# 7. STORM DRAINS

A storm drain is that portion of the highway drainage system that receives surface water through inlets and conveys the water through conduits to an outfall. It is composed of different lengths and sizes of pipe or conduit connected by appurtenant structures. A section of conduit connecting one inlet or appurtenant structure to another is termed a "segment" or "run." The storm drain conduit is most often a circular pipe, but can also be a box or other enclosed conduit shapes. Appurtenant structures include inlet structures (excluding the actual inlet opening), access holes, junction chambers, and other miscellaneous structures. Generalized design considerations for these structures were presented in Chapter 6. The computation of energy losses through these structures will be included here.

## 7.1 Hydraulics of Storm Drainage Systems

Hydraulic design of storm drainage systems requires an understanding of basic hydrologic and hydraulic concepts and principles. Hydrologic concepts were discussed in Chapter 3. Important hydraulic principles include flow classification, conservation of mass, conservation of momentum, and conservation of energy. Chapter 5 introduced some of these elements. Additional discussion of these topics can be found in References 7, 31, and 36. The following sections assume a basic understanding of these topics.

### 7.1.1 Flow Type Assumptions

The design procedures presented here assume that flow within each storm drain segment is steady and uniform. This means that the discharge and flow depth in each segment are assumed to be constant with respect to time and distance. Also, since storm drain conduits are typically prismatic, the average velocity throughout a segment is considered to be constant.

In actual storm drainage systems, the flow at each inlet is variable, and flow conditions are not truly steady or uniform. However, since the usual hydrologic methods employed in storm drain design are based on computed peak discharges at the beginning of each run, it is a conservative practice to design using the steady uniform flow assumption.

### 7.1.2 Open Channel vs. Pressure Flow

Two design philosophies exist for sizing storm drains under the steady uniform flow assumption. The first is referred to as open channel or gravity flow design. To maintain open channel flow, the segment must be sized so that the water surface within the conduit remains open to atmospheric pressure. For open channel flow, flow energy is derived from the flow velocity (kinetic energy), depth (pressure), and elevation (potential energy). If the water surface throughout the conduit is to be maintained at atmospheric pressure, the flow depth must be less than the height of the conduit.

Pressure flow design requires that the flow in the conduit be at a pressure greater than atmospheric. Under this condition, there is no exposed flow surface within the conduit. In pressure flow, flow energy is again derived from the flow velocity, depth, and elevation. The significant difference here is that the pressure head will be above the top of the conduit, and will not equal the depth of flow in the conduit. In this case, the pressure head rises to a level represented by the hydraulic grade line (see Section 7.1.4 for a discussion of the hydraulic grade line).

The question of whether open channel or pressure flow should control design has been debated among various highway agencies. For a given flow rate, design based on open channel flow requires larger conduit sizes than those sized based on pressure flow. While it may be more expensive to construct storm drainage systems designed based on open channel flow, this design procedure provides a margin of safety by providing additional headroom in the conduit to accommodate an increase in flow above the design discharge. This factor of safety is often desirable since the methods of runoff estimation are not exact, and once placed, storm drains are difficult and expensive to replace.

However, there may be situations where pressure flow design is desirable. For example, on some projects, there may be adequate headroom between the conduit and inlet/access hole elevations to tolerate pressure flow. In this case, a significant costs savings may be realized over the cost of a system designed to maintain open channel flow. Also, in some cases it may be necessary to use an existing system that must be placed under pressure flow to accommodate the proposed design flow rates. In instances such as these, there may be advantages in making a cursory hydraulic and economic analysis of a storm drain using both design methods before making a final selection.

Under most ordinary conditions, it is recommended that storm drains be sized based on a gravity flow criteria at flow full or near full. Designing for full flow is a conservative assumption since the peak flow capacity actually occurs at 93% of the full flow depth. However, the designer should maintain awareness that pressure flow design may be justified in certain instances. When pressure flow is allowed, special emphasis should be placed on the proper design of the joints so that they are able to withstand the pressure flow.

### 7.1.3 Hydraulic Capacity

A storm drain's size, shape, slope, and friction resistance controls its hydraulic capacity. Several flow friction formulas have been advanced which define the relationship between flow capacity and these parameters. The most widely used formula for designing storm drains is Manning's Equation.

The Manning's Equation was introduced in Chapter 5 for computing the capacity for roadside and median channels (Equation 5-5). For circular storm drains flowing full, Manning's Equation becomes:

$$V = (K_V/n)\, D^{0.67}\, S_o^{\,0.5} \qquad Q = (K_Q/n)\, D^{2.67}\, S_o^{\,0.5} \qquad (7\text{-}1)$$

where:

| | | |
|---|---|---|
| $V$ | = | Mean velocity, m/s (ft/s) |
| $Q$ | = | Rate of flow, $m^3/s$ ($ft^3/s$) |
| $K_V$ | = | 0.397 (0.59 in English units) |
| $K_Q$ | = | 0.312 (0.46 in English units) |
| $n$ | = | Manning's coefficient (Table 7-1) |
| $D$ | = | Storm drain diameter, m (ft) |
| $S_o$ | = | Slope of the energy grade line, m/m (ft/ft) |

Chart 23 presents a nomograph solution of Manning's Equation for full flow in circular conduits. Table 7-1 provides representative values of the Manning's coefficient for various storm drain materials. It should be remembered that the values in the table are for new pipe tested in a laboratory. Actual field values for storm drains may vary depending on the effect of abrasion, corrosion, deflection, and joint conditions.

Figure 7-1 illustrates storm drain capacity sensitivity to the parameters in the Manning's equation. This figure can be used to study the effect changes in individual parameters will have on storm drain capacity. For example, if the diameter of a storm drain is doubled, its capacity will be increased by a factor of 6.35; if the slope is doubled, the capacity is increased by a factor of 1.4; however, if the roughness is doubled, the pipe capacity will be reduced by 50%.

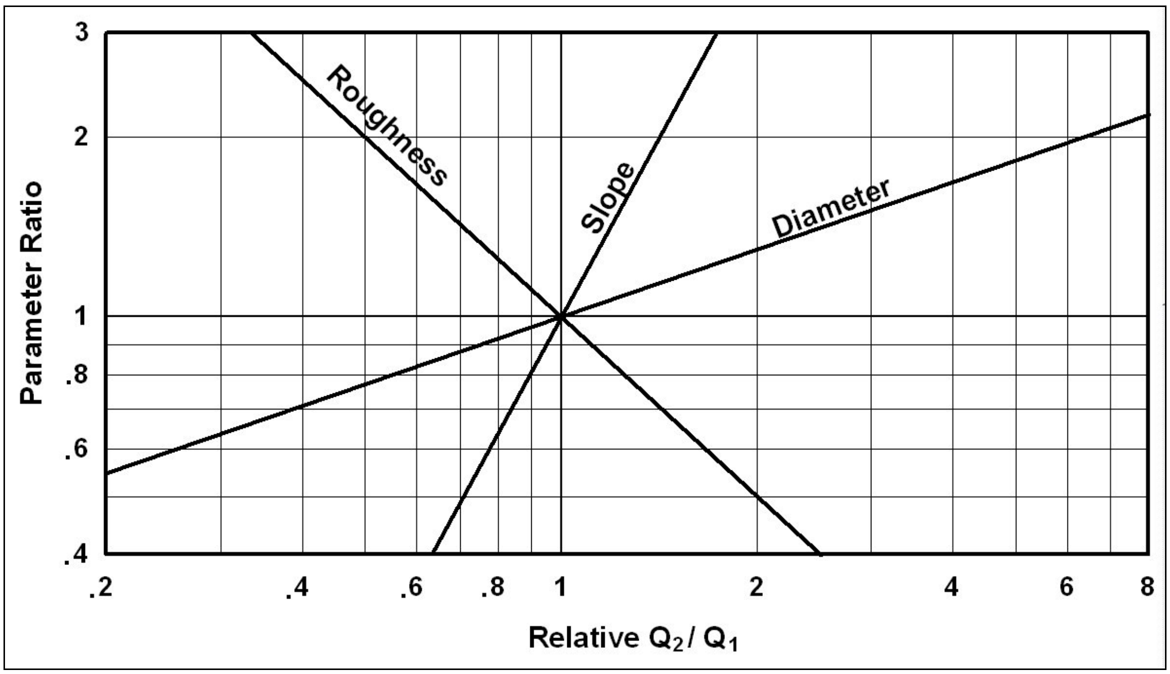


**Figure 7-1. Storm drain capacity sensitivity.**

The hydraulic elements graph in Chart 24 is provided to assist in the solution of the Manning's equation for part full flow in storm drains. The hydraulic elements chart shows the relative flow conditions at different depths in a circular pipe and makes the following important points:

1. Peak flow occurs at 93% of the height of the pipe. This means that if the pipe is designed for full flow, the design will be slightly conservative.

2. Velocity in a pipe flowing half-full is the same as the velocity for full flow.

3. Flow velocities for flow depths greater than half-full are greater than velocities at full flow.

4. As the depth of flow drops below half-full, the flow velocity drops off rapidly.

**Table 7-1. Manning's Coefficients for Storm Drain Conduits.***[2]

| Type of Culvert | Roughness or Corrugation | Manning's n |
|---|---|---|
| Concrete Pipe | Smooth | 0.010-0.011 |
| Concrete Boxes | Smooth | 0.012-0.015 |
| Spiral Rip Metal Pipe | Smooth | 0.012-0.013 |
| Corrugated Metal Pipe, Pipe-Arch and Box (Annular or Helical Corrugations -- see Figure B-3 in Reference 2, Manning's n varies with barrel size) | 68 by 13 mm<br>2-2/3 by 1/2 in Annular | 0.022-0.027 |
| | 68 by 13 mm<br>2-2/3 by 1/2 in<br>Helical | 0.011-0.023 |
| | 150 by 25 mm<br>6 by 1 in<br>Helical | 0.022-0.025 |
| | 125 by 25 mm<br>5 by 1 in | 0.025-0.026 |
| | 75 by 25 mm<br>3 by 1 in | 0.027-0.028 |
| | 150 by 50 mm<br>6 by 2 in<br>Structural Plate | 0.033-0.035 |
| | 230 by 64 mm<br>9 by 2-1/2 in<br>Structural Plate | 0.033-0.037 |
| Corrugated Polyethylene | Smooth | 0.009-0.015 |
| Corrugated Polyethylene | Corrugated | 0.018-0.025 |
| Polyvinyl chloride (PVC) | Smooth | 0.009-0.011 |

*NOTE: Manning's n values indicated in this table were obtained in the laboratory and are supported by the provided reference. Actual field values for culverts may vary depending on the effect of abrasion, corrosion, deflection, and joint conditions.

The shape of a storm drain conduit also influences its capacity. Although most storm drain conduits are circular, a significant increase in capacity can be realized by using an alternate shape. Table 7-2 provides a tabular listing of the increase in capacity which can be achieved using alternate conduit shapes that have the same height as the original circular shape, but have a different cross sectional area. Although these alternate shapes are generally more expensive then circular shapes, their use can be justified in some instances based on their increased capacity.

In addition to the nomograph in Chart 23, numerous charts have been developed for conduits having specific shapes, roughness, and sizes. Reference 36 contains a variety of design charts for circular, arched, and oval conduits that are commonly used in the design of storm drainage systems.

**Table 7-2. Increase in Capacity of Alternate Conduit Shapes Based on a Circular Pipe with the Same Height.**

| | Area (Percent Increase) | Conveyance (Percent Increase) |
|---|---|---|
| Circular | -- | -- |
| Oval | 63 | 87 |
| Arch | 57 | 78 |
| Box (B = D) | 27 | 27 |

***Example 7-1***

***Given:*** *Q = 0.50 $m^3/s$ (17.6 $ft^3/s$)*
*$S_o$ = 0.015 m/m (ft/ft)*

***Find:*** *The pipe diameter needed to convey the indicated design flow. Consider use of both concrete and helical corrugated metal pipes.*

***Solution:***

***<u>SI Units</u>***

*(1) Concrete pipe*

*Using Equation 7-1 or Chart 23 with n = 0.013 for concrete*

$D = [(Q\ n)/(K_Q\ S_o^{0.5})]^{0.375}$
$D = [(0.50)(0.013)/\{(0.312)(0.015)^{0.5}\}]^{0.375}$
$D = 0.514\ m = 514\ mm$
*Use D =530 mm diameter standard pipe size.*

*(2) Helical corrugated metal pipe.*

*Using Equation 7-1 or Chart 23*
*Assume n = 0.017*

$D = [(Q\ n)/(K_Q\ S_o^{0.5})]^{0.375}$

***<u>English Units</u>***

*(1) Concrete pipe*

*Using Equation 7-1 or Chart 23 with n = 0.013 for concrete*

$D = [(Q\ n)/(K_Q\ S_o^{0.5})]^{0.375}$
$D = [(17.6)(0.013)/\{(0.46)(0.015)^{0.5}\}]^{0.375}$
$D = 1.69\ ft = (20.3\ in)$
*Use D = 21 in diameter standard pipe size.*

*(2) Helical corrugated metal pipe.*

*Using Equation 7-1 or Chart 23*
*Assume n = 0.017*

$D = [(0.50)(0.017)/\{(0.312)(0.015)^{0.5}\}]^{0.375}$
$D = 0.569$ m = 569 mm
*Use D = 610 mm diameter standard size. (Note: The n value for 610 mm = 0.017. The pipe size and n value must coincide as shown in Table 7-1.)*

$D = [(Q\ n)/(K_Q\ S_o^{0.5})]^{0.375}$
$D = [(17.6)(0.017)/\{(0.46)(0.015)^{0.5}\}]^{0.375}$
$D = 1.87$ ft = 22.4 in
*Use D = 24 in diameter standard size. (Note: The n value for 24 in = 0.017. The pipe size and n value must coincide as shown in Table 7-1.)*

***Example 7-2***

***Given:*** *The concrete and helical corrugated metal pipes in Example 7-1.*

***Find:*** *The full flow pipe capacity and velocity.*

***Solution:*** *Use Equation 7-1 or Chart 23.*

***SI Units***

*(1) Concrete pipe*

$Q = (K_Q/n)\ D^{2.67}\ S_o^{0.5}$
$Q = (0.312)/(0.013)\ (0.530)^{2.67}\ (0.015)^{0.5}$
$Q = 0.54\ m^3/s$

$V = (K_V/n)\ D^{0.67}\ S_o^{0.5}$
$V = (0.397)/(0.013)\ (0.530)^{0.67}\ (0.015)^{0.5}$
$V = 2.44$ m/s

***English Units***

*(1) Concrete pipe*

$Q = (K_Q/n)\ D^{2.67}\ S_o^{0.5}$
$Q = (0.46)/(0.013)\ (1.75)^{2.67}\ (0.015)^{0.5}$
$Q = 19.3\ ft^3/s$

$V = (K_V/n)\ D^{0.67}\ S_o^{0.5}$
$V = (0.59)/(0.013)\ (1.75)^{0.67}\ (0.015)^{0.5}$
$V = 8.0$ ft/s

***SI Units***

*(2) Helical corrugated metal pipe*

$Q = (K_Q/n)\ D^{2.67}\ S_o^{0.5}$
$Q = (0.312)/(0.017)\ (0.610)^{2.67}\ (0.015)^{0.5}$
$Q = 0.60\ m^3/s$

$V = (K_V/n)\ D^{0.67}\ S_o^{0.5}$
$V = (0.397)/(0.017)\ (0.610)^{0.67}\ (0.015)^{0.5}$
$V = 2.05$ m/s

***English Units***

*(2) Helical corrugated metal pipe*

$Q = (K_Q/n)\ D^{2.67}\ S_o^{0.5}$
$Q = (0.46)/(0.017)\ (2.0)^{2.67}\ (0.015)^{0.5}$
$Q = 21.1\ ft^3/s$

$V = (K_V/n)\ D^{0.67}\ S_o^{0.5}$
$V = (0.59)/(0.017)\ (2.0)^{0.67}\ (0.015)^{0.5}$
$V = 6.8$ ft/s

### 7.1.4 Energy Grade Line/Hydraulic Grade Line

The energy grade line (EGL) is an imaginary line that represents the total energy along a channel or conduit carrying water. Total energy includes elevation (potential) head, velocity head and pressure head. The calculation of the EGL for the full length of the system is critical to the evaluation of a storm drain. In order to develop the EGL it is necessary to calculate all of the losses through the system. The energy equation states that the energy head at any cross section must equal that in any other downstream section plus the intervening losses. The intervening losses are typically classified as either friction losses or form losses. Knowledge of the location of the EGL is critical to the understanding and estimating the location of the hydraulic grade line (HGL).

The hydraulic grade line (HGL) is a line coinciding with the level of flowing water at any point along an open channel. In closed conduits flowing under pressure, the hydraulic grade line is the level to which water would rise in a vertical tube at any point along the pipe. The hydraulic grade line is used to aid the designer in determining the acceptability of a proposed storm drainage system by establishing the elevation to which water will rise when the system is operating under design conditions.

HGL, a measure of flow energy, is determined by subtracting the velocity head ($V^2/2g$) from the EGL. Energy concepts, introduced in Chapter 5, can be applied to pipe flow as well as open channel flow. Figure 7-2 illustrates the energy and hydraulic grade lines for open channel and pressure flow in pipes.

When water is flowing through the pipe and there is a space of air between the top of the water and the inside of the pipe, the flow is considered as open channel flow and the HGL is at the water surface. When the pipe is flowing full under pressure flow, the HGL will be above the crown of the pipe. When the flow in the pipe just reaches the point where the pipe is flowing full, this condition lies in between open channel flow and pressure flow. At this condition the pipe is under gravity full flow and the flow is influenced by the resistance of the total pipe circumference. Under gravity full flow, the HGL coincides with the crown of the pipe.

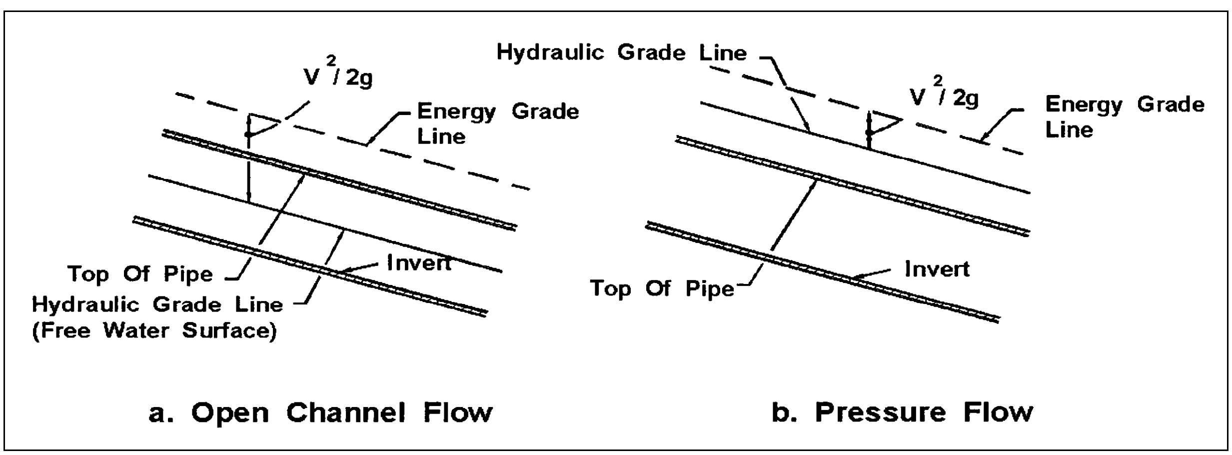


**Figure 7-2. Hydraulic and energy grade lines in pipe flow.**

Inlet surcharging and possible access hole lid displacement can occur if the hydraulic grade line rises above the ground surface. A design based on open channel conditions must be carefully planned as well, including evaluation of the potential for excessive and inadvertent flooding created when a storm event larger than the design storm pressurizes the system. As hydraulic calculations are performed, frequent verification of the existence of the desired flow condition should be made. Storm drainage systems can often alternate between pressure and open channel flow conditions from one section to another.

Methods for determining energy losses in a storm drain are presented in Section 7.1.6. A detailed procedure for evaluating the energy grade line and the hydraulic grade line for storm drainage systems is presented in Section 7.5.

### 7.1.5 Storm Drain Outfalls

All storm drains have an outlet where flow from the storm drainage system is discharged. The discharge point can be a natural river or stream, an existing storm drainage system, or a channel that is either existing or proposed for the purpose of conveying the storm water away from the highway. The procedure for calculating the energy grade line through a storm drainage system begins at the outfall. Therefore, consideration of outfall conditions is an important part of storm drain design.

Several aspects of outfall design must be given serious consideration. These include the flowline or invert (inside bottom) elevation of the proposed storm drain outlet, tailwater elevations, the need for energy dissipation, and the orientation of the outlet structure.

**The flowline or invert elevation** of the proposed outlet should be equal to or higher than the flowline of the outfall. If this is not the case, there may be a need to pump or otherwise lift the water to the elevation of the outfall.

**The tailwater depth or elevation** in the storm drain outfall must be considered carefully. Evaluation of the hydraulic grade line for a storm drainage system begins at the system outfall with the tailwater elevation. For most design applications, the tailwater will either be above the crown of the outlet or can be considered to be between the crown and critical depth of the outlet. The tailwater may also occur between the critical depth and the invert of the outlet. However, the starting point for the hydraulic grade line determination should be either the design tailwater elevation or the average of critical depth and the height of the storm drain conduit, $(d_c + D)/2$, whichever is greater.

An exception to the above rule would be for a very large outfall with low tailwater where a water surface profile calculation would be appropriate to determine the location where the water surface will intersect the top of the barrel and full flow calculations can begin. In this case, the downstream water surface elevation would be based on critical depth or the design tailwater elevation, whichever was highest.

If the outfall channel is a river or stream, it may be necessary to consider the joint or coincidental probability of two hydrologic events occurring at the same time to adequately determine the elevation of the tailwater in the receiving stream. The relative independence of the discharge from the storm drainage system can be qualitatively evaluated by a comparison of the drainage area of the receiving stream to the area of the storm drainage system. For example, if the storm drainage system has a drainage area much smaller than that of the receiving stream, the peak discharge from the storm drainage system may be out of phase with the peak discharge from the receiving watershed. Table 7-3 provides a comparison of discharge frequencies for coincidental occurrence for a 10- and 100-year design storm. This