Designing Storm Drain Inlets

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3 PDH HOURS

DESIGNING STORM DRAIN INLETS

When a storm sewer system is designed, determining the correct hydrology, calculating time of concentration, and determining rainfall are important components. Once the hydrology is completed, the focus moves to the storm sewer system to be sure that the pipes are large enough to convey the design flow. These are all necessary, important steps, but there is one more step necessary in designing a storm sewer. Calculating the number, size and location of the inlets is required to be sure that the design flows can reach the storm sewer pipes needs to be completed.

The primary purpose of this course is to describe the four different types of inlets that are commonly used, understand when and where they should be used, and become familiar with the equations related to sizing. An understanding of inlet design allows storm water engineers and managers to make decisions which will result in systems that will perform as intended.

TYPES OF INLETS

There are four common types of inlets used to convey storm water runoff into a storm sewer. These include grates, curb openings, combination inlets and slotted drains.

Grates

A storm drain grate is a feature that consists of a cast iron or ductile iron frame and a cast iron or ductile iron top that is mostly open. This casting allows the water from the street to be intercepted and transported to a below ground system. The grate is typically placed on a circular or rectangular concrete box and this entire structure is often called an inlet or catch basin. A pipe from the catch basin conveys the water to a manhole that is part of the storm sewer system. Sometimes, the catch basin also serves as a storm sewer manhole. In this case, the storm sewer is located in the gutter line of the roadway. Some entities consider this undesirable, while other entities see this as a way to reduce overall costs.

Municipalities often have a small number of grates that are standard for use within their jurisdiction. This is important because while grates are strong, they do sometimes break and need to be replaced. Having a small number of standard grates allows the municipality to have a small number of replacement grates on hand when one breaks.

Storm drain grates have a number of vertical bars in two directions (see Figure 1). These bars provide the structural support. Most grates are designed to be suitable for highway traffic loads, but it is important to verify this with the manufacturer. The bars impede the flow of water through the grate so fewer bars more widely spaced are most desirable from a hydraulic standpoint. A special type of grate is a vane-style grate (see Figure 2). With a vane-style grate, the bars on the grate are constructed at an angle, rather than vertical.

When water falls into an opening, it doesn't fall vertically but rather at an angle, depending on the velocity of the water. The vanes of a vane-style grate attempt to match the angle of flow, which makes them more efficient.

A grate inlet tends to be very effective at intercepting the flow in the gutter line that is within the width of the grate, but they are relatively ineffective at intercepting flow in the street that is beyond the width of the grate.

Grates are most commonly located immediately adjacent to the curb, in the concrete gutter. It is important to locate the grate as close to the curb as possible because the deepest flow is at the face of the curb. In parking lots, grates are located at the low point of an area of the parking lot, which can be anywhere in the lot. Grates can be used on a continuous grade or in a sag, or a low point the roadway profile. They are also used in sags in parking lots.

One disadvantage of grates is that they are subject to clogging by leaves and debris. In order to maintain the full capacity of a grate, routine maintenance is required. This condition tends to be more a problem in a sag condition than on a continuous grade because on a continuous grade, the flow can bypass the grate and continue to the next inlet, but in a sag, the water ponds until it overflows to some other location, which is usually an undesirable and unplanned condition. The impacts of clogging will be analysed further later in this course.

Figure 1 – Grate Inlet

Figure 2 – Vane Style Inlet

Curb Opening

The second type of inlet is a curb opening. A curb opening conveys water from the street sideways into an opening in the curb. This requires that the flow direction of the water is changed, which is an inefficient process. Some curb openings are constructed using a standard casting, similar to a grate (see Figure 3). These openings are typically relatively short (1-3 feet). Other curb openings are constructed by casting concrete around a form to create the opening in the concrete curb (see Figure 4). These openings can be much longer (20 feet or more).

A curb opening directs water to a catch basin or vault that is typically located under the sidewalk. The vault for the curb opening is as long as the opening, so for a long opening, the vault is a long structure. One advantage of a curb opening is that they are not as subject to clogging due to leaves and debris. Most of the time the leaves, small twigs and other debris will be washed into the vault and usually into the storm sewer system, leaving the inlet mostly clear. Curb openings can be used on a continuous grade or in a sag. They tend to be relatively inefficient on a continuous grade but are relatively efficient in a sag condition.

Figure 3 – Short Curb Opening Inlet

Figure 4 – Long Curb Opening Inlet

Combination Inlets

The third type of inlet is a combination inlet. This inlet consists of a standard grate with a small curb opening adjacent to the grate (see Figure 5). This inlet also has a catch basin or vault under the grate with the catch basin connected by a pipe to the storm sewer system.

The hydraulics of this inlet type are very similar to those of a standard grate inlet. The flow adjacent to the curb is intercepted by the grate. The curb opening provides very little additional capacity because under most flow conditions, the grate is adequate to intercept all of the flow adjacent to the curb. One advantage that a combination inlet does provide is that it is less susceptible to clogging. While a portion of the grate might become clogged, the curb opening will still function to intercept some water.

There are two basic types of combination inlets. Figure 5 shows an equal length combination inlet, where the length of the grate and the length of the curb opening are the same. The other type of combination inlet is a sweeper combination inlet. With a sweeper inlet, the curb opening is longer than the grate and the upstream part of the curb opening extends upstream from the grate. The advantage of a sweeper combination inlet is some of the trash and debris that is carried in the runoff gets swept into the curb opening before it has a chance to plug the grate.

Figure 5 – Combination Inlet

Slotted Drains

A slotted drain consists of a longitudinal opening in the gutter parallel to the curb line, connected to a corrugated galvanized steel pipe under the gutter (see Figure 6). The opening in the gutter consists of two long parallel pieces of steel about 2 inches apart (typically 3/16” thick), with steel spacers (also typically 3/16” thick) placed about every 6 inches along the length of the drain. The pipe under the opening can vary from 12-inch diameter to 36-inch diameter. Slotted drain is typically provided in 20-foot lengths but can be provided in 10-foot lengths. Additional sections of slotted drain can be connected together to create a length of more than 20 feet where required.

The slope on the pipe below the gutter is typically the same as the slope of the gutter so slotted drains are most commonly used on continuous grades. The pipe can be manufactured with a varying height grate, which can create up to a 1% slope even on a flat grade. This option is only available on lengths up to 20 feet.

Figure 6 – Slotted Drain

GUTTER FLOW CALCULATIONS

The capacity of an inlet on a continuous grade depends on the geometry and flow characteristics of the gutter. Therefore an examination of flow in a gutter is necessary to understand the capacity of an inlet.

There are two types of common gutter configurations. Figure 7 shows a uniform section, where the cross slope of the concrete gutter is the same as the cross slope (or crown) of the roadway section. Most roadways have a normal crown of 2% or 3%. Figure 8 shows a composite section, where the cross slope of the concrete gutter is different than the cross slope of the roadway section. Many standard details show the cross slope of the concrete gutter to be about 4%.

Integrating Manning's equation across width of gutter section yields:

$$Q = (K_u/n)\, S_x^{1.67}\, S_L^{0.5}\, T^{2.67} \qquad \text{Equation 1}$$

Where

Ku = 0.56
n = Manning's coefficient
S_x = Transverse slope (Cross-slope), ft/ft
S_L = Longitudinal slope, ft/ft
T = Top width, ft

Normally the design flow for a section of roadway is a known based on a hydrologic analysis. Equation 1 can be rearranged to solve for the top width, yielding Equation 2:

$T = [(Qn)/(Ku\ S_x^{1.67}\ S_L^{0.5})]^{0.375}$ Equation 2

Example 1: Find the top width for a flow of 1.2 cfs on a roadway with a uniform section, a cross-slope of 2%, a longitudinal slope of 0.5% and a Manning's roughness coefficient of 0.15:

$T = [(1.2)*(0.015)/(0.56\ (0.02)^{1.67}\ (0.005)^{0.5}\ )]^{0.375}$
T = 8.58 ft

The velocity of this flow is also important. The velocity in a uniform section can be easily solved by Equation 3:

Q = VA or V = Q/A Equation 3

The area of the flow is just the area of a triangle:

A = ½ * Top width * depth = ½ * 8.58 * (8.58*0.02) = 0.736 sq.ft.

So

V = Q/A = 1.2 cfs / 0.736 sq.ft. = 1.63 ft/sec.

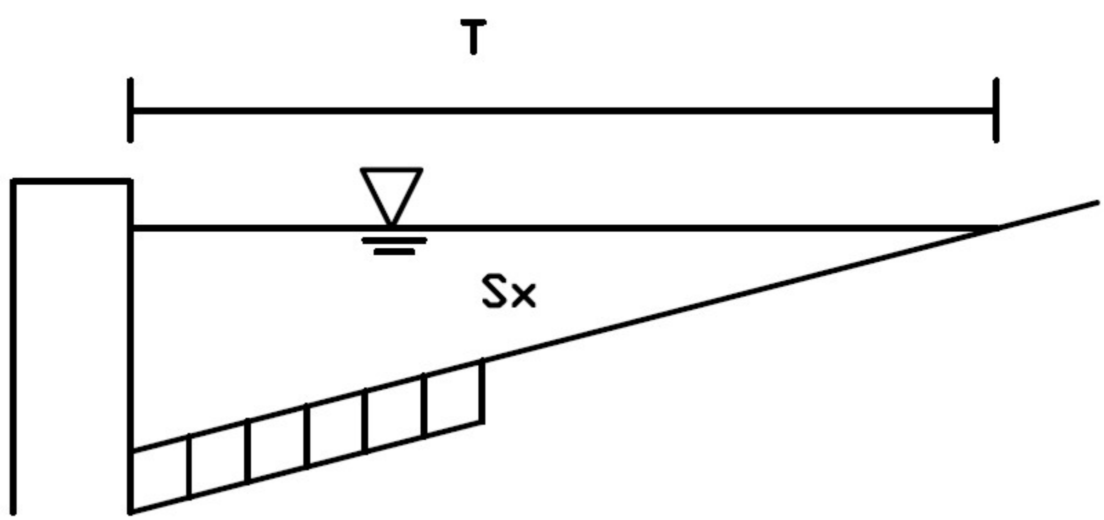


Figure 7 – Uniform Gutter Section

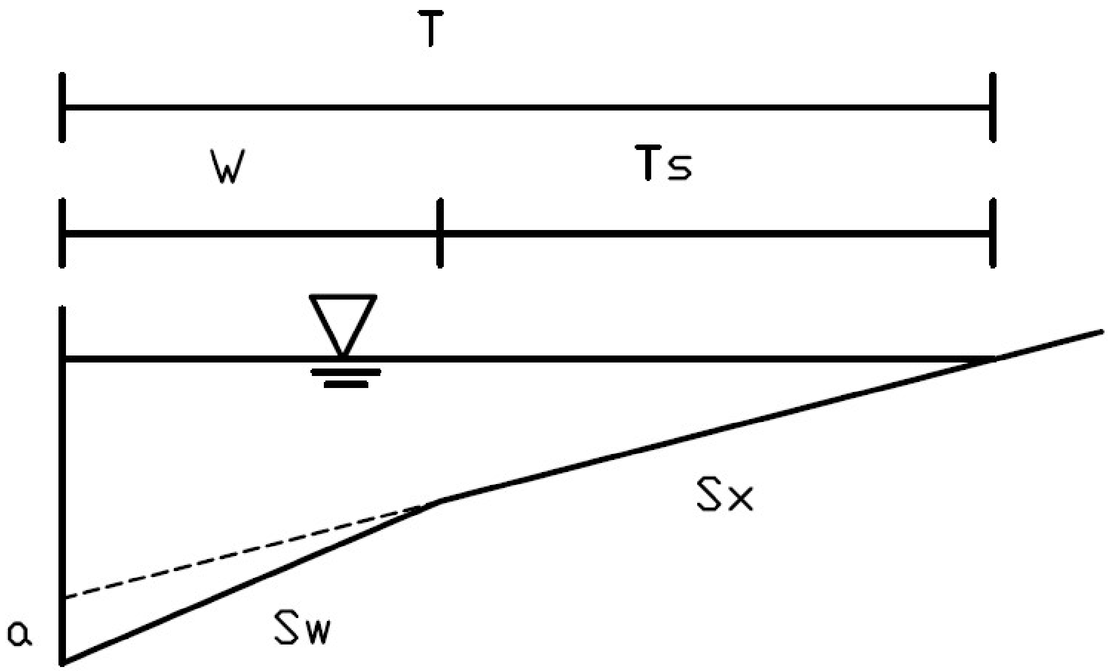


Figure 8 – Composite Gutter Section

The flow calculations for a composite section are much more complex. The first step is to calculate the ratio of flow in the width of the concrete gutter (Qw) to the total flow. This can be accomplished using Equation 4.

$$E_o = 1/\left\{1+\frac{S_w/S_x}{\left[1+\frac{S_w/S_x}{\frac{T}{W}-1}\right]^{2.67}-1}\right\}$$

Equation 4 – Ratio of gutter flow to total flow

The parameters in Equation 4 include:

Qw – Flow rate in the steeper section of the gutter, cfs

Q = Total flow rate, cfs

Qs = Flow rate beyond the steeper section of the gutter

Eo = Ratio of flow in the selected width to the total gutter flow

Sw = Slope of the steeper section of the gutter (Sx + a/W in Figure 8)

Equation 4 is used in conjunction with Equations 5 and 6 to determine the total flow.

$Qw = Q – Qs$ Equation 5

$Q = Qs / (1 – Eo)$ Equation 6

Example 2: Find the total flow for a top width of 8.58 feet. Use all the same parameters from Example 1, with the modification that the slope of the gutter (Sw) is 4% and the gutter is 2 feet wide.

Solving Equation 4 yields a value of Eo of 0.561, so 56.1% of the flow is contained in the two feet immediately adjacent to the curb.

In order to determine the flow beyond the steeper section, Equation 1 can be used with a top width equal to 8.58 – 2 = 6.58 feet. This yields a flow (Qs) equal to 0.59 cfs. Using this value and Eo in Equation 6 yields a total flow of 1.34 cfs. This compares to a flow of 1.2 cfs with the same top width and a uniform section (see Example 1).

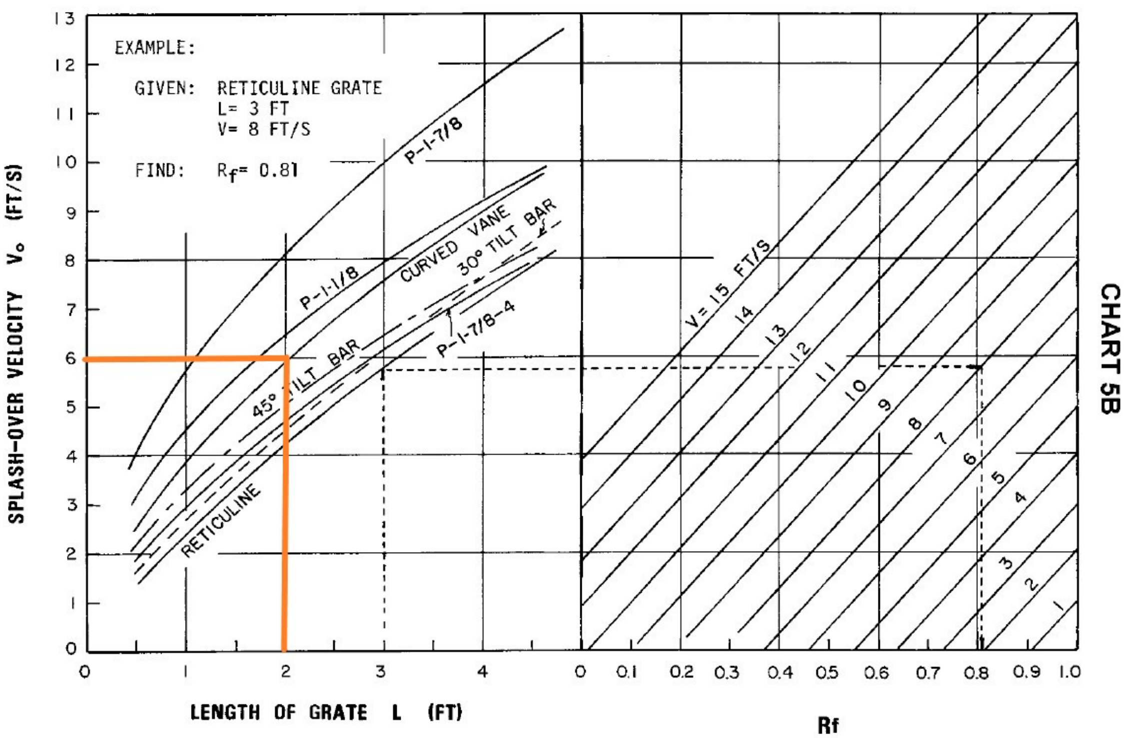
INLETS ON CONTINUOUS GRADES

Inlets can be placed at two distinctly different locations in the roadway profile and the flow calculations are much different for each location. Inlets can be placed along a continuous grade, where the roadway continues to slope down from the downstream end of the inlet. Inlets are placed along a continuous grade to intercept some of the water that flows in the gutter, so the flow width does not continue to increase. Inlets placed along a continuous grade can intercept a significant amount of water, but it is very difficult to intercept all of the water. When this happens, the water that is not intercepted is referred to as bypass flow, because it bypasses the inlet. If one inlet does not intercept a large enough percentage of the water a second inlet can be added. However, it is necessary to install the second inlet some distance from the first one. This concept will be discussed in more detail as part of this course.

The second location for inlets is in a sag or low point. In this location, the intent is for the inlet to intercept all of the water that reaches this location. If the inlet selected is too small, water may pond deeper than desired, or it may pond so deep that it overflows the low point in the roadway profile and starts to flood adjacent properties.

Splash Over Velocity

The first concept that needs to be addressed in the evaluation of inlets on a continuous grade is the splash over velocity for a grate. For any grate, at low velocity, all of the water that reaches the front of the grate will be intercepted by the grate. As the flow velocity increases, some of the water starts to splash beyond the front of the grate. With higher velocities, some of this water splashes past the end of the grate and continues to flow in the gutter downstream from the grate. The splash over velocity of a grate is a function of the length of the grate and the configuration of the grate. FHWA has conducted tests on a number of different types of grates to determine the splash over velocity. FHWA has published a chart showing the splash over velocity for these grates in HEC-22. Figure 9 shows Chart 5B from HEC-22.



. Grate Inlet Frontal Flow Interception Efficiency

Figure 9 – Splash over velocity for selected grates

The orange lines on Figure 9 represent an example of use of this figure. For a curved vane grate (such as that shown in Figure 2) that is 2 feet long (parallel to the direction of flow), the splash over velocity is about 6 feet per second. If the velocity in the gutter upstream from this grate is less than 6 feet per second, no flow will splash over the grate. However, that does not mean that the grate intercepts all of the flow.

Frontal Flow Interception

There are two different flow considerations in analyzing inlets on a continuous grade. The first type is called frontal flow. This is flow that is intercepted by the front of the grate (see Figure 10). The ratio of frontal flow to total flow is expressed by Equation 7.

$E_o = 1 - (1 - (W/T))^{2.67}$ Equation 7

Where:

W = width of the grate

T = Top width of the flow

For the flow in Example 1 (T = 8.58 ft), if the grate is 2.0 feet wide (perpendicular to the flow direction), the ratio of frontal flow to total flow is:

$Eo = 1 – (1 – (2.0/8.58))^{2.67} = 0.51$

So about 51% of the total flow is being conveyed in the 2-foot width closest to the curb or about 0.61 cfs of the 1.2 cfs total. While this portion of the gutter represents only about 23% of the flow width, the flow depth is obviously greatest next to the curb, so it should not be surprising that the frontal flow is significantly greater than 23% of the total flow.

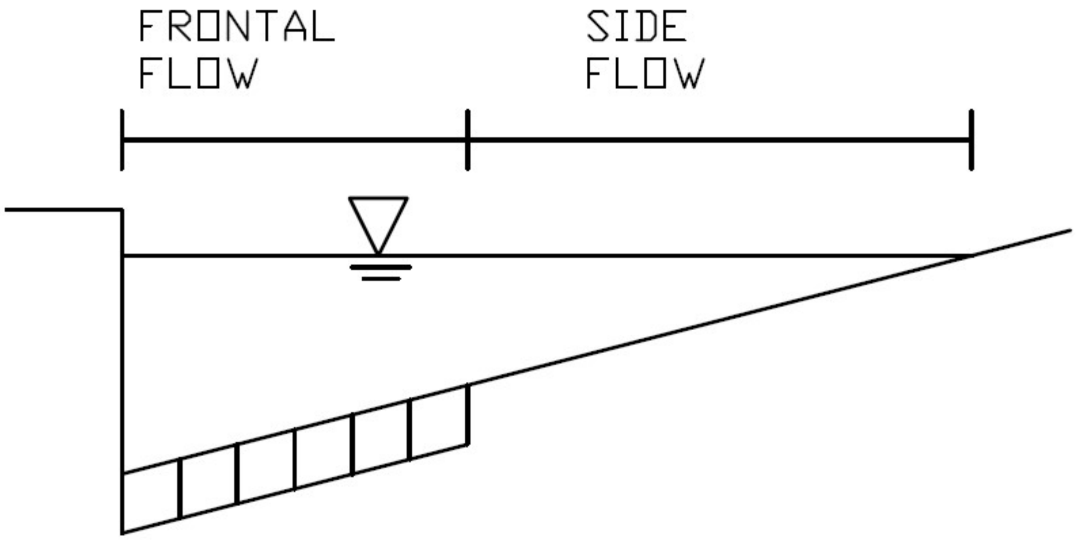


Figure 10 – Frontal flow and side flow on a continuous grade

Grates tend to be very efficient at intercepting frontal flow. The efficiency of frontal flow interception can be calculated using Equation 8.

$Rf = 1 – K (V – Vo)$ Equation 8

Where:

Rf = ratio of frontal flow intercepted

K = constant, 0.09

V = velocity of flow in the gutter

Vo = splash over velocity for the selected grate

For a 2-foot wide, 2-foot long vaned-style grate in Example 1, with a splash over velocity of 6 feet per second and a gutter velocity of 1.63 feet per second, solving Equation 8 yields:

$Rf = 1 – 0.09 * (1.63 – 6.0) = 1.39$

This would indicate that the grate will intercept 139% of the frontal flow. This is not a reasonable result however, because the grate cannot intercept more than 100% of the frontal flow, so the actual value of Rf in this case is 1.0 or. The fact that the equation yields a value greater than 1.0 simply means that the velocity in the gutter as the water reaches the grate is less than the splash over velocity, so no water splashed over the grate.

Side Flow Interception

The second flow consideration is side flow. When the width of flow is greater than the width of the grate, some of the flow is moving past the grate closer to the centerline of the roadway. This flow cannot be intercepted by the front of the grate and therefore must be intercepted by the side of the grate.

In order for the flow beyond the grate to be intercepted by the grate, the flow direction has to be changed. The flow direction is parallel to the curb as the flow reaches the grate. The transverse slope (or roadway crown) tends to move the water closer to the curb, so this slope starts to re-direct the water adjacent to the grate into the grate. This is an inefficient process.

The ratio of side flow intercepted can be calculated using Equation 9.

$Rs = 1 / \{1 + [(Ks * V^{1.8})/(S_x * L^{2.3})]\}$ Equation 9

Where

Ks = constant, 0.15

V = gutter velocity

S_x = transverse slope

L = Length of grate

Continuing the example using a 2-foot wide, 2-foot long vaned-style grate in Example 1, the ratio of side flow intercepted would be:

$Rs = 1 / \{1 + [(0.15 * 1.63^{1.8})/(0.02 * 2^{2.3})]\} = 0.214$

So about 21.4% of the water flowing beyond the edge of grate is re-directed into the grate. The total side flow is the total flow (1.2 cfs) minus the frontal flow (0.61 cfs) or about 0.59 cfs. The amount of this that is intercepted is 0.214 * 0.59 = 0.13 cfs. The total flow intercepted by this grate is therefore 0.61 cfs of frontal flow plus 0.13 cfs of side flow, or about 0.74 cfs. This represents about 62% of the total flow.

To further illustrate the impact of frontal flow and side flow, another example will be examined. In this example, the flow parameters are the same as in Example 1, but a rectangular grate, rather than a square grate will be used. The grate will have dimensions of 2-feet by 3-feet. If this grate is installed so that the 2-foot dimension is parallel to the roadway, the width of frontal flow is 3 feet and the total water intercepted increases from 0.74 cfs to about 0.93 cfs. If the grate is rotated 90 degrees so that the 2-foot dimension is perpendicular to the roadway, the width of frontal flow is 2 feet and the total water intercepted increases from 0.74 cfs to 0.85 cfs. These values represent 78% of the total flow and 71% of the total flow, respectively, for the larger grate.

INLETS IN SAGS

When an inlet is placed is a sag, it normally will intercept 100% of the flow that reaches the inlet. The water will pond over the inlet until the hydraulic conditions are such that all of the water goes into the inlet. However, if the water gets deep enough, it may overflow the sag of the roadway. This could occur if the water gets over the top of the curb. It could also occur when the sag is created by the normal crowns of intersecting streets. In this condition, the depth of the sag is small, often less than the height of the curb. Installing an adequate number of inlets in a sag will control the depth of ponding that occurs.

An inlet in a sag can function as either a weir or an orifice, depending on the depth of water. Normally the inlet will function as a weir at small depths, transitioning to orifice flow as the depth increases. The only way to know for sure the flow regime is to calculate the flow at a given depth using both the weir equation and the orifice equation. The smaller flow value will determine the type of control.

Weir Capacity

To determine the capacity in weir control, Equation 10 can be used:

$$Q = CLH^{1.5} \qquad \text{Equation 10}$$

Where:

Q = Flow in cfs
C = Weir coefficient (generally between 2.6 and 3.3)
L = length of weir, ft
H = Head (or water depth), ft

The length of the weir is a function of the size of the grate and also the location. If the grate is located immediately adjacent to the curb (see Figure 1), water can enter the grate from only three sides.

Example 3: Find the flow capacity of a 2.0-foot wide (perpendicular to the curb) by 2.5-foot long (parallel to the curb) grate in a sag, if the water depth is 0.2 ft. The grate is on a roadway with a standard crown of 2%. Determine if the grate is functioning as a weir or an orifice.

For the first part of Example 3, it is necessary to determine the weir flow capacity. For the length of the weir, there are two sides each 2.0 feet long and one side 2.5 feet long.

This yields a total weir length of 6.5 feet. If the water depth is 0.2 feet at the face of the curb, the water depth at the edge of the grate farthest from the curb is 0.2 ft – (2 ft * 0.02 ft/ft) = 0.16 ft. The average depth is therefore (0.20 + 0.16)/2 = 0.18 ft. If the average depth is used in Equation 10, with a weir coefficient of 3.0, the flow would be:

$$Q = (3.0) * (6.5) * (0.18^{1.5}) = 1.49 \text{ cfs.}$$

A more rigorous analysis of the hydraulics would indicate that the average depth of 0.18 ft is only appropriate for the two sides that are perpendicular to the curb and a depth of 0.16 ft is technically correct for the one side parallel to the curb. With this adjustment, the corrected flow would be:

$$Q = (3.0) * (4.0) * (0.18^{1.5}) + (3.0) * (2.5) * (0.16^{1.5}) = 1.40 \text{ cfs.}$$

Orifice Capacity

To determine the capacity in orifice control, Equation 11 can be used:

$$Q = C\,Ag\,(2\,g\,d)^{0.5} \qquad \text{Equation 11}$$

Where:
Q = Flow in cfs
C = Orifice coefficient (generally between 0.60 and 0.67)
Ag = Open area of the grate, sq.ft.
g = acceleration due to gravity (ft/sec/sec)
d = depth of water, ft

The open area of the grate is the amount of the grate that is not blocked by the vertical bars that make up the grate. This value is unique for each manufacturer's grate design. The best source of information on this parameter is obtained from the manufacturer. These values will generally be in the range of 60% to 70% of the total area of the grate.

Example 3 (continued): Assume the open area of the grate is 3 square feet (60% open) and a reasonable orifice coefficient is 0.65.

Orifice capacity is:

$$Q = 0.65 * (3.0) * (2 * 32.2 * 0.18)^{0.5} = 6.64 \text{ cfs}$$

Based on this analysis, the capacity of this grate in weir flow is 1.40 cfs and in orifice flow is 6.64 cfs. The grate will therefore function as a weir at this depth, and the capacity will be 1.40 cfs.

CURB OPENINGS

As noted earlier, curb openings are used in many geographic areas. The hydraulic analysis of a curb opening requires a different set of equations. In order for the water flowing in a gutter on a continuous grade to drop into a curb opening, it has to change directions. This is similar to the process required for side flow interception of a grate, which as indicated has a relatively low efficiency. The equations for analyzing a curb opening are based on laboratory testing and don't conveniently fall into the categories of weir flow or orifice flow. They are essentially a side-opening weir, which is a very specialized category of weir that is not frequently used.

The first step in the hydraulic analysis of a curb opening on a continuous grade is to determine the length of opening that is necessary to intercept 100% of the flow. Equation 12 can be used to calculate this length:

$L_T = Kc\ Q^{0.42}\ S_L^{0.3}\ [1/(n\ S_x)]^{0.6}$ Equation 12

Where:

L_T = Length of curb opening required for 100% interception, ft

Kc = Constant, 0.6

Q = Design flow, cfs

S_L = Longitudinal slope, ft/ft

n = Manning's roughness coefficient

S_x = Transverse slope, ft/ft

Example 1, solution for curb opening: Find the length of curb opening required to intercept 100% of the flow, for a flow of 1.2 cfs on a roadway with a uniform section, a cross-slope of 2%, a longitudinal slope of 0.5% and a Manning's roughness coefficient of 0.15:

$L_T = 0.6 * (1.2)^{0.42} * (0.005)^{0.3}\ [1/(0.015)*(0.02))]^{0.6}\ = 17.0$ ft

In order to intercept the entire 1.2 cfs, a curb opening 17 feet long would be necessary.

If this length of curb opening is not constructed, or not desirable, the next step is to calculate the efficiency of the selected opening length. Equation 13 can be used to calculate the efficiency of a shorter curb opening length:

$E = 1 - [1 - (L/L_T)]^{1.8}$ Equation 13

For example, if an 8-foot long curb opening is constructed for Example 1, the efficiency would be:

$E = 1 - [1 - (8/17)]^{1.8}\ = 0.677$

An 8-foot long curb opening would therefore intercept about 0.677 * 1.2 cfs = 0.81 cfs. This compares to 0.74 cfs intercepted by a 2-foot wide, 2-foot long grate.

To increase the capacity of a curb opening, the gutter adjacent to the curb opening is often depressed, creating a gutter section similar to a composite section (see Figure 8). If this is the case, Equation 12 can be modified to use the effective slope, Se, rather than the transverse slope, Sx. Equation 14 can be used to calculate the effective slope:

Se = Sx + a/W Equation 14

Where

Se = Effective slope

Sx = Transverse slope

a = depth of gutter depression (see a in Figure 8)

W = width of concrete gutter

If the curb opening in Example 2 is modified to depress the curb opening by 1 inch (0.08 ft), then the effective slope becomes:

Se = 0.02 + (0.08/2) = 0.06 ft/ft

Using an effective slope of 0.06 ft/ft in Equation 12, the required length for 100% interception is 8.8 feet, instead of 17 feet. If an 8-foot opening is used, it will intercept 1.18 cfs, or about 98.5% of the total flow. This example shows that a depressed curb opening is much more efficient than a standard curb opening.

For a curb opening in a sag, the opening will function as a weir, and the calculation of depth can be completed using Equation 10.

Curb Openings for LID features

Curb openings are commonly used to direct flow from a roadway gutter to a Low Impact Development (LID) feature adjacent to the roadway. However, the hydraulics of the curb opening are clearly often overlooked because many LID features have very short curb openings. In many cases, the curb opening is only 12 inches to 18 inches wide. Example 4 provides a case of a relatively low flow through a short curb opening.

Example 4: Design flow is 0.5 cfs, longitudinal slope is 0.5%, transverse slope is 2.0%. Solving Equation 12, the required curb length to intercept 100% of the flow is 11.7 feet. Using Equation 13, the efficiency of a 1.5-foot long curb opening is 0.216, so the opening will intercept about 0.11 cfs of the 0.5 cfs flowing past the opening. If the design flow is only 0.2 cfs, the 1.5-foot long opening is about 31% efficient and intercepts about 0.06 cfs, so even at very low flows, a high percentage of the flow bypasses the curb opening.

Figure 11 shows a curb opening into an LID feature. Water is flowing from right to left in this picture. The width of flow is about equal to the width of the concrete gutter (about 18 inches) but some flow is already bypassing this curb opening. The picture was taken shortly after the curb opening was constructed, and even in the short time period that this opening has been in place, some sediment is starting to build up in the opening. Due to the flow path from the gutter into the concrete opening, sediment is accumulating inside the opening on the upstream side. This process will continue and the capacity of the opening will be reduced by the presence of this sediment.

Figure 11 – Curb opening into LID feature

USE OF FHWA SOFTWARE

This course has presented information on a variety of inlet configurations and the associated equations needed to appropriately analyze the inlet capacity. This information is useful in selecting the appropriate size and number of inlets. The equations, while not extremely complex, can be somewhat cumbersome to work with. The Federal Highway Administration (FHWA) has developed software that solves a number of different hydraulic situations encountered during roadway design, including inlet capacity. This software is in the public domain and therefore free for download. It can be found by searching for “FHWA Hydraulic Toolbox.” When the software is loaded and opened, the start window is shown in Figure 12.

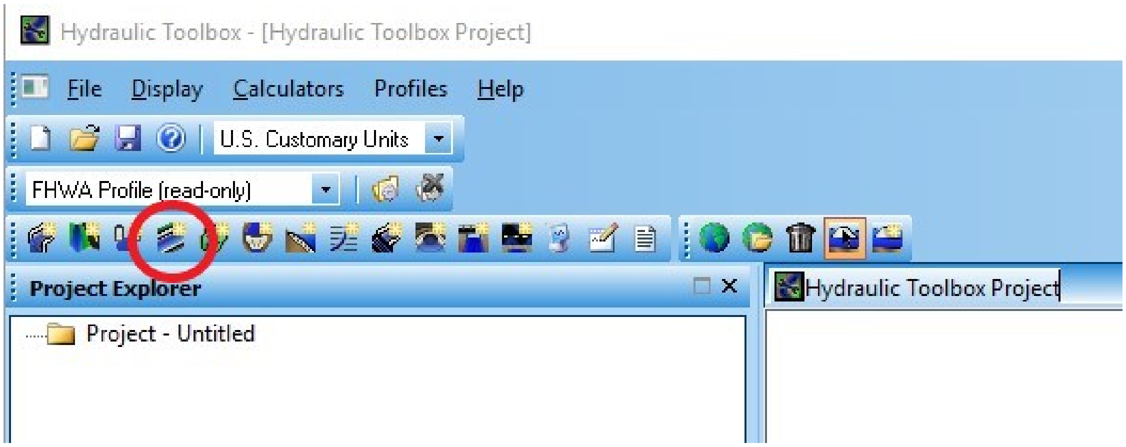


Figure 12 – FHWA Hydraulic Toolbox, Start Page

The icon circled in red on Figure 12 is "New Curb and Gutter Analysis." When this icon is clicked, a curb and gutter analysis line will show up below the project line. Clicking on this line will open up the data entry window (see Figure 13). The types of inlets that can be analyzed by this tool include:

- Inlet on grade
- Inlet in sag
- Grate
- Curb-opening
- Slotted Drain
- Sweeper Combination
- Equal Length Combination

Detailed pictures of the grate types are shown in FHWA Publication HEC-22. These types include:

- P – 1-7/8
- P – 1-7/8-4
- P – 1-1/8
- Curved Vane
- 45-degree tilt bar with 2-1/4 inch
- 45-degree tilt bar with 3-1/4 inch
- 30-degree tilt bar
- Reticuline

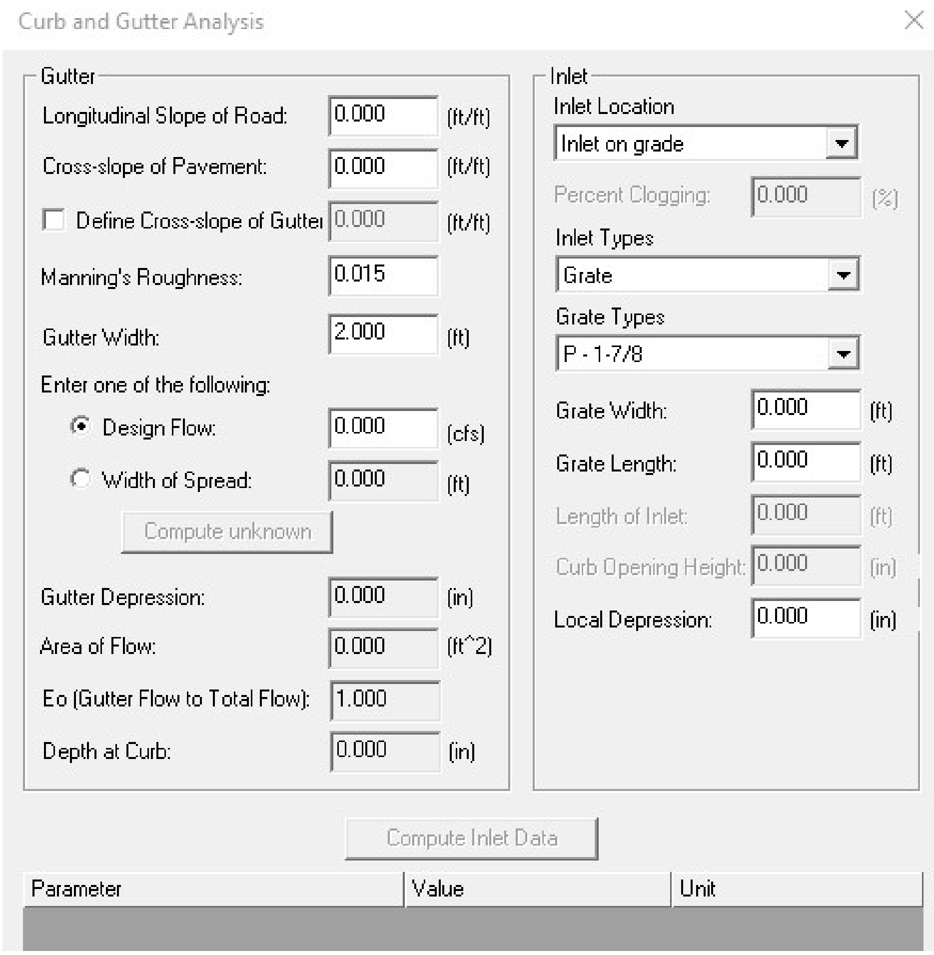


Figure 13 – Curb and Gutter Analysis Data Window

The window in Figure 14 is filled in with the data from Example 1, using a 2-foot by 2-foot curved vane grate. The hand calculation presented previously in this course showed an interception total of 0.74 cfs, essentially matching the 0.736 cfs in Figure 14. The use of this software package allows for an easy analysis of a wide variety of configuration options.

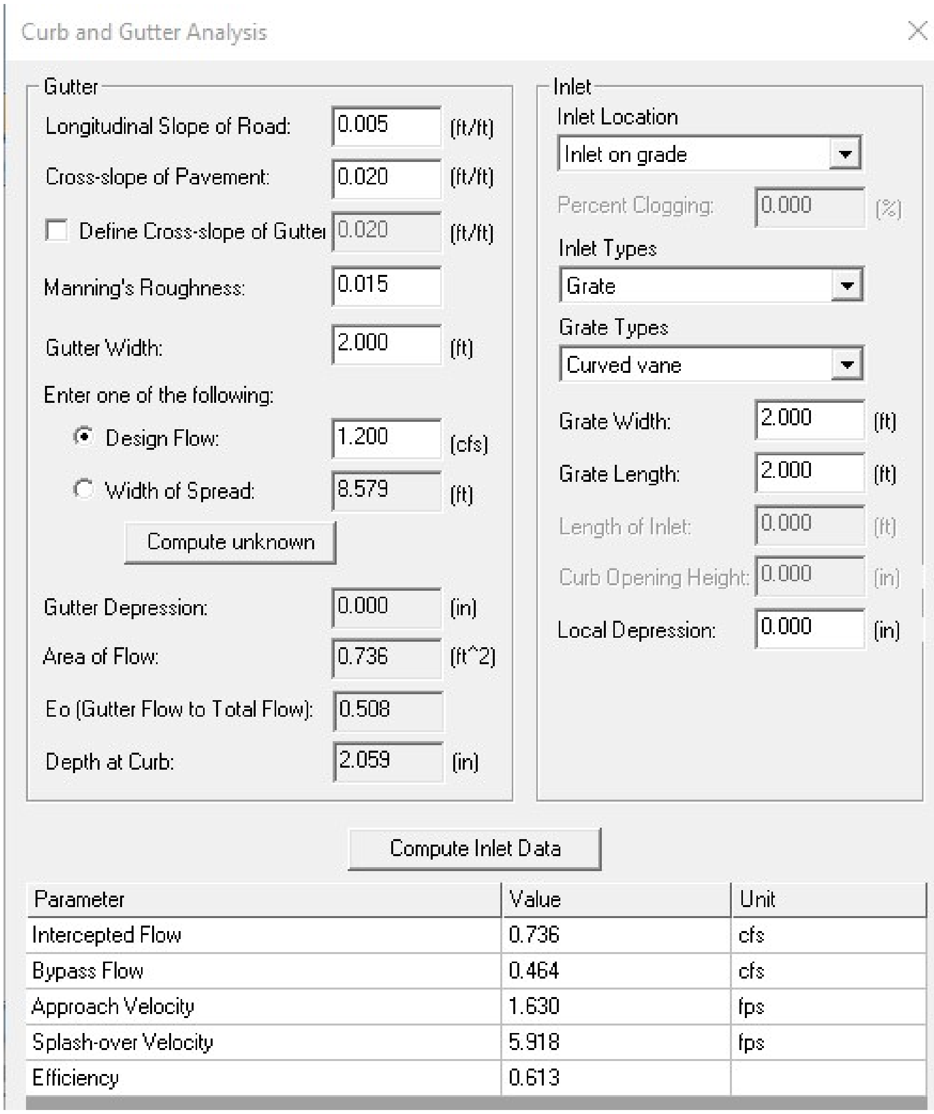


Figure 14 – Example 1 with curved vane grate

MULTIPLE INLETS

When one inlet does not intercept enough water, it is common practice to add a second inlet. It is also fairly common for design engineers to assume that adding a second inlet will simply double the inlet capacity. Through the use of the FHWA Hydraulic Toolbox, this assumption will be analyzed.

Multiple inlets on a continuous grade

The first case to be reviewed is multiple inlets on a continuous grade. The conditions in Example 2 will be carried into Example 4.

Example 4:

Design flow = 1.2 cfs

Longitudinal slope = 0.5%

Transverse slope = 2.0%

Mannings n = 0.015

The configuration of the inlets will make a significant difference in the ability of the second inlet to intercept additional flow. The first option analyzed (see Figure 15) assumes that the second inlet is placed adjacent to the curb, immediately downstream from the first inlet. This makes the inlet configuration the same as a curved vane inlet with a width of 2 feet and a length of 4 feet. As shown in Figure 14, a single inlet intercepts 61.3% of the total flow. As shown in Figure 15, the double inlet with both grates against the curb increases the interception efficiency to 79.0%.

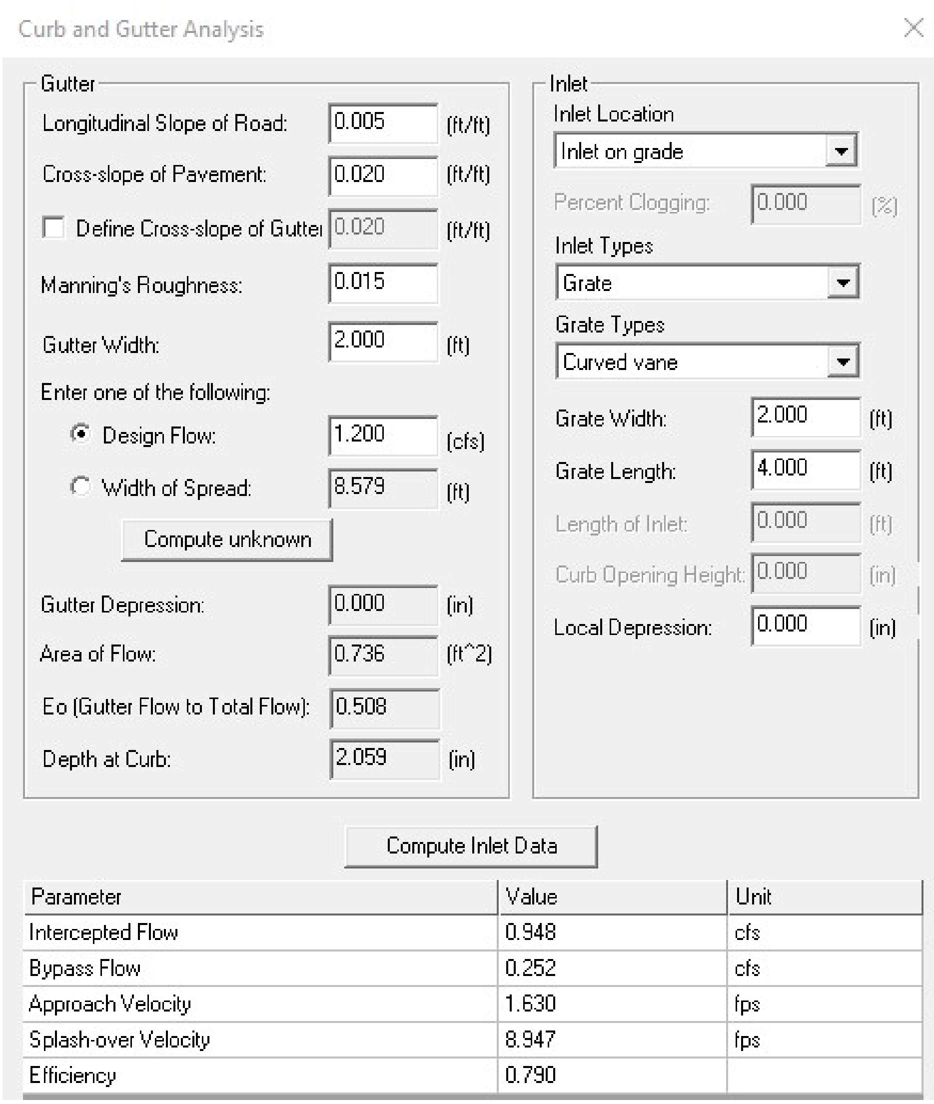


Figure 15 – Example 4, double inlets parallel to curb

The second option is to install the grates so that they extend 4 feet out from the face of the curb. As shown in Figure 16, this results in the efficiency being increased to 90.7%.

While one inlet intercepts 61.3% of the total flow, a second inlet does not increase the interception efficiency to 100%. In fact, if the second inlet is placed against the curb, the second inlet only increases the interception efficiency by 17.7%.

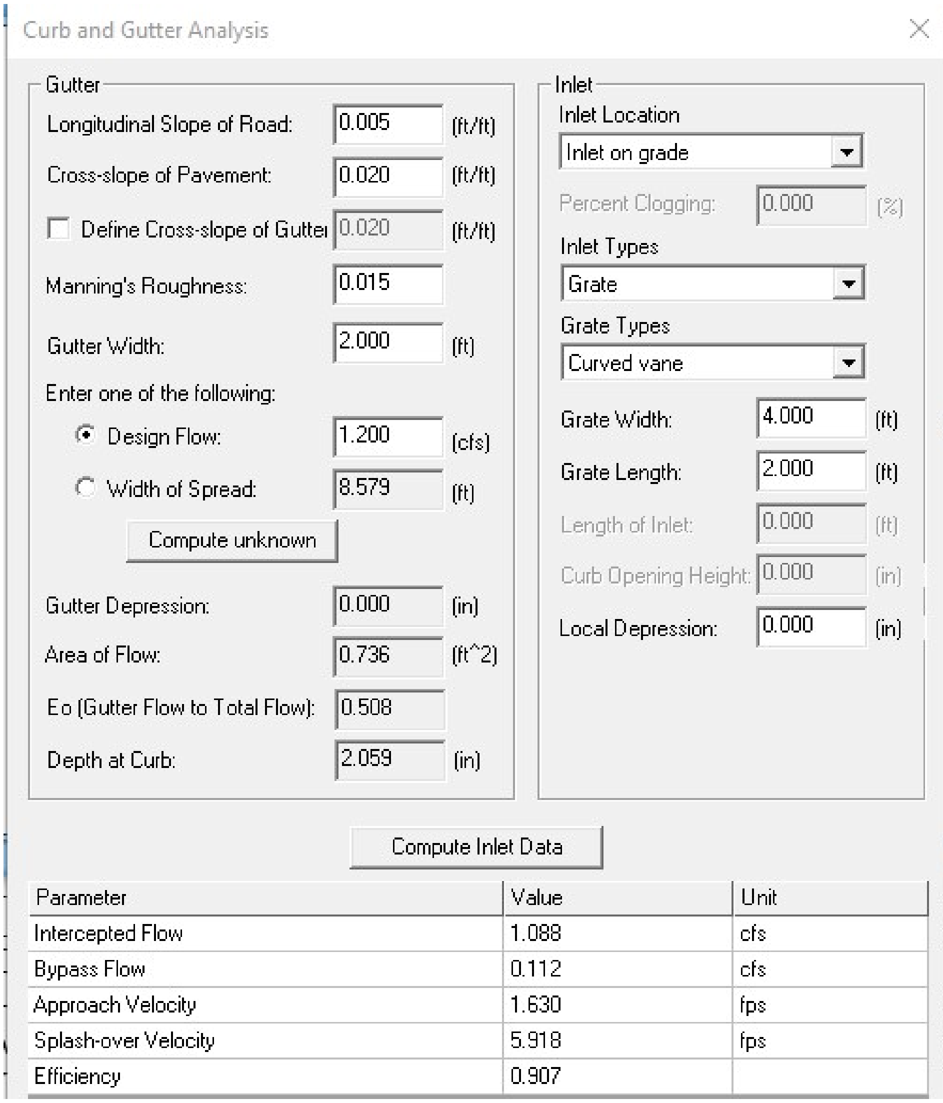


Figure 16 – Example 4, double inlets perpendicular to curb

As an alternative to adding a second grate immediately adjacent to the first grate, the second grate can be constructed downstream from the first grate (see Figure 17). In Figure 17, the flow is from the bottom of the picture towards the top of the picture. Water that bypasses the first grate has the opportunity to move towards the curb after the first grate. When this water encounters the second grate, it is now frontal flow for the second grate. As indicated earlier in this course, grates are much more effective intercepting frontal flow than they are intercepting side flow. If the grates are far enough apart, they will function independently because all of the bypass flow from the first grate will reach equilibrium in the gutter. The appropriate spacing for multiple grates in this configuration is not well defined. The necessary distance is a function of the cross-slope of the roadway along with the longitudinal slope of the roadway. The combination of these two slopes will create a resultant slope that will direct the bypass flow towards the curb. However, the momentum of the water will tend to move the flow in a longitudinal direction also, so a single resultant flow direction is complex.

Figure 17 – Double inlets, spaced 8 feet apart

Multiple inlets in a sag

When multiple inlets are placed in a sag location, proper hydraulic analysis of the inlets requires an adequate description of how the inlets are configured. Revisiting Example 3 to add a second grate:

Example 3: Find the flow capacity of a 2.0-foot wide (perpendicular to the curb) by 2.5-foot long (parallel to the curb) grate in a sag, if the water depth is 0.2 ft (average depth of 0.18 ft). The grate is on a roadway with a standard crown of 2%. This grate was determined to be functioning as a weir with a capacity of 1.4 cfs. These results are very similar to what was found using the FHWA Hydraulic Toolbox (see Figure 18).

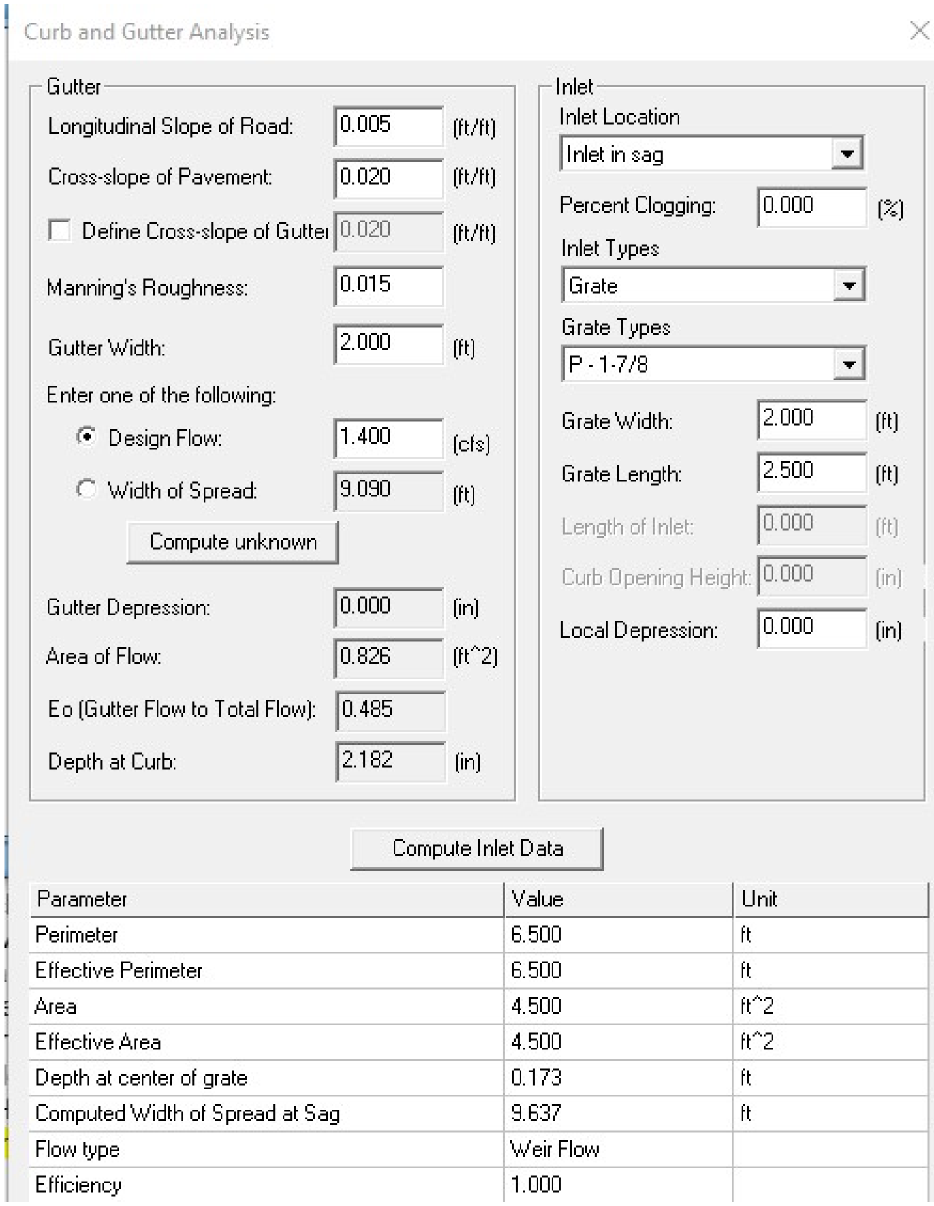


Figure 18 – Single grate in a sag

If a second grate is added parallel to the curb, then the total length of the grate is 5.0 feet. Figure 19 shows the results of this analysis if the depth at the center of the grate remains about 0.18 ft (depth at the curb is 0.20 ft). The flow into the grate increases from 1.4 cfs to about 2.0 cfs. This represents an increase of 0.6 cfs or about 43%, much less than doubling the capacity.

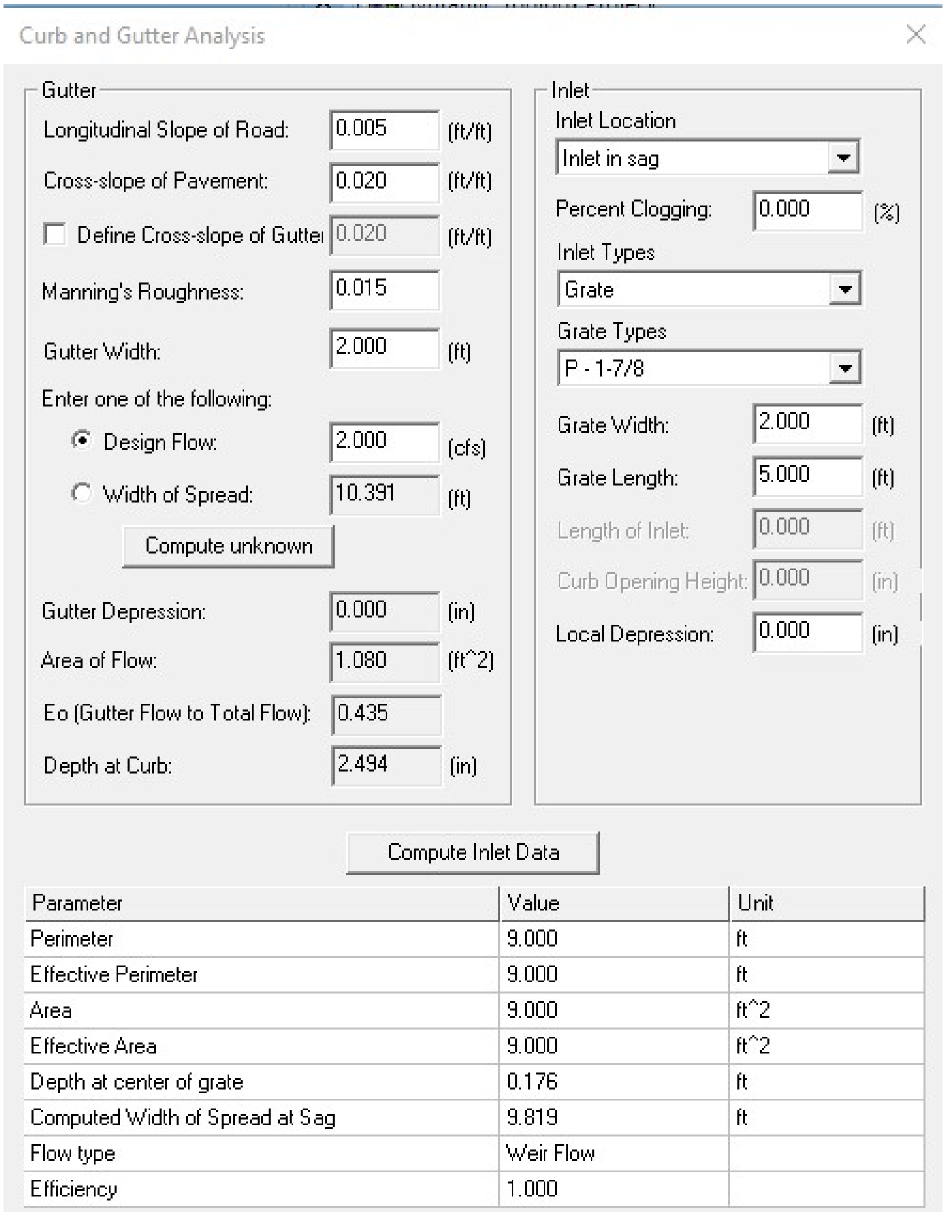


Figure 19 – Double grate in a sag

Grates are also located in parking lots where flow can enter the grate from all four sides (see Figure 20). When multiple grates are included, the configuration determines how they will function. In the configuration shown in Figure 20, there is very little room between the two grates, so they will essentially function as a single grate with the overall dimensions of the two grates combined. The FHWA Hydraulic Toolbox is not designed to analyze this type of grate configuration. It will only analyze grates that are next to a curb. The software can be manipulated to approximate this condition, but care should be taken when doing this.

Figure 20 – Multiple grates in a parking lot

INLET CLOGGING

One of the challenges of using grates for inlets is that they are subject to being clogged by leaves, trash and other debris. Some jurisdictions require that the design engineer consider this clogging as part of the design effort. Few design manuals provide a very good description of what this actually means, however. The typical approach is to include a statement such as "use a 35% clogging factor for grates, apply to open area of grate." The intent of these types of requirements is to consider that the capacity of an inlet can be reduced due to clogging. How these requirements are implemented, however, is often a function of the knowledge of the design engineer. In some cases, they will just assume that the inlet has 35% less capacity. However, the use of the FHWA Hydraulic Toolbox allows for a careful analysis of how clogging might actually impact the capacity of the inlet.

Clogging on a continuous grade

When a grate on a continuous grade is clogged, it is typically the front of the grate that is covered. If a grate is 2 feet long and 2 feet wide and the front 35% of the grate is clogged, the functional part of the grate changes from 2 feet wide to 1.3 feet long. Using the FHWA toolbox and the parameters in Example 1, Figure 14 shows that the grate is 61.3% efficient if there is no clogging. Figure 21 shows this same grate assuming that it is 35% clogged. The grate is 55.3% efficient and the intercepting flow is reduced from 0.736 cfs to 0.664 cfs. This represents a reduction in capacity of only 0.072 cfs, or about 10%.

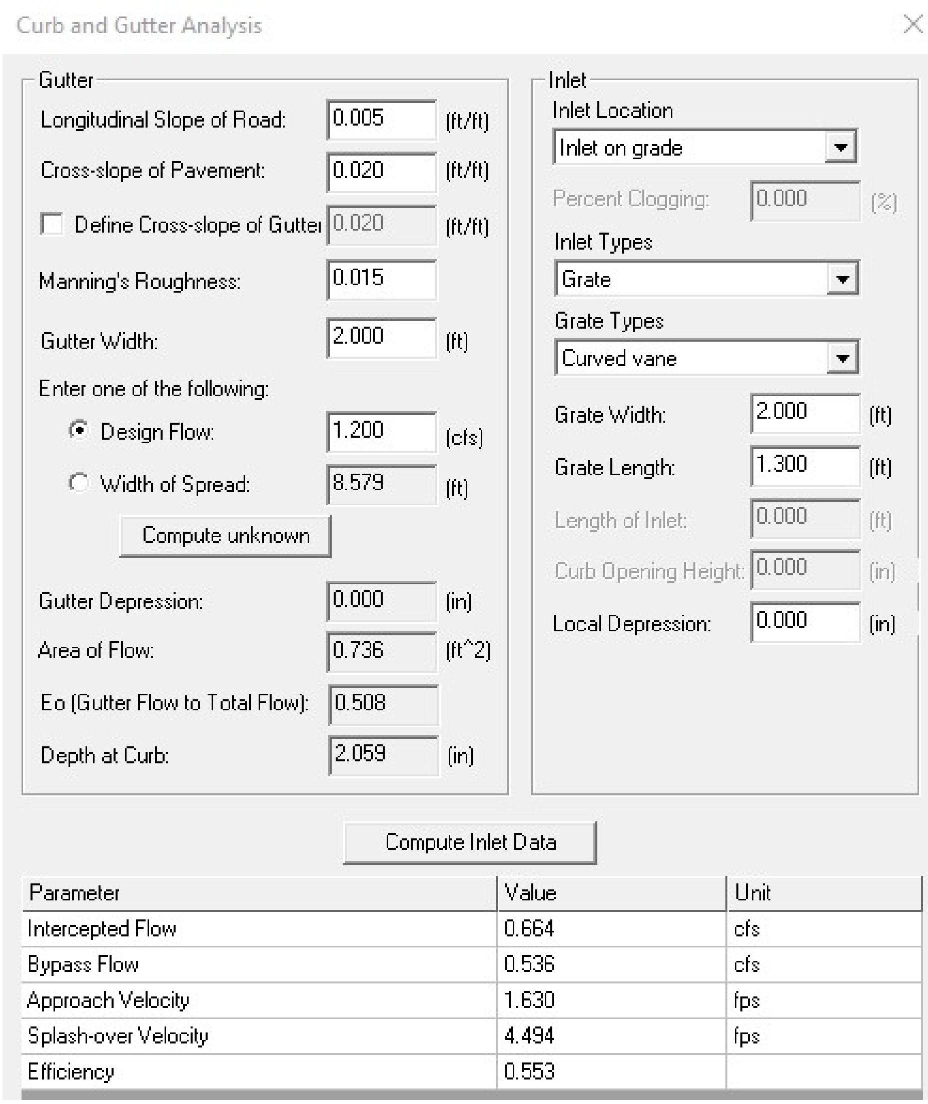


Figure 21 – Grate on a continuous grade, 35% clogged

Clogging in a sag

When an inlet in a sag is clogged, the open area of the grate is reduced and the perimeter of the weir is reduced. In most cases of flow in a roadway, the grate is functioning as a weir, so the clogging reduces the weir length.

Example 3 presented the results of a 2-foot by 2.5-foot grate in a sag, showing that the capacity was about 1.4 cfs at a maximum depth of 0.20 ft (average depth of 0.18 ft). See Figure 18. If the grate is clogged by 35%, this would effectively reduce the length of the grate by 35%, to 1.75 feet. Making this change in the FHWA Hydraulic Toolbox yields a capacity at an average depth of 0.18 ft. of about 1.3 cfs, a reduction of about 7% (see Figure 22). The FHWA Hydraulic Toolbox also has an option to input the percent clogging, which is available only when the inlet location is in a sag. Using this option with a 35% clogging factor results in a capacity of about 0.95 cfs at an average depth of 0.18 ft. (see Figure 23). This is essentially a reduction of 35% of the capacity. This exercise indicates the importance of proper definition of the clogging percentage.

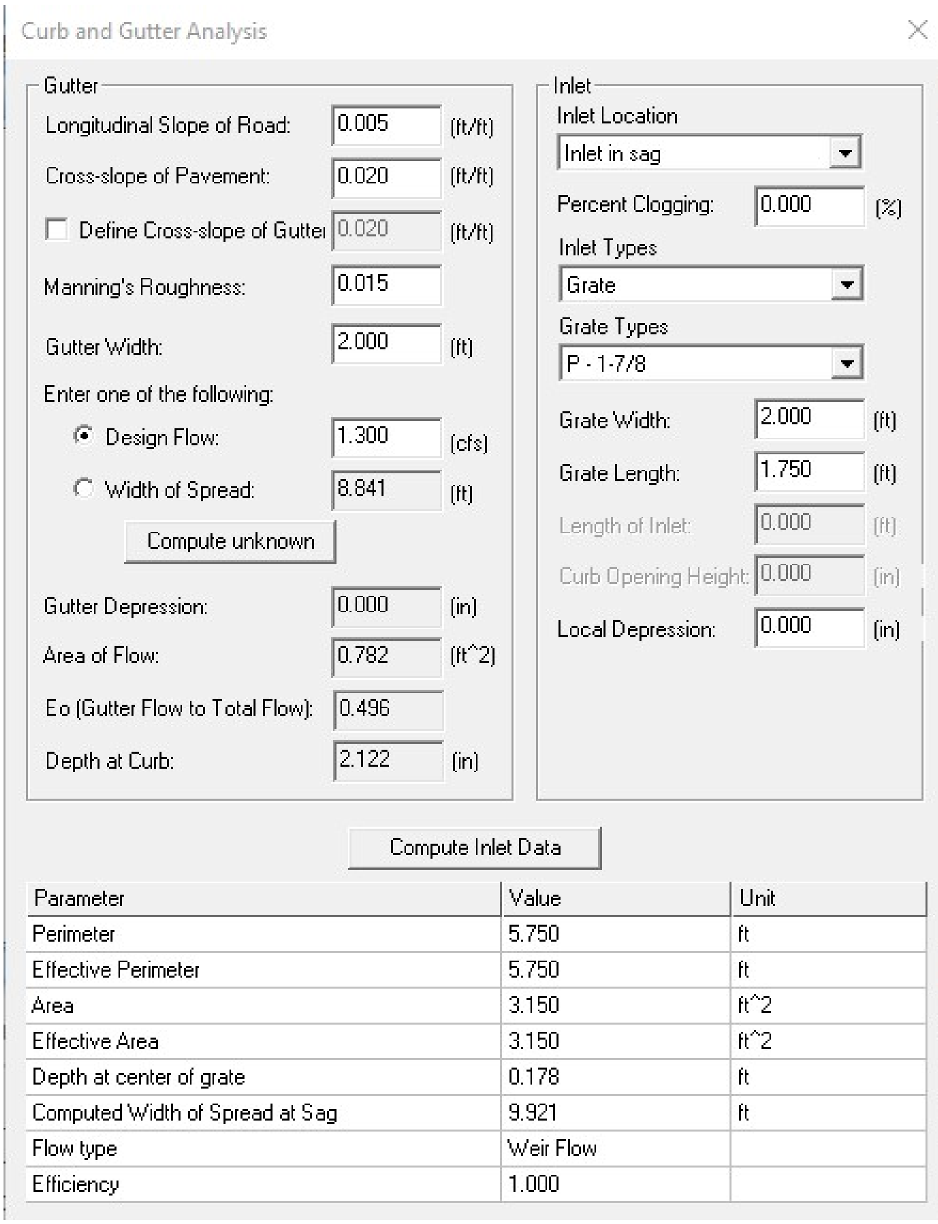


Figure 22 – Grate in a sag, length reduced by clogging

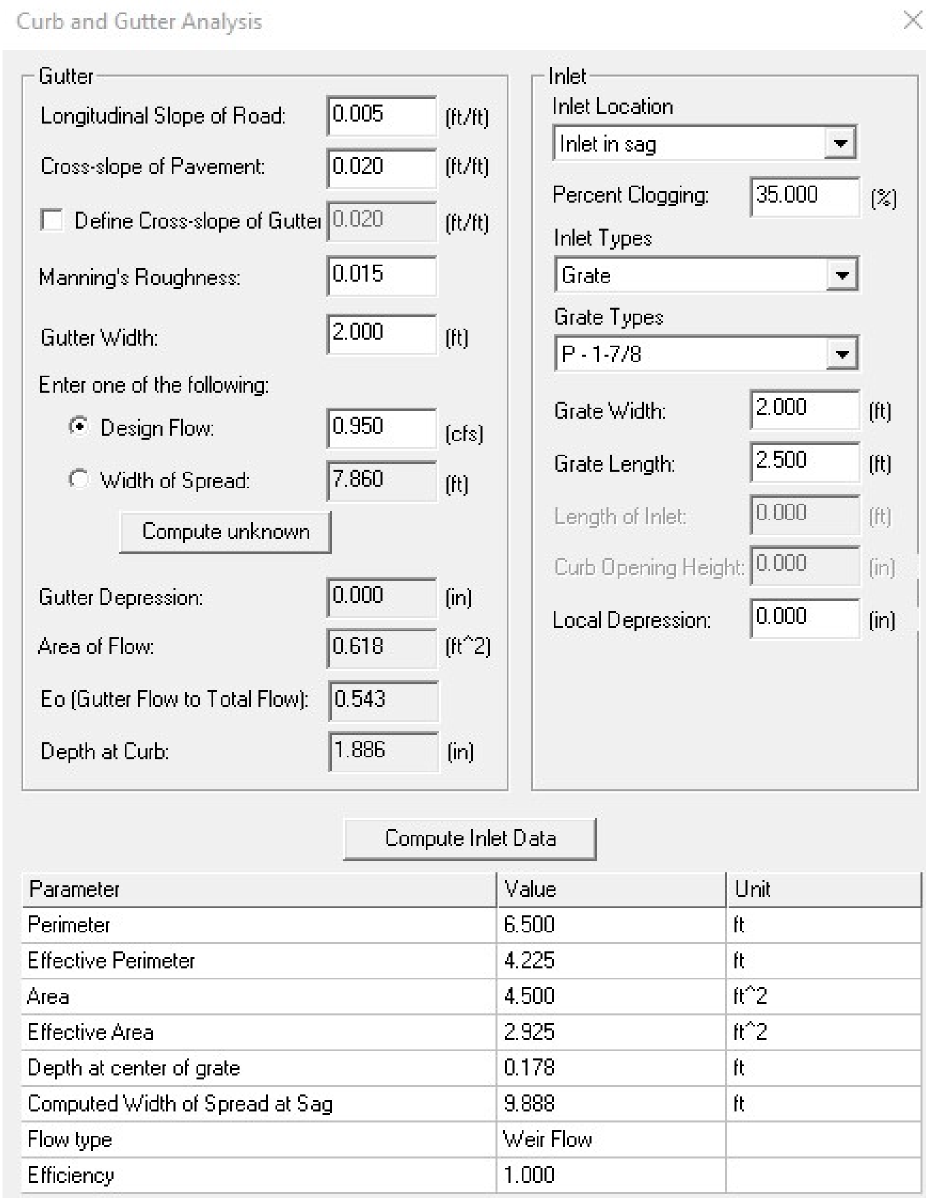


Figure 23 – Grate in a sag, clogging factor used

INCORPORATING INLETS INTO STORM SEWER MODELS

While a clear understanding of how water flows into an inlet is important in the design of a storm sewer, most storm sewer designs are completed using a computer model to simulate all of the functions of the system. In order to properly model the inlet capacity issues described in this course it is important to develop a computer model that addresses the issue.

Many models of storm sewer systems are developed that route the runoff from a small drainage basin directly into a manhole for the storm sewer system. This shortcut makes the assumption that the inlet intercepts 100% of the runoff that reaches the inlet. The information provided in this course has demonstrated that this is not always a valid assumption, especially if the inlet is on a continuous grade.

The process to incorporate inlet capacity into a storm sewer model involves three steps:

1. Develop a relationship between depth, flow intercepted and flow bypassed
2. Develop an overflow relationship
3. Split the flow between interception and bypass/overflow

<u>Develop relationship between depth, flow intercepted and flow bypassed</u>

The first step is to develop a tabular relationship between the depth of flow reaching the grate and the flow intercepted by the grate. This can be easily done using the FHWA Hydraulic Toolbox for each inlet location. Using a 2-foot wide by 2-foot long curved vane grate, Table 1 can be readily developed for a grate on a continuous grade.

Table 1

Flow, cfs	Depth, in	Flow Intercepted, cfs	Flow Bypassed, cfs
0	0	0	0
0.2	1.05	0.176	0.024
0.4	1.36	0.313	0.087
0.6	1.59	0.433	0.167
0.8	1.77	0.541	0.259
1.0	1.92	0.641	0.359
1.2	2.06	0.736	0.464
1.4	2.18	0.825	0.575
1.6	2.29	0.910	0.690

The depth and flow intercepted values are used to determine the flow that reaches the storm sewer system. The depth and flow bypassed values are used to determine the flow that bypasses the inlet and continues downstream if the inlet is on a continuous grade.

<u>Develop overflow relationship</u>

If the inlet is in a sag, at some point the water will overflow the sag condition. For example, if the sag is created only by the roadway crowns of two intersecting streets, each roadway is 36 feet side (18 feet from face of curb to centerline) and each road has a 2% normal crown, the overtopping elevation would be 0.36 feet (18 feet x 2% slope) above the low spot in the sag. Depending on the configuration of the intersecting streets, the length of the weir could be in the range of 15 or 20 feet long. If this weir is assumed to be 15 feet long and function as a broad-crested weir (with a weir coefficient of 2.6), the weir overflow could be computed using the weir equation:

$Q = 2.6 * 15 * (d-0.36)^{1.5}$

Where
Q = overflow in cfs,
d = depth of water in the sag

Using Example 3: A 2.0-foot wide (perpendicular to the curb) by 2.5-foot long (parallel to the curb) grate in a sag. The grate is on a roadway with a standard crown of 2%. Table 2 shows the relationship between depth, intercepted flow and overflow.

Table 2

Flow, cfs	Depth, ft	Flow Intercepted, cfs	Flow Bypassed, cfs
0	0	0	0
0.5	0.11	0.50	0.00
1.0	0.16	1.00	0.00
1.5	0.20	1.50	0.00
2.0	0.24	2.00	0.00
2.5	0.27	2.50	0.00
3.0	0.31	3.00	0.00
3.5	0.34	3.50	0.00
3.8	0.36	3.85	0.00
4.45	0.38	4.30	0.15
5.28	0.41	4.80	0.48

Splitting flow between interception and bypass/overflow

The method for splitting flow between interception and bypass or overflow will be demonstrated using the EPA SWMM software. A very simple example will show how to address both inlets on a continuous grade and inlets in a sag. Figure 23 shows two drainage basins. Basin 1 drains to an inlet on a continuous grade (labelled “Grade Inlet”). Basin 2 drains to an inlet in a sag created by the intersection of two roadway crowns (labelled “Sag Inlet”). Each inlet is represented as a storage node to simplify the process of dividing the flow. The storage-depth relationship for Grade Inlet is very small since almost no water is stored at the inlet. The storage-depth relationship for Sag Inlet represents the small storage volume available between the curb and the roadway crowns. When runoff from Basin 1 reaches Grade Inlet, the flow is split between Grate Intercept and Grate Bypass (see Figure 24) based on the relationship shown in Table 1. The flow that is intercepted is directed to MH1, which is the start of the storm sewer system. The flow that is bypassed continues in the street to the next inlet, which is Sag Inlet. The runoff from Basin 2 drains to Sag Inlet, along with any flow that bypasses Grate Inlet. The flow that reaches Sag Inlet is split between Sag Intercept and Sag Bypass based on the relationship in Table 2. The flow that is intercepted is directed to MH2, which is part of the storm sewer system. If the depth of ponding continues to increase, eventually water flows over the crown of the road. This flow is represented by Sag Bypass, and this flow then continues in the street beyond the sag.

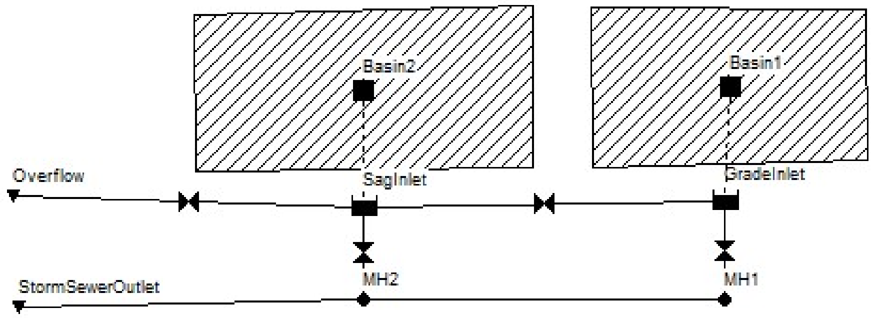


Figure 23 – EPA SWMM, Basins and Nodes

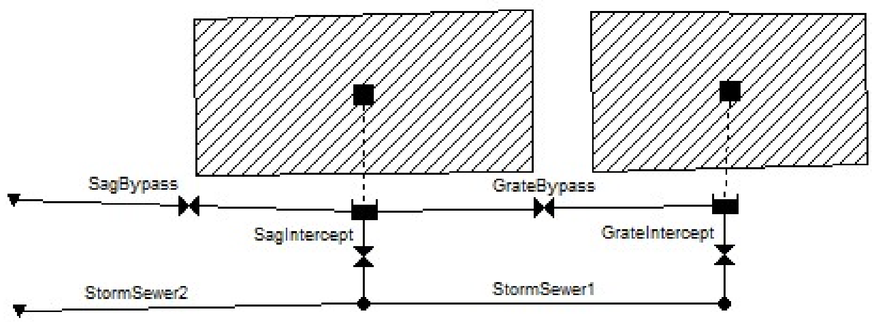


Figure 24 – EPA SWMM, Conduits

Using this approach, each inlet in the storm sewer system can be appropriately modeled. The relationships for each grate need to be developed, but in many cases, a relatively constant roadway grade is part of the design, so the same relationship can be used for many grates. Similarly, the representation of inlets in a sag can be the same for many locations.

The alternative to modeling each inlet is to make the assumption that all of the water that reaches an inlet is directed to the storm sewer. In the case of an inlet on a continuous grade, that is a very bad assumption. In the case of an inlet in a sag, it could be a valid assumption, but proper modeling can verify whether any water bypasses the sag.

REFERENCE

1. Federal Highway Administration, Hydraulic Engineering Circular 22, "Urban Drainage Design Manual."

Designing Storm Drain Inets

Updated: 7/16/2020

1. An inlet with bars at an angle is called which of the following?

   a. A curb opening
   b. A combination inlet
   c. A vane style grate
   d. A slotted drain

2. Which of the following is a most susceptible to clogging by leaves and debris?

   a. Grates
   b. Curb Openings
   c. Slotted Drains
   d. Combination Inlets

3. What type of pipe is typically located below the vertical slot in a slotted drain inlets?

   a. Corrugated steel
   b. Concrete
   c. PVC
   d. HDPE

4. Which of the following factors impacts the top width of flow in a gutter section?

   a. Total flow
   b. Longitudinal slope
   c. Transverse slope
   d. All of the above

5. In a composite gutter section, how does the slope of the concrete gutter compare to the roadway slope?

   a. The gutter slope is steeper
   b. The gutter slope is flatter
   c. The slopes are the same
   d. Either a or b.

6. Which of the following is true if the splash over velocity of the selected grate on a continuous grade is greater than the gutter velocity?

a. 100% of the total flow is intercepted
b. 100% of the frontal flow is intercepted
c. 100% of the side flow is intercepted
d. All of the above

7. Which type of flow are grates most efficient at intercepting?

a. Side flow
b. Frontal flow
c. Both of the above
d. None of the above

8. At small depths an inlet in a sag will normally function as which of the following?

a. Weir
b. Orifice
c. Both of the above
d. None of the above

9. Which of the following is a reasonable orifice coefficient?

a. 0.6
b. 2.6
c. 3.0
d. 3.3

10. If the gutter adjacent to a curb opening is depressed so that the slope of the gutter is steeper than the cross-slope of the roadway, how is the capacity of a curb opening impacted?

a. The capacity increases
b. The capacity decreases
c. There is no impact on capacity
d. It depends on the longitudinal slope

11. The FHWA Hydraulic Toolbox will analyze which of the following inlet types?

a. Grate inlet on grade
b. Curb opening in sag
c. Slotted drain on grade
d. All of the above

12. When a second inlet is required to intercept more flow, which of the following locations results in a more efficient configuration?

a. The second inlet next to the curb
b. The second inlet closer to centerline
c. Both locations result in the same efficiency
d. A second inlet will not increase efficiency

13. How is the capacity of inlets in a sag changed when a second inlet is added?

a. The capacity doubles
b. The capacity increases, but by less than 100%
c. The capacity decreases
d. There is no change in capacity

14. If the front one-foot of a two-foot long grate on a continuous grade is clogged by debris, how is the capacity impacted?

a. The capacity is reduced by 50%
b. The capacity is reduced, but by less than 50%
c. The capacity is reduced by more than 50%
d. The capacity is not changed

15. When modeling an inlet on a continuous grade, where should bypass flow be directed?

a. Into the storm sewer
b. In the gutter continuing down the street to the next inlet
c. It should be stored until it can enter the storm sewer
d. It can be ignored