures 6 through 19. When flow, slope and roughness coefficient are known, pipe size and the resulting velocity for full flow can be determined.

**Partially Full Flow Graphs.** Velocity, hydraulic radius and quantity and area of flow vary with the depth of flow. These values are proportionate to full flow values and for any depth of flow are plotted for circular pipe, horizontal elliptical pipe, vertical elliptical pipe, arch pipe, and box sections in Figures 20 through 24.

## DETERMINATION OF FLOW VELOCITY

**Minimum Velocity.** Slopes required to maintain a velocity of 2 feet per second under full flow conditions with various "*n*" values are listed in Table 7 for circular pipe. The slopes required to maintain velocities other than 2 feet per second under full flow conditions can be obtained by multiplying the tabulated values by one-fourth of the velocity squared or by solving Manning's formula using Figures 2 through 19.

**Maximum Velocity.** Maximum design velocities for clear effluent in concrete pipe can be very high. Unless governed by topography or other restrictions, pipe slopes should be set as flat as possible to reduce excavation costs and consequently velocities are held close to the minimum.

# STORM SEWERS

## DETERMINATION OF SEWER SYSTEM TYPE

Storm sewers are designed to carry precipitation runoff, surface waters and, in some instances, ground water. Storm water flow is analyzed on the basis of having the flow characteristics of water.

## DETERMINATION OF DESIGN FLOW

The Rational Method is widely used for determining design flows in urban and small watersheds. The method assumes that the maximum rate of runoff for a given intensity occurs when the duration of the storm is such that all parts of the watershed are contributing to the runoff at the interception point. The formula used is an empirical equation that relates the quantity of runoff from a given area to the total rainfall falling at a uniform rate on the same area and is expressed as:

$$Q = CiA \quad (3)$$

The runoff coefficient "C" and the drainage area "A" are both constant for a given area at a given time. Rainfall intensity " i ", however, is determined by using an appropriate storm frequency and duration which are selected on the basis of economics and engineering judgment. Storm sewers are designed on the basis that they will flow full during storms occurring at certain intervals. Storm frequency is selected through consideration of the size of drainage area, probable flooding, possible flood damage and projected development schedule for the area.

**Runoff Coefficient.** The runoff coefficient “C” is the ratio of the average rate of rainfall on an area to the maximum rate of runoff. Normally ranging between zero and unity, the runoff coefficient can exceed unity in those areas where rainfall occurs in conjunction with melting snow or ice. The soil characteristics, such as porosity, permeability and whether or not it is frozen are important considerations. Another factor to consider is ground cover, such as paved, grassy or wooded. In certain areas, the coefficient depends upon the slope of the terrain. Duration of rainfall and shape of area are also important factors in special instances. Average values for different areas are listed in Table 8.

**Rainfall Intensity.** Rainfall intensity “ i “ is the amount of rainfall measured in inches per hour that would be expected to occur during a storm of a certain duration. The storm frequency is the time in years in which a certain storm would be expected again and is determined statistically from available rainfall data.

Several sources, such as the U. S. Weather Bureau, have published tables and graphs for various areas of the country which show the relationship between rainfall intensity, storm duration and storm frequency. To illustrate these relationships, the subsequent figures and tables are presented as examples only, and specific design information is available for most areas. For a 2-year frequency storm of 30-minute duration, the expected rainfall intensities for the United States are plotted on the map in Figure 25. These intensities could be converted to storms of other durations and frequencies by using factors as listed in Tables 9 and 10 and an intensity-duration-frequency curve constructed as shown in Figure 26.

**Time of Concentration.** The time of concentration at any point in a sewer system is the time required for runoff from the most remote portion of the drainage area to reach that point. The most remote portion provides the longest time of concentration but is not necessarily the most distant point in the drainage area. Since a basic assumption of the Rational Method is that all portions of the area are contributing runoff, the time of concentration is used as the storm duration in calculating the intensity. The time of concentration consists of the time of flow from the most remote portion of the drainage area to the first inlet (called the inlet time) and the time of flow from the inlet through the system to the point under consideration (called the flow time). The inlet time is affected by the rainfall intensity, topography and ground conditions. Many designers use inlet times ranging from a minimum of 5 minutes for densely developed areas with closely spaced inlets to a maximum of 30 minutes for flat residential areas with widely spaced inlets. If the inlet time exceeds 30 minutes, then a detailed analysis is required because a very small inlet time will result in an overdesigned system while conversely for a very long inlet time the system will be underdesigned.

**Runoff Area.** The runoff area “A” is the drainage area in acres served by the storm sewer. This area can be accurately determined from topographic maps or field surveys.

## SELECTION OF PIPE SIZE

**Manning's Formula.** Manning's formula for selecting pipe size is:

$$Q = \frac{1.486}{n} AR^{2/3} S^{1/2} \qquad (1)$$

A constant $C_1 = \frac{1.486}{n} AR^{2/3}$ which depends only on the geometry and characteristics of the pipe enables Manning's formula to be written as:

$$Q = C_1 S^{1/2} \qquad (2)$$

Tables 3, 4, 5 and 6 for circular pipe, elliptical pipe, arch pipe, and box sections with full flow and Table A-1 in the Appendix for values of $C_1$ and $S^{1/2}$ respectively are used to solve formula (2). Graphical solutions of Manning's formula (1) are presented in Figures 2 through 5 for circular pipe, and Figures 6 through 19 for horizontal elliptical pipe, vertical elliptical pipe, arch pipe and box sections under full flow conditions.

Partial flow problems can be solved with the proportionate relationships plotted in Figure 20 through 24.

**Manning's "*n*" Value.** The difference between laboratory test values of Manning's "*n*" and accepted design values is significant. Numerous tests by public and other agencies have established Manning's "*n*" laboratory values. However, these laboratory results were obtained utilizing clean water and straight pipe sections without bends, manholes, debris, or other obstructions. The laboratory results indicated the only differences were between smooth wall and rough wall pipes. Rough wall, or corrugated pipe, have relatively high "*n*" values which are approximately 2.5 to 3 times those of smooth wall pipe.

All smooth wall pipes, such as concrete and plastic, were found to have "*n*" values ranging between 0.009 and 0.010, but, historically, engineers familiar with sewers have used 0.012 or 0.013. This "design factor" of 20-30 percent takes into account the difference between laboratory testing and actual installed conditions. The use of such design factors is good engineering practice, and, to be consistent for all pipe materials, the applicable Manning's "*n*" laboratory value should be increased a similar amount in order to arrive at design values.

## DETERMINATION OF FLOW VELOCITY

**Minimum Velocity.** The debris entering a storm sewer system will generally have a higher specific gravity than sanitary sewage, therefore a minimum velocity of 3 feet per second is usually specified. The pipe slopes required to maintain this velocity can be calculated from Table 7 or by solving Manning's formula using Figures 2 through 19.

**Maximum Velocity.** Tests have indicated that concrete pipe can carry clear water of extremely high velocities without eroding. Actual performance records of storm sewers on grades up to 45 percent and carrying high percentages of solids indicate that erosion is seldom a problem with concrete pipe.

# EXAMPLE PROBLEMS

## EXAMPLE 2 - 1
## STORM SEWER FLOW

**Given:** The inside diameter of a circular concrete pipe storm sewer is 48 inches, "*n*" = 0.012 and slope is 0.006 feet per foot.

**Find:** The full flow capacity, "Q".

**Solution:** The problem can be solved using Figure 4 or Table 3.

**Figure 4** The slope for the sewer is 0.006 feet per foot or 0.60 feet per 100 feet. Find this slope on the horizontal axis. Proceed verticaly along the 0.60 line to the intersection of this line and the curve labelled 48 inches. Proceed horizontally to the vertical axis and read Q = 121 cubic feet per second.

**Table 3** Enter Table 3 under the column $n = 0.012$ for a 48-inch diameter pipe and find $C_1$, = 1556. For S = 0.006, find $S^{1/2} = 0.07746$ in Table A-1. Then Q = 1556 X 0.07746 or 121 cubic feet per second.

**Answer:** Q = 121 cubic feet per second.

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## EXAMPLE 2 - 2
## REQUIRED SANITARY SEWER SIZE

**Given:** A concrete pipe sanitary sewer with "*n*" = 0.013, slope of 0.6 percent and required full flow capacity of 110 cubic feet per second.

**Find:** Size of circular concrete pipe required.

**Solution:** This problem can be solved using Figure 5 or Table 3.

**Figure 5** Find the intersection of a horizontal line through Q = 110 cubic feet per second and a slope of 0.60 feet per 100 feet. The minimum size sewer is 48 inches.

**Table 3** For Q = 110 cubic feet per second and $S^{1/2} = 0.07746$

$$C_1 = \frac{Q}{S^{1/2}} = \frac{110}{0.07746} = 1420$$

In the table, 1436 is the closest value of $C_1$, equal to or larger than 1420, so the minimum size sewer is 48 inches.

**Answer:** A 48-inch diameter circular pipe would have more than adequate capacity.

**EXAMPLE 2 - 3**
**STORM SEWER MINIMUM SLOPE**

**Given:** A 48-inch diameter circular concrete pipe storm sewer, "*n*" = 0.012 and flowing one-third full.

**Find:** Slope required to maintain a minimum velocity of 3 feet per second.

**Solution:** Enter Figure 20 on the vertical scale at Depth of Flow = 0.33 and project a horizontal line to the curved line representing velocity. On the horizontal scale directly beneath the point of intersection read a value of 0.81 which represents the proportional value to full flow.

$$\frac{V}{V_{full}} = 0.81$$

$$V_{full} = \frac{V}{0.81}$$

$$= \frac{3}{0.81}$$

$$= 3.7$$

Enter Figure 4 and at the intersection of the line representing 48-inch diameter and the interpolated velocity line of 3.7 read a slope of 0.088 percent on the horizontal scale.

**Answer:** The slope required to maintain a minimum velocity of 3 feet per second at one-third full is 0.088 percent.

**EXAMPLE 2 - 4**
**SANITARY SEWER DESIGN**

**General:** A multi-family housing project is being developed on 350 acres of rolling to flat ground. Zoning regulations establish a population density of 30 persons per acre. The state Department of Health specifies 100 gallons per capita per day as the average and 500 gallons per capita per day as the peak domestic sewage flow, and an infiltration allowance of 500 gallons per acre per day.

Circular concrete pipe will be used, "*n*"= 0.013, designed to flow full at peak load with a minimum velocity of 2 feet per second at one-third peak flow. Maximum spacing between manholes will be 400 feet.

**Given:**

| | | |
|---|---|---|
| Population Density | = | 30 persons per acre |
| Average Flow | = | 100 gallons per capita per day |
| Peak Flow | = | 500 gallons per capita per day |
| Infiltration | = | 500 gallons per acre per day |
| Manning’s Roughness | = | 0.0 13 *(See discussion of Manning’s Coefficient “n” Value)* |
| Minimum Velocity | = | 2 feet per second @ 1/3 peak flow |

**Find:** Design the final 400 feet of pipe between manhole Nos. 20 and 21, which serves 58 acres in addition to carrying the load from the previous pipe which serves the remaining 292 acres.

**Solution:** 1. Design Flow

Population-Manhole 1 to 20 = 30 X 292 = 8760
Population-Manhole 20 to 21 = 30 X 58 = 1740

| | | | |
|---|---|---|---|
| Total population | | 10,500 | persons |
| Peak flow-Manhole 1 to 20 = 500 X 8760 | = | 4,380,000 | gallons per day |
| Infiltration-Manhole 1 to 20 - 500 X 292 | = | 146,000 | gallons per day |
| Peak flow-Manhole 20 to 21 = 500 X 1740 | = | 870,000 | gallons per day |
| Infiltration-Manhole 20 to 21 = 500 X 58 | = | 29,000 | gallons per day |
| Total Peak flow | = | 5,425,000 | gallons per day |

use 5,425,000 gallons per day or 8.4 cubic feet per second

2. Selection of Pipe Size

In designing the sewer system, selection of pipe begins at the first manhole and proceeds downstream. The section of pipe preceding the final section is an 18-inch diameter, with slope = 0.0045 feet per foot. Therefore, for the final section the same pipe size will be checked and used unless it has inadequate capacity, excessive slope or inadequate velocity.

Enter Figure 5, from Q = 8.4 cubic feet per second on the vertical scale project a horizontal line to the 18-inch diameter pipe, read velocity = 4.7 feet per second.

From the intersection, project a vertical line to the horizontal scale, read slope = 0.63 feet per 100 feet.

3. Partial Flow

Enter Figure 20, from Proportion of Value for Full Flow = 0.33 on the horizontal scale project a line vertically to "flow" curve, from intersection project a line horizontally to "velocity" curve, from intersection project a line vertically to horizontal scale, read Proportion of Value for Full Flow - 0.83.

Velocity at minimum flow = 0.83 X 4.7 = 3.9 feet per second.

**Answer:** Use 18-inch diameter concrete pipe with slope of 0.0063 feet per foot.

The preceding computations are summarized in the following tabular forms, Illustrations 2.1 and 2.2.

**Illustration 2.1 - Population and Flow**

| Manhole No. | DRAINAGE AREA | | | PEAK-FLOW - MGD | | | | | Cum. Flow cfs. |
|---|---|---|---|---|---|---|---|---|---|
| | Zoning | Acres | Ultimate Population | Domestic | Indus-trial | Infil-tration | Total | Cum. Total | |
| 19 | From Preceeding Computations ........ | | | | | | | 4.53 | 7.0 |
| 20 | Multi-family | 58 | 1740 | .087 | – | 0.03 | 0.90 | 5.43 | 8.4 |
| 21 | Trunk Sewer Interceptor Manhole | | | | | | | | |

**Illustration 2.2 - Sanitary Sewer Design Data**

| Manhole | | Flow cfs | SEWER | | | | | Manhole Flow-line Elevations | |
|---|---|---|---|---|---|---|---|---|---|
| No. | Sta. | | Length ft. | Slope ft./ft. | Pipe Dia. in. | Velocity fps | Fall ft. | In | Out |
| 19 | 46 | 7.0 | | | | | | | 389.51 |
| 20 | 50 | 8.4 | 400 | 0.0045 | 18 | 4.0 | 1.80 | 387.71 | 387.71 |
| 21 | 54 | | 400 | 0.0063 | 18 | 4.7 | 2.52 | 385.19 | |

## EXAMPLE 2 - 5
## STORM SEWER DESIGN

**General:** A portion of the storm sewer system for the multi-family development is to serve a drainage area of about 30 acres. The state Department of Health specifies a 10-inch diameter minimum pipe size.

Circular concrete pipe will be used,"n" = 0.011, with a minimum velocity of 3 feet per second when flowing full. Minimum time of concentration is 10 minutes with a maximum spacing between manholes of 400 feet.

| | | |
|---|---|---|
| **Given:** | Drainage Area | A = 30 acres (total) |
| | Runoff Coefficient | C = 0.40 |
| | Rainfall Intensity | i as shown in Figure 26 |
| | Roughness Coefficient | n = 0.0 11 (See discussion of Manning's "n" Value) |
| | Velocity | V = 3.0 feet per second (minimum at full flow) |

**Find:** Design of the storm system as shown in Illustration 2.3, "Plan for Storm Sewer Example," adapted from "Design and Construction of Concrete Sewers," published by the Portland Cement Association.

**Solution:** The hydraulic properties of the storm sewer will be entered as they are determined on the example form Illustration 2.4, "Computation Sheet for Hydraulic Properties of Storm Sewer." The design of the system begins at the upper manhole and proceeds downstream.

The areas contributing to each manhole are determined, entered incrementally in column 4, and as cumulative totals in column 5. The initial inlet time of 10 minutes minimum is entered in column 6, line 1, and from Figure 26 the intensity is found to be 4.2 inches per hour which is entered in column 8, line 1. Solving the Rational formula, Q = 1.68 cubic feet per second is entered in column 9, line 1. Enter Figure 3, for V = 3 feet per second and Q = 1.68 cubic feet per second, the 10-inch diameter pipe requires a slope = 0.39 feet per 100 feet. Columns 10, 12, 13, 14, 15 and 16, line 1, are now filled in. The flow time from manhole 7 to 6 is found by dividing the length (300 feet) between manholes by the velocity of flow (3 feet per second) and converting the answers to minutes (1.7 minutes) which is entered in column 7, line 1. This time increment is added to the 10-minute time of concentration for manhole 7 to arrive at 11.7 minutes time of concentration for manhole 6 which is entered in column 6, line 2.

From Figure 26, the intensity is found to be 4.0 inches per hour for a time of concentration of 11.7 minutes which is entered in column 8, line 2. The procedure outlined in the preceding paragraph is repeated for each section of sewer as shown in the table.

**Answer:** The design pipe sizes, slopes and other properties are as indicated in Illustration 2.4.

**Illustration 2.3-Plan for Storm Sewer Example**

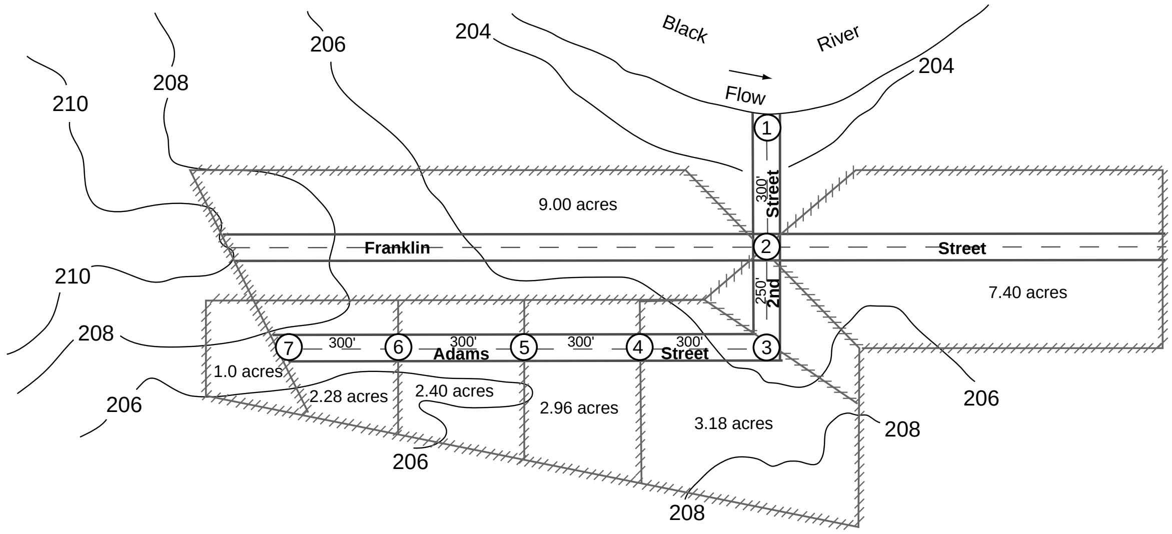


**Illustration 2.4-Computation Sheet for Hydraulic Properties of Storm Sewer**

| Line Number | SEWER LOCATION | | | TRIBUTARY AREA | | TIME OF FLOW (minutes) | | Rate of Rainfall (in. per hour) *i* | Runoff (cfs.) Q | SEWER DESIGN | | | | | PROFILE: Elevation of Invert | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Street | From M. H. | To M. H. | Increments Acres | Total Acres A | To Upper End | In Section | | | Slope (ft. per 100 ft.) | Diameter (in.) | Capacity (cfs.) | Velocity (fps.) | Length (ft.) | Upper End | Lower End |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| 1 | Adams | 7 | 6 | 1.00 | 1.00 | 10.0 | 1.7 | 4.2 | 1.68 | 0.39 | 10 | 1.7 | 3.0 | 300 | 200.00 | 198.83 |
| 2 | Adams | 6 | 5 | 2.28 | 3.28 | 11.7 | 1.7 | 4.0 | 5.25 | 0.18 | 18 | 5.3 | 3.0 | 300 | 198.16 | 197.62 |
| 3 | Adams | 5 | 4 | 2.40 | 5.68 | 13.4 | 1.3 | 3.8 | 8.63 | 0.23 | 21 | 8.65 | 3.8 | 300 | 197.37 | 196.68 |
| 4 | Adams | 4 | 3 | 2.96 | 8.64 | 14.7 | 1.2 | 3.7 | 12.0 | 0.23 | 24 | 13.0 | 4.1 | 300 | 196.43 | 195.74 |
| 5 | 2nd | 3 | 2 | 3.18 | 11.82 | 15.9 | 0.9 | 3.6 | 17.0 | 0.23 | 27 | 17.0 | 4.5 | 250 | 195.49 | 194.91 |
| 6 | 2nd | 2 | 1 | 17.84 | 29.66 | 16.8 | - | 3.5 | 41.6 | 0.30 | 36 | 42.0 | 6.1 | 300 | 194.41 | 193.51 |

## EXAMPLE 2 - 6
## SANITARY SEWER DESIGN

**Given:** A concrete box section sanitary sewer with "*n*" = 0.013, slope of 1.0% and required full flow capacity of 250 cubic feet per second.

**Find:** Size of concrete box section required for full flow.

**Solution:** This problem can be solved using Figure 19 or Table 6.

**Figure 19** Find the intersection of a horizontal line through Q = 250 cubic feet per second and a slope of 1.0 feet per 100 feet. The minimum size box section is either a 6 foot span by 4 foot rise or a 5 foot span by 5 foot rise.

**Table 6** For Q = 250 cubic feet per second and $S^{1/2}$ = 0. 100

$$C_1 = \frac{Q}{S^{1/2}} = \frac{250}{0.100} = 2{,}500$$

In Table 6, under the column headed $n = 0.013$, 3,338 is the first value of $C_1$, equal to or larger than 2,500, therefore a box section with a 5 foot span X a 5 foot rise is adequate. Looking further in the same column, a box section with a 6 foot span and a 4 foot rise is found to have a $C_1$, value of 3,096, therefore a 6 X 4 box section is also adequate.

**Answer:** Either a 5 foot X 5 foot or a 6 foot X 4 foot box section would have a full flow capacity equal to or greater than Q = 250 cubic feet per second.