# Scattergraph Principles and Practice

## *Characterization of Sanitary Sewer and Combined Sewer Overflows*

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**ABSTRACT** Sewer overflows pose a significant threat to public health and the environment, contributing to beach closures, contamination of drinking water, and other concerns. Knowing when and where they occur – as well as their duration, volume, and frequency – are important pieces of information needed to assess their impact and minimize their future occurrence.

Sewer overflows are readily identified by evaluating flow monitor data on a scattergraph. Practical examples from flow monitor locations throughout the United States are provided, demonstrating the scattergraph signatures of sanitary sewer overflows (SSOs) and combined sewer overflows (CSOs) under various conditions. Techniques are also developed to estimate their duration and volume from flow monitor data.

**KEY WORDS** Flow Monitoring, CSO, Scattergraph, SSO

# Introduction

Sewer overflows pose a significant threat to public health and the environment, contributing to beach closures, contamination of drinking water, and other concerns. Knowing when and where they occur – as well as their duration, volume, and frequency – are important pieces of information needed to assess their impact and minimize their future occurrence.

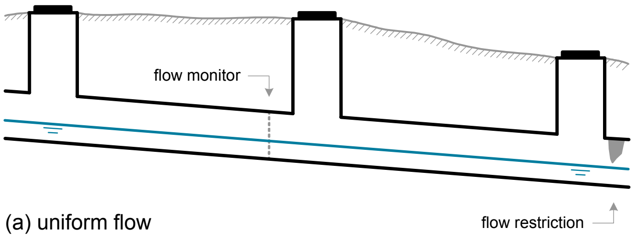
Sewer overflows are readily identified by evaluating flow monitor data on a scattergraph. The scattergraph is a graphical tool that displays flow depth and velocity data from a sewer flow monitor. The resulting patterns form characteristic signatures that provide insight into conditions within a sewer.[1] Scattergraph signatures for sewer overflows have been previously reported by Stevens and Sands.[2] The scattergraph signatures of sanitary sewer overflows (SSOs) and combined sewer overflows (CSOs) are further discussed in this paper, along with techniques to estimate their duration and volume from flow monitor data.

# Sanitary Sewer Overflows

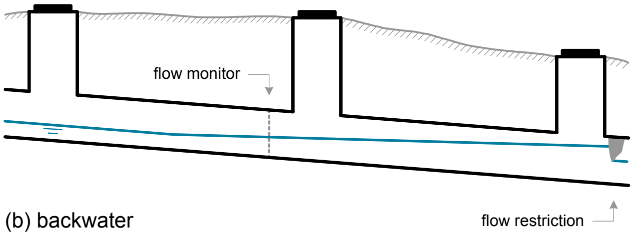
A sanitary sewer overflow (SSO) is a discharge of untreated wastewater from a sanitary sewer system. According to the Environmental Protection Agency (EPA), SSOs are caused by a variety of reasons – including inadequate sewer design and construction, insufficient operation and maintenance, power failures, and vandalism.[3] These situations are often compounded by infiltration and inflow – contributing to an increase in the duration, volume, and/or frequency of overflow events.

Regardless of the contributing factors, sewers often experience a common sequence of hydraulic events prior to an SSO – including uniform flow, backwater, and surcharge conditions. Profile views depicting this sequence are provided in Figure 1.

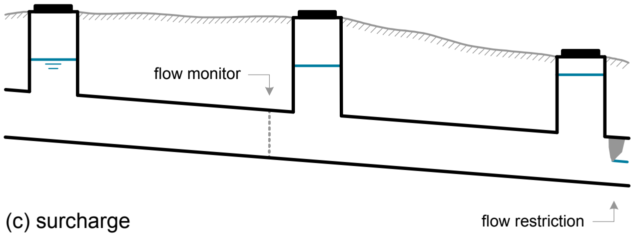
**FIGURE 1: Prelude to an SSO — a Profile View**



(a) uniform flow



(b) backwater

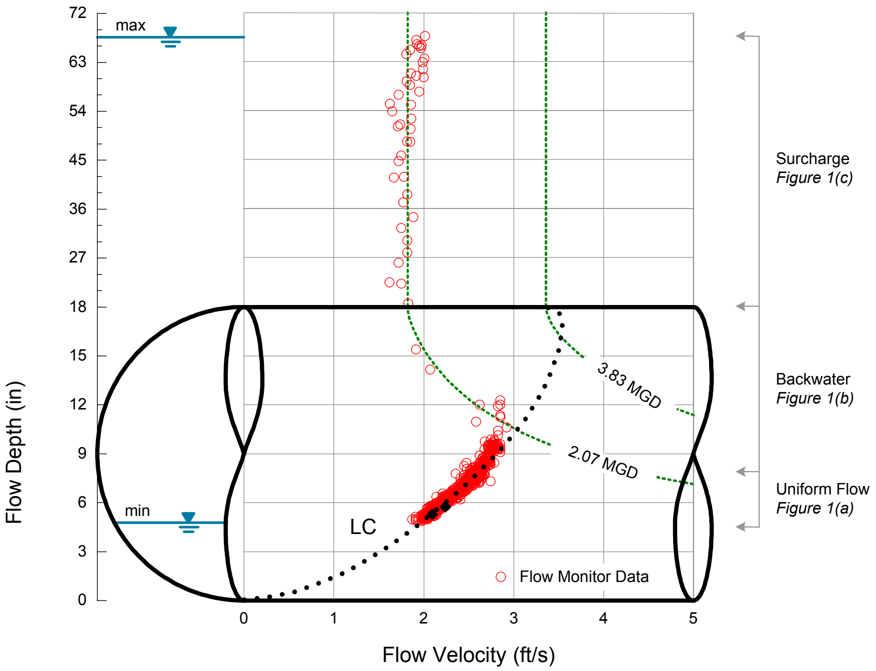


(c) surcharge

Uniform flow conditions are often assumed in a sewer under normal flow conditions, as shown in Figure 1(a). Although a flow restriction is shown in this example, flow conditions are not adversely affected at lower flow depths. However, as the flow depth increases, the flow restriction throttles flow through the sewer, resulting in backwater and surcharge conditions, as shown in Figures 1(b) and 1(c), respectively. The operational capacity of this sewer is less than its intended design capacity, and once the surcharge depth reaches the rim elevation of a nearby manhole, an SSO occurs.

Note the location of the flow monitor relative to the flow restriction in Figure 1. The flow restriction is located downstream from the flow monitor. As a result, the sequence of hydraulic events that leads to an SSO leaves a distinct pattern that can be identified on a scattergraph of flow depth and velocity data, as shown in Figure 2.

**FIGURE 2: Prelude to an SSO — a Scattergraph View**



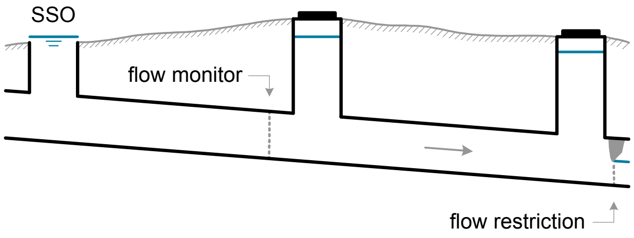
During uniform flow conditions, the relationship between flow depth and velocity is described by the Manning Equation.[4] This equation is depicted by the *pipe curve* shown in Figure 2. Uniform flow conditions are identified on a scattergraph when the flow monitor data are consistent with the *pipe curve*. However, as backwater conditions develop, flow conditions become deeper and slower and are revealed on the scattergraph as a departure from the *pipe curve*. The flow rate at which this occurs is noted by an iso-Q™ line and represents an operational capacity that is only 54% of the expected capacity of this sewer.[5]

The scattergraph signatures of SSOs under various conditions are discussed in the following sections. Despite the variations, the common sequence of hydraulic events shown in Figure 2 is noted in each case.

## Sanitary Sewer Overflow (Upstream)

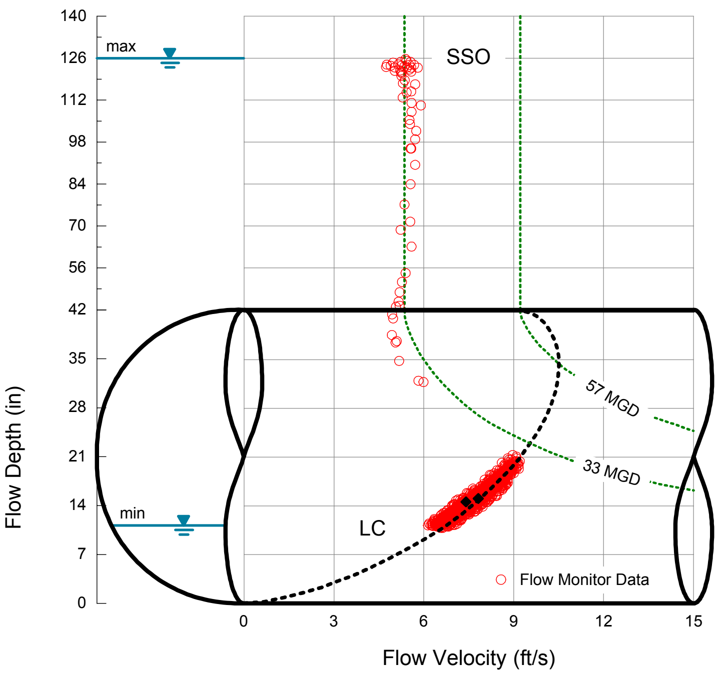
The scattergraph signature of an SSO depends on the type of overflow and its position relative to a flow monitor. A profile view of an SSO that occurs upstream from a flow monitor is shown in Figure 3.

**FIGURE 3: Upstream SSO**



This SSO is identified on a scattergraph by a cluster of surcharge data points at a constant flow depth and a constant velocity, as shown in Figure 4. The depth reported by the flow monitor during the SSO is controlled by the overflow elevation, and the velocity is controlled by the operational capacity of the downstream sewer.

**FIGURE 4: Scattergraph of an Upstream SSO**

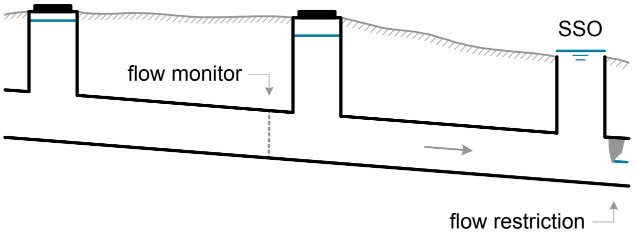


Based on the scattergraph, the operational capacity of this sewer is 33 MGD – only 58% of the expected capacity under uniform flow conditions. Surcharge conditions are observed up to a flow depth of nearly 126 inches when an SSO occurs upstream from the flow monitor.

## Sanitary Sewer Overflow (Downstream)

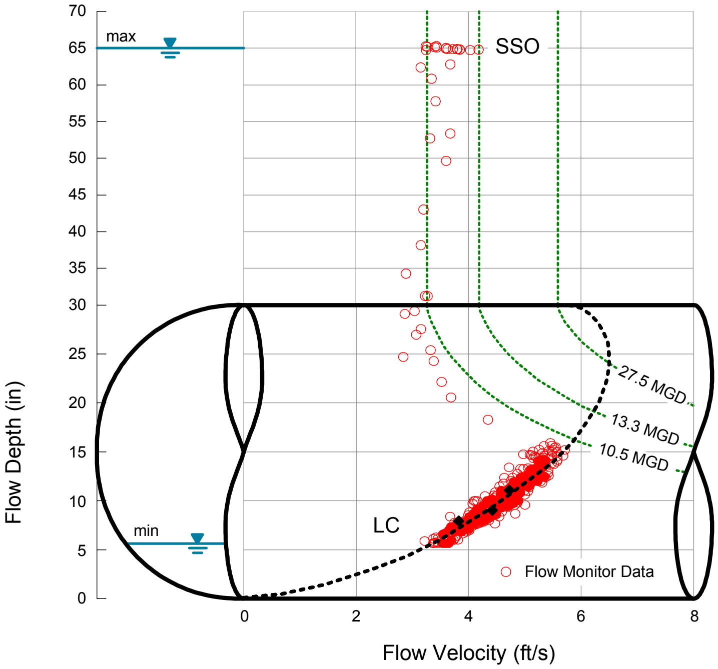
The scattergraph signature of a downstream SSO can also be identified. A profile view of an SSO that occurs downstream from a flow monitor is shown in Figure 5.

**FIGURE 5: Downstream SSO**



Both upstream and downstream SSOs are characterized by a constant flow depth during an overflow. However, the additional flow escaping the system during a downstream SSO is detected by the flow monitor as an increase in velocity during the overflow event, as shown in Figure 6.

**FIGURE 6: Scattergraph of a Downstream SSO**

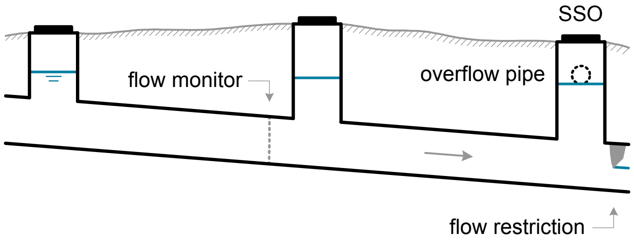


Based on the scattergraph, the operational capacity of this sewer is about 10.5 MGD – only 38% of the expected capacity under uniform flow conditions. Surcharge conditions are observed up to a flow depth of nearly 65 inches when an SSO occurs downstream from the flow monitor. The maximum overflow rate is determined using iso-Q lines and is approximately 2.8 MGD (13.3 MGD – 10.5 MGD).

## Sanitary Sewer Overflow from an Overflow Pipe

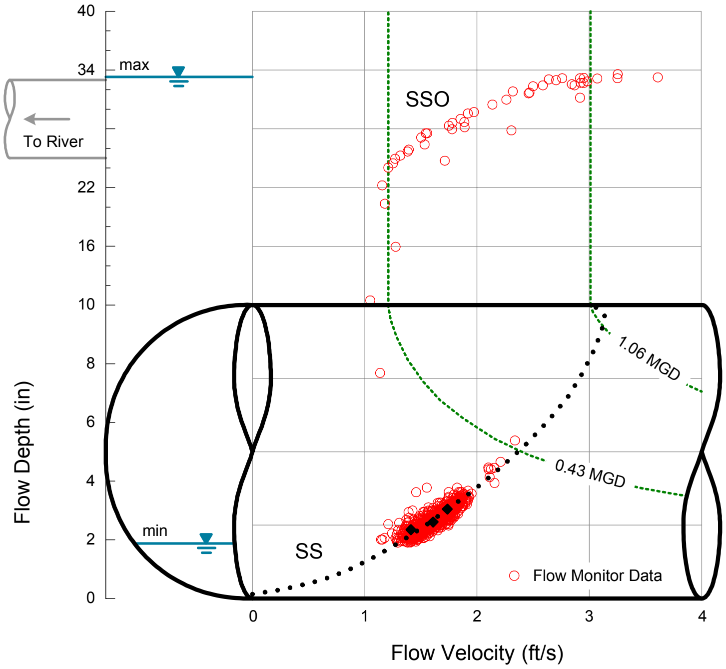
Some municipalities have SSOs from fixed points within the sewer system that overflow to a storm sewer or directly to receiving waters.[3] A profile view of an SSO that occurs from an overflow pipe is shown in Figure 7.

**FIGURE 7: SSO from Overflow Pipe**



The scattergraph shown in Figure 8 is from a 10-inch sewer equipped with an 8-inch overflow pipe located in a manhole downstream from the flow monitor.

**FIGURE 8: Scattergraph of an SSO from an Overflow Pipe**

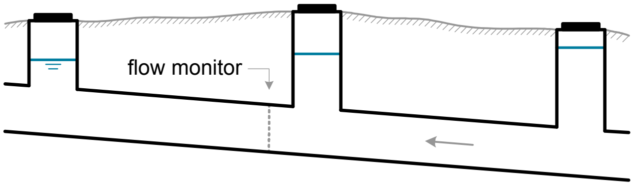


Based on the scattergraph, the operational capacity of this sewer is 0.43 MGD – only 41% of the expected capacity under uniform flow conditions. The SSO is activated at a flow depth of 25 inches – the invert elevation of the 8-inch overflow pipe.

## Reverse Flow

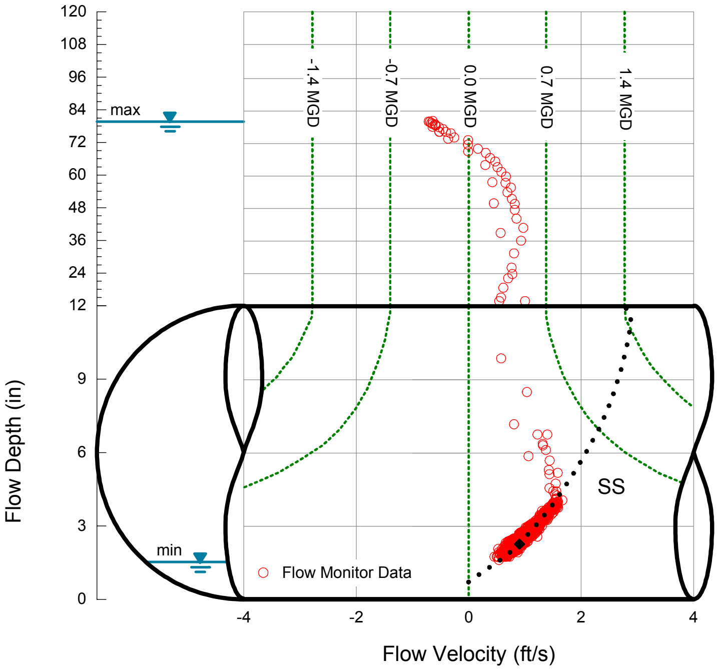
Reverse flow in a sewer system is rare but can occur in certain situations. A profile view of reverse flow is shown in Figure 9.

**FIGURE 9: Reverse Flow**



The scattergraph shown in Figure 10 is from a 12-inch sewer that is *overpowered* by a much larger downstream interceptor.

**FIGURE 10: Scattergraph of Reverse Flow**



During a rain event, this sewer experiences backwater and surcharge conditions. However, note the sequence of events that occurs during surcharge conditions. The flow rate begins to slow down at 42 inches and eventually comes to a momentary stop at 72 inches. Reverse flow is observed above this depth and may have led to an SSO.

## Combined Sewer Overflows

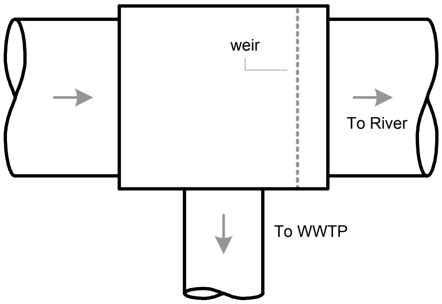
A combined sewer overflow (CSO) is a discharge of untreated wastewater from a combined sewer system, most often occurring at a CSO regulator designed for this purpose. CSOs generally occur during wet weather events, when the combined flow rate of wastewater and storm water exceeds the capacity that a regulator structure is configured to convey to the WWTP.[3] Excess flows are discharged to receiving waters.

Most combined sewers experience a common sequence of hydraulic events prior to a CSO, based on the design of the CSO regulator. Those equipped with end weirs or side weirs often generate backwater conditions in the incoming sewer, and once the backwater depth reaches the weir elevation, a CSO occurs. This sequence of hydraulic events leaves a distinct pattern that can be identified on a scattergraph of flow depth and velocity data. The scattergraph signatures of CSOs from regulator structures equipped with end weirs or side weirs are discussed in the following sections.

## Combined Sewer Overflow (End Weir)

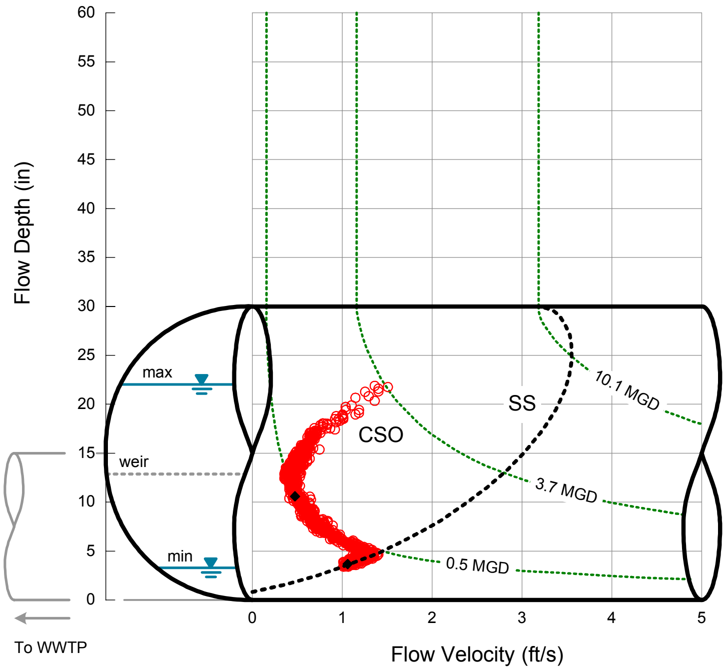
Some CSO regulators are equipped with an end weir that is constructed perpendicular to the incoming wastewater flow. Dry weather flow is diverted to the WWTP. However, once the flow depth exceeds the weir height, additional flow is carried over the weir and is discharged to the receiving water. A plan view of a CSO regulator equipped with an end weir is shown in Figure 11.

**FIGURE 11: Plan View of a CSO Regulator with an End Weir**



The scattergraph shown in Figure 12 displays data from a flow monitor installed in a 30-inch sewer located just upstream from a CSO regulator equipped with an end weir.

**FIGURE 12: Scattergraph of a CSO from an End Weir**

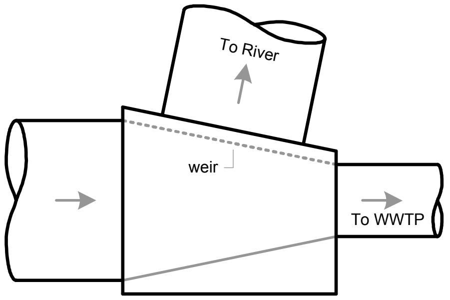


Dry weather flows are diverted to the WWTP through a 15-inch sewer. Based on the scattergraph, the 15-inch sewer conveys flows up to 0.5 MGD to the WWTP, and the CSO is activated at a weir elevation of 13 inches. The maximum overflow rate is determined using iso-Q lines and is approximately 3.2 MGD (3.7 MGD – 0.5 MGD).

## Combined Sewer Overflow (Side Weir)

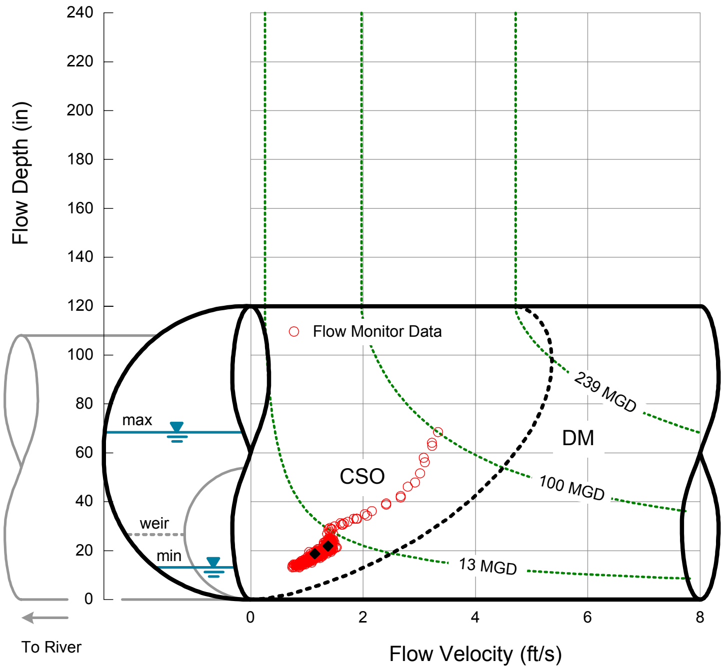
Some CSO regulators are equipped with a side weir that is constructed along the side of the incoming sewer. Dry weather flows are funneled into a smaller sewer and continue to the WWTP. However, once the flow depth exceeds the weir height, additional flow is carried over the side weir and is discharged to the receiving water. A plan view of a CSO regulator equipped with a side weir is shown in Figure 13.

**FIGURE 13: Plan View of a CSO Regulator with a Side Weir**



The scattergraph shown in Figure 14 displays data from a flow monitor installed in a 120-inch sewer located just upstream from a CSO regulator equipped with a side weir.

**FIGURE 14: Scattergraph of a CSO from a Side Weir**



Dry weather flows are funneled to the WWTP through a 54-inch sewer. Based on the scattergraph, the 54-inch sewer conveys flows up to 13 MGD to the WWTP, and the CSO is activated at a weir elevation of 27 inches. The maximum overflow rate is determined using iso-Q lines and is approximately 87 MGD (100 MGD – 13 MGD).

# Overflow Duration and Volume

Once the signature of an SSO or CSO has been identified on a scattergraph and the flow depth ($d_0$) and flow rate ($Q_0$) at the onset of the overflow have been determined, the overflow duration and volume can be estimated from flow monitor data. Procedures for estimating these parameters are described in the following sections.

**Overflow Duration**

The overflow duration ($t_{OF}$) is calculated by determining the number of recorded flow monitor readings where $d > d_0$ and multiplying by the sample period between readings, as shown in Equation (1).

$$t_{OF} = n \times T \tag{1}$$

where: $t_{OF}$ = overflow duration, min
$n$ = number of flow monitor readings where $d > d_0$
$T$ = sample period, min

**Overflow Volume**

The overflow volume ($V_{OF}$) is calculated using Equations (2) through (4). These three equations can also be algebraically rearranged and condensed into one equation as shown in Equation (5).

$$Q_{OFi} = Q_i - Q_0 \tag{2}$$

$$V_{OFi} = Q_{OFi} T \tag{3}$$

$$V_{OF} = \sum_{i=1}^{n} V_{OFi} \tag{4}$$

$$V_{OF} = \sum_{i=1}^{n} \left[ (Q_i - Q_0) \times T \right] \tag{5}$$

where: $Q_{OFi}$ = overflow rate at time t = i, gpm
$Q_i$ = flow rate at time t = i, gpm
$Q_0$ = flow rate at onset of overflow, gpm
$V_{OFi}$ = overflow volume at time t = i, gal
$T$ = sample period, min
$V_{OF}$ = total overflow volume, gal
$n$ = number of flow monitor readings where $d > d_0$

An example is provided to demonstrate these procedures.

**EXAMPLE**

Flow monitor data from a 12-inch sewer are plotted on a scattergraph and suggest that an SSO has occurred downstream from the monitoring location.

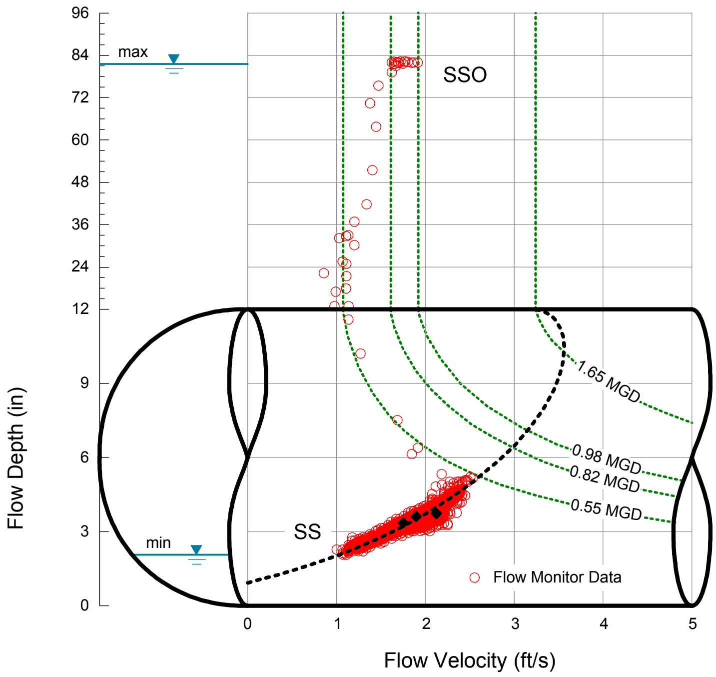
(a) Use the scattergraph provided below to determine $d_0$ and $Q_0$.

(b) Use the tabular data provided on the following page to estimate the duration and volume of the downstream SSO.

*Solution*

(a) A downstream SSO is characterized by an increase in flow velocity at a constant surcharge depth. Based on the scattergraph provided, this increase occurs at a flow depth of 81 inches. Therefore, $d_0$ = 81 inches.

Using the iso-Q lines provided on the scattergraph, this SSO begins when the sewer flow rate increases to 0.82 MGD. Therefore, $Q_0$ = 0.82 MGD.



(b) Based on the flow depth (d) data provided, the SSO begins on 03/20 at 18:00 when the flow depth rises above $d_0$ (81 inches). The flow depth remains above $d_0$ until 03/21 at 02:00 — an overflow duration of about 8 hours.

Based on the flow rate (Q) data provided, calculate the overflow rate ($Q_{OFi}$) for each flow monitor reading using Equation 2. Convert the units to gpm, and determine the overflow volume ($V_{OFi}$) using Equation 3. Add the overflow volumes for each flow monitor reading to determine the total overflow volume ($V_{OF}$) using Equation 4. The overflow volume for this SSO is about 20,000 gal.

**EXAMPLE**

SSO begins when the flow depth rises above $d_0$ (81 inches)

Flow monitor data is obtained at a sample period (T) equal to 15 minutes

Peak overflow rate ($Q_{OF}$) is 107.46 gpm

SSO ends when the flow depth drops below $d_0$ (81 inches)

| date<br>mm/dd | time<br>hh:mm | d<br>in | v<br>ft/s | Q<br>MGD | $Q_{OF}$<br>MGD | $Q_{OF}$<br>gpm | $V_{OF}$<br>gal |
|---|---|---|---|---|---|---|---|
| 03/20 | 17:00 | 12.77 | 0.98 | 0.498 | 0.000 | 0.00 | 0 |
| 03/20 | 17:15 | 33.09 | 1.14 | 0.579 | 0.000 | 0.00 | 0 |
| 03/20 | 17:30 | 70.29 | 1.38 | 0.701 | 0.000 | 0.00 | 0 |
| 03/20 | 17:45 | 80.90 | 1.67 | 0.848 | 0.000 | 0.00 | 0 |
| 03/20 | 18:00 | 81.79 | 1.62 | 0.822 | 0.002 | 1.70 | 25 |
| 03/20 | 18:15 | 82.01 | 1.62 | 0.822 | 0.002 | 1.70 | 25 |
| 03/20 | 18:30 | 82.01 | 1.62 | 0.822 | 0.002 | 1.70 | 25 |
| 03/20 | 18:45 | 82.04 | 1.63 | 0.828 | 0.008 | 5.22 | 78 |
| 03/20 | 19:00 | 82.06 | 1.64 | 0.833 | 0.013 | 8.75 | 131 |
| 03/20 | 19:15 | 81.97 | 1.65 | 0.838 | 0.018 | 12.27 | 184 |
| 03/20 | 19:30 | 81.94 | 1.65 | 0.838 | 0.018 | 12.27 | 184 |
| 03/20 | 19:45 | 81.77 | 1.88 | 0.954 | 0.134 | 93.36 | 1,400 |
| 03/20 | 20:00 | 81.47 | 1.75 | 0.888 | 0.068 | 47.53 | 713 |
| 03/20 | 20:15 | 81.28 | 1.65 | 0.838 | 0.018 | 12.27 | 184 |
| 03/20 | 20:30 | 80.88 | 1.68 | 0.853 | 0.033 | 22.85 | 343 |
| 03/20 | 20:45 | 82.19 | 1.67 | 0.848 | 0.028 | 19.32 | 290 |
| 03/20 | 21:00 | 82.15 | 1.66 | 0.843 | 0.023 | 15.80 | 237 |
| 03/20 | 21:15 | 82.19 | 1.65 | 0.838 | 0.018 | 12.27 | 184 |
| 03/20 | 21:30 | 82.22 | 1.65 | 0.838 | 0.018 | 12.27 | 184 |
| 03/20 | 21:45 | 82.17 | 1.78 | 0.904 | 0.084 | 58.11 | 872 |
| 03/20 | 22:00 | 82.11 | 1.65 | 0.838 | 0.018 | 12.27 | 184 |
| 03/20 | 22:15 | 82.16 | 1.72 | 0.873 | 0.053 | 36.95 | 554 |
| 03/20 | 22:30 | 82.18 | 1.78 | 0.904 | 0.084 | 58.11 | 872 |
| 03/20 | 22:45 | 82.12 | 1.82 | 0.924 | 0.104 | 72.21 | 1,083 |
| 03/20 | 23:00 | 82.04 | 1.62 | 0.822 | 0.002 | 1.70 | 25 |
| 03/20 | 23:15 | 81.97 | 1.72 | 0.873 | 0.053 | 36.95 | 554 |
| 03/20 | 23:30 | 82.00 | 1.78 | 0.904 | 0.084 | 58.11 | 872 |
| 03/20 | 23:45 | 82.09 | 1.88 | 0.954 | 0.134 | 93.36 | 1,400 |
| 03/21 | 00:00 | 82.12 | 1.85 | 0.939 | 0.119 | 82.79 | 1,242 |
| 03/21 | 00:15 | 82.07 | 1.88 | 0.954 | 0.134 | 93.36 | 1,400 |
| 03/21 | 00:30 | 81.97 | 1.92 | 0.975 | 0.155 | 107.46 | 1,612 |
| 03/21 | 00:45 | 81.97 | 1.88 | 0.954 | 0.134 | 93.36 | 1,400 |
| 03/21 | 01:00 | 81.88 | 1.88 | 0.954 | 0.134 | 93.36 | 1,400 |
| 03/21 | 01:15 | 81.80 | 1.88 | 0.954 | 0.134 | 93.36 | 1,400 |
| 03/21 | 01:30 | 81.71 | 1.72 | 0.873 | 0.053 | 36.95 | 554 |
| 03/21 | 01:45 | 81.52 | 1.68 | 0.853 | 0.033 | 22.85 | 343 |
| 03/21 | 02:00 | 79.18 | 1.62 | 0.822 | 0.000 | 0.00 | 0 |
| 03/21 | 02:15 | 75.29 | 1.48 | 0.751 | 0.000 | 0.00 | 0 |
| 03/21 | 02:30 | 63.66 | 1.45 | 0.736 | 0.000 | 0.00 | 0 |
| | | | | | | | 19,958 |

Overflow duration is about 8 hours

Overflow volume is about 20,000 gal

**Limitations**

The calculation procedures described here are best applied to SSOs and CSOs that are located downstream from a flow monitor when backwater conditions are experienced prior to an overflow event. The overflow duration can also be estimated for SSOs that occur upstream from a flow monitor; however, the overflow volume cannot be determined using these procedures.

Overflow duration and volume estimates obtained using this method are a function of the quality and repeatability of the flow monitor data on which they are based. If data are missing during portions of an overflow event, the application of this method is compromised. The sample rate at which the data are obtained is also a factor. The accuracy of overflow duration and volume estimates increases as the sample rate of the flow monitor increases.

# Conclusion

Sewer overflows are readily identified by evaluating flow monitor data on a scattergraph. Scattergraph signatures of sewer overflows under various hydraulic conditions have been presented in this paper, along with techniques to estimate their duration and volume from flow monitor data. These methods provide important pieces of information needed to assess the impact of sewer overflows and minimize their future occurrence.

# Symbols and Notation

The following symbols and notation are used in this paper:

<u>VARIABLES</u>

$d$ = flow depth, in
$v$ = flow velocity, ft/s
$Q$ = flow rate, MGD or gpm
$d_0$ = flow depth at onset of overflow, in
$Q_0$ = flow rate at onset of overflow, MGD or gpm
$Q_{OFi}$ = overflow rate at time $t = i$, MGD or gpm
$V_{OFi}$ = overflow volume at time $t = i$, gal
$V_{OF}$ = overflow volume, gal
$T$ = sample period, min
$n$ = number of flow monitor readings where $d > d_0$

# Acknowledgement

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