ADS ENVIRONMENTAL SERVICES®

Scattergraph Principles and Practice

by Patrick L. Stevens, P.E. and Kevin L. Enfinger, P.E.

Overview

The scattergraph is a powerful tool that displays depth and velocity data from a sewer flow monitor. The resulting patterns form characteristic signatures that provide insight into conditions within a sewer. The flow monitor data also leave distinct patterns that even allow the performance of the flow monitor itself to be evaluated.

This poster is an educational resource for wastewater professionals, including operators, engineers, and managers. It provides a collection of scattergraphs, along with a brief explanation of what can be learned from each one. Basic principles are introduced, and practical applications are explored, addressing both engineering and operational situations.

Several important tools, including the Design Method, Lanfear-Coll Method, Stevens-Schutzbach Method, iso-Q™ lines, and iso-Froude lines are discussed and are designed to give physical perspective and context to the data. Often referred to as the *wallpaper* of a scattergraph, these tools make it easy to evaluate sewer performance and capacity.

These examples were selected from thousands of flow monitor locations evaluated by ADS. The data originate from 24 cities in 15 states in sewers ranging from 10 to 120 inches in diameter. Examples include common situations encountered in sanitary and combined sewers, as well as uncommon and entertaining examples captured over the years.

Acknowledgements

The authors acknowledge the contributions others have made to the scattergraph, including the Water Research Centre, Peter Keefe, Jim Schutzbach, Burt Curry, and David Butler, as well as research by Willi Hager and Hubert Chanson.

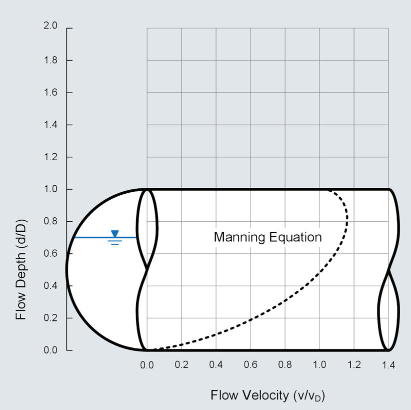
www.adsenv.com/scattergraph

1. Manning Equation

The *Manning Equation* is an empirical formula that describes a relationship between depth and velocity under ideal conditions and is commonly used to design sewer systems.

$$v = \frac{1.486}{n} R^{2/3} S^{1/2}$$

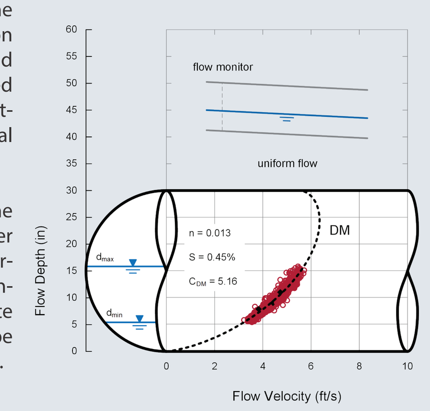
This relationship is depicted here as a *pipe curve* and provides a convenient reference to evaluate flow monitor data. The Manning Equation is an important component of the scattergraph and can be applied using three methods as shown in the following panels.



2. Design Method

The *Design Method* is a traditional use of the Manning Equation and requires information regarding the roughness coefficient (n) and the pipe slope (S). These values are obtained from design or as-built records. The resulting pipe curve is then compared to actual flow monitor data ○.

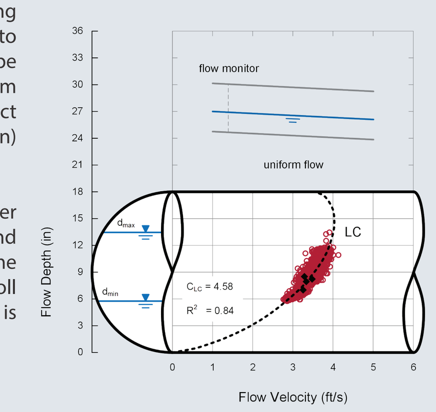
The fact that these data coincide with the pipe curve is evidence that this sewer operates as designed. Three manual confirmations ◆ are shown as well and demonstrate the accuracy of the flow monitor. Note that the Design Method results in a pipe curve that is constrained to the origin (0,0).



3. Lanfear-Coll Method

The *Lanfear-Coll Method* uses a curve fitting technique to fit the Manning Equation to flow monitor data. This method can be applied to data obtained under uniform flow conditions and requires no direct knowledge of the roughness coefficient (n) or slope (S).

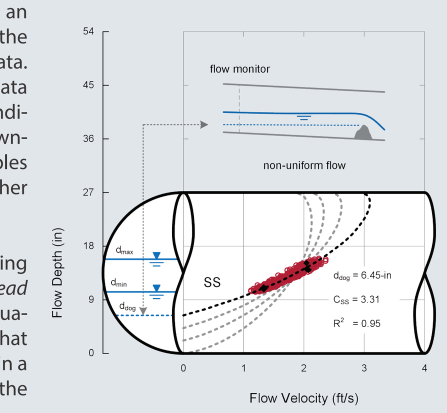
This method is demonstrated here. Under ideal conditions, the Design Method and the Lanfear-Coll Method generate the same pipe curve. Note that the Lanfear-Coll Method results in a pipe curve that is constrained to the origin (0,0).



4. Stevens-Schutzbach Method

The *Stevens-Schutzbach Method* uses an iterative curve fitting technique to fit the Manning Equation to flow monitor data. This method can be applied to data obtained under non-uniform flow conditions resulting from a variety of downstream obstructions or *dead dogs*. Examples include offset joints, silt, debris, and other related conditions.

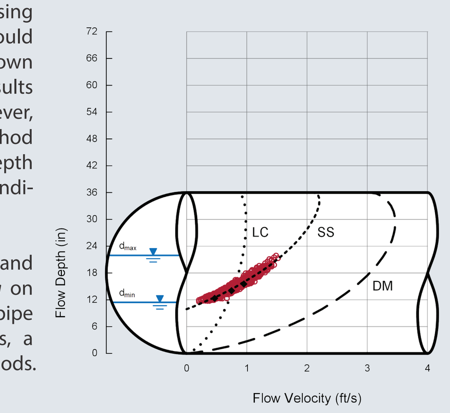
This method is demonstrated here using four iterations. The magnitude of the *dead dog* (d_{dog}) is varied until the Manning Equation best fits the observed data. Note that the Stevens-Schutzbach Method results in a pipe curve that is not constrained to the origin (0,0).



5. Comparison of Three Applications of the Manning Equation

The Manning Equation can be applied using three methods, but which method should be used? Laboratory results have shown that these methods provide similar results under uniform flow conditions. However, only the Stevens-Schutzbach Method describes the relationship between depth and velocity under non-uniform flow conditions caused by a *dead dog*.

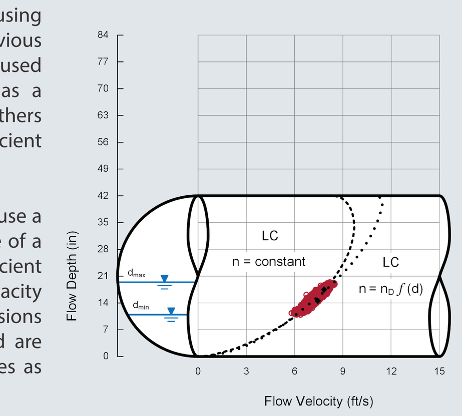
This example illustrates this concept and demonstrates the effect of a *dead dog* on sewer capacity. The predicted full-pipe velocities range from 1 ft/s to 3 ft/s, a three-fold difference among these methods.



6. Comparison of Constant and Varying Roughness Coefficient

The Manning Equation can be applied using three methods, as described in the previous panels. The roughness coefficient (n) used in these methods is often treated as a constant value. However, Camp and others have shown that the roughness coefficient varies as a function of flow depth.

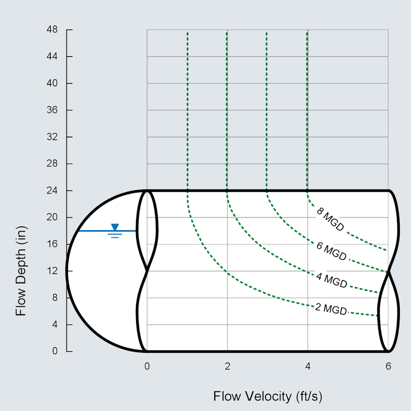
All three methods can be modified to use a varying roughness coefficient. The use of a constant or varying roughness coefficient can result in estimates of sewer capacity that differ by 20% or more. Both versions are used in the following panels and are identified using dashed or dotted lines as shown here.



7. Iso-Q™ Lines

The relationship between flow depth and velocity is important to understanding the hydraulic conditions in a sewer. The addition of flow rates (Q) to a scattergraph deepens the operational understanding of these conditions. Flow rates can be scaled within a scattergraph and displayed using *iso-Q lines*.

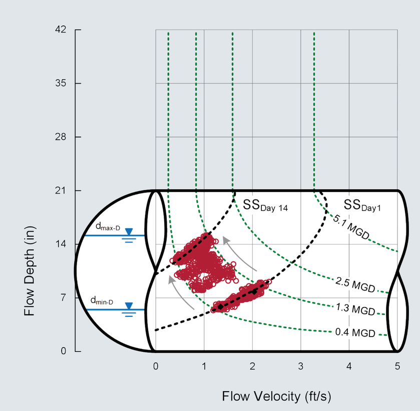
Simply put, an iso-Q is a line of constant flow rate and is analogous to a contour line on a topographic map. Iso-Qs play an important role in evaluating sewer capacity and are incorporated in the following panels.



8. Blockage

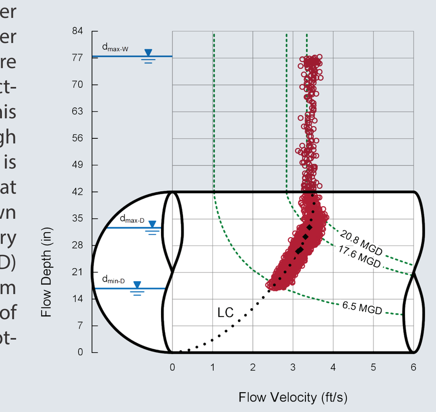
Blockages can cause a significant reduction in sewer capacity and may eventually lead to overflows. This example displays four groups of data that document a developing blockage over a 14-day period. Note how the flow depth in each group increases while the flow velocity decreases. Despite these changes, the minimum and maximum dry weather flow rates remain within the same range, as shown using two iso-Qs.

The Stevens-Schutzbach Method is used to estimate the sewer capacity on Day 1 and Day 14 and assess the impact of the sewer blockage. These capacities are denoted using two additional iso-Q lines and reveal a capacity loss of 51% (2.5 MGD vs. 5.1 MGD) resulting from this blockage.



9. Surcharge

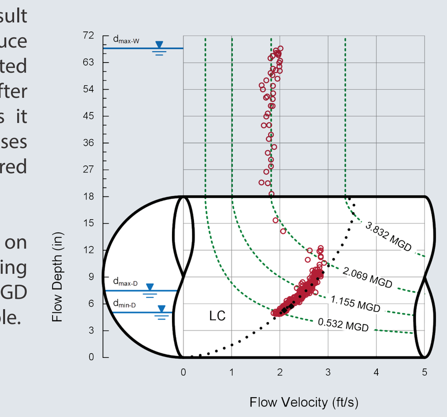
Surcharge conditions are common in sewer systems, especially during wet weather events. The flow monitor data shown here indicate that this sewer operates as expected up to its rated capacity of 20.8 MGD. This value is shown using an iso-Q. Although surcharge conditions are common, it is uncommon to find a surcharged sewer that actually conveys its rated capacity, as shown here. The minimum and maximum dry weather flow rates (6.5 MGD and 17.6 MGD) are also shown using iso-Qs. The maximum dry weather flow occurs at a d/D ratio of 0.77, a depth in excess of generally accepted design guidelines.



10. Backwater and Surcharge

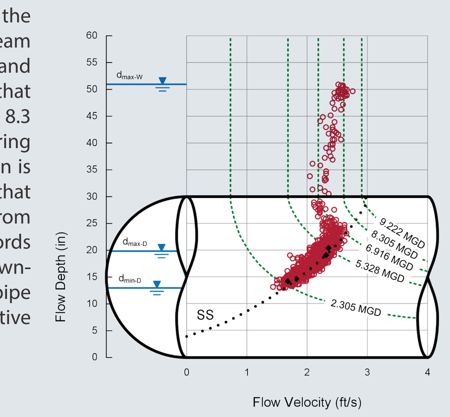
Most surcharge conditions in sewers result from downstream restrictions that reduce capacity. This sewer operates as expected up to a flow depth of about 9 inches after which a downstream restriction forces it into backwater. A restriction that causes data to adhere to an iso-Q is often referred to as a *hard restriction*.

The effect of a downstream restriction on sewer capacity is readily identified using iso-Qs. A capacity loss of 46% (2.069 MGD vs. 3.832 MGD) is observed in this example.



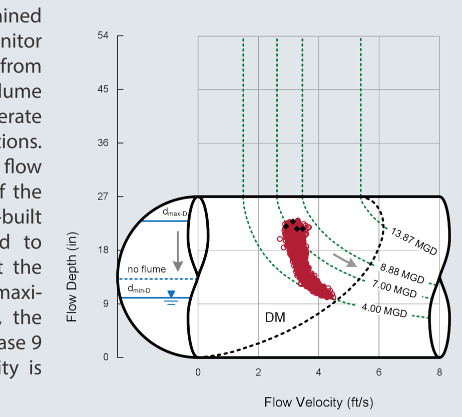
11. Backwater and Surcharge with Orifice Flow

The scattergraph shown here reveals the presence of a *dead dog* and a downstream restriction that cause backwater and surcharge conditions. However, note that the flow rate increases from 6.9 MGD to 8.3 MGD as the flow depth increases. This phenomenon is described as *orifice flow* and indicates that free flow conditions exist downstream from the restriction. A review of as-built records indicates both the *dead dog* and the downstream restriction are attributed to a pipe segment that was constructed at a negative slope.



12. Continuous Backwater

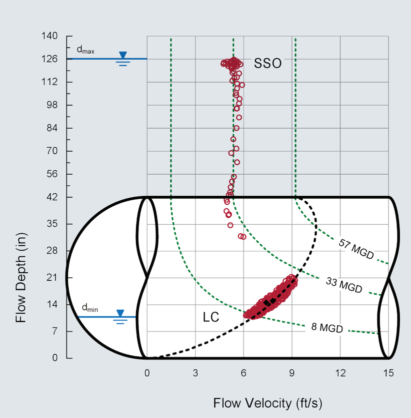
This scattergraph displays data obtained during dry weather from a flow monitor installed in a 27-in sewer just upstream from a 12-in Parshall flume. By design, the flume causes the upstream sewer to operate under continuous backwater conditions. This flume is no longer used for flow measurement. What would happen if the flume were removed? Based on as-built records, the Design Method is used to estimate the flow conditions without the flume. Following an iso-Q from the maximum flow depth to the pipe curve, the maximum depth is estimated to decrease 9 inches. As a result, the sewer capacity is expected to increase nearly two-fold.



13. Sanitary Sewer Overflow from Upstream Manhole

This example displays flow monitor data that show the tell-tale signs of a sanitary sewer overflow (SSO) located upstream from the monitoring location. An upstream SSO is identified by a cluster of surcharge data points at a constant flow depth and a constant flow velocity, as shown here. The depth is controlled by the overflow elevation, and the velocity is controlled by the capacity of the downstream sewer.

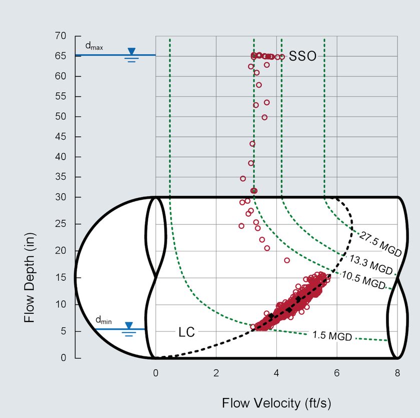
Viewing these data in a hydrograph reveals that this SSO lasted for almost eight hours. However, since the SSO occurred upstream, the overflow volume cannot be estimated.



14. Sanitary Sewer Overflow from Downstream Manhole

This scattergraph exhibits the classic signature of an SSO located downstream from a flow monitor location. 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 event.

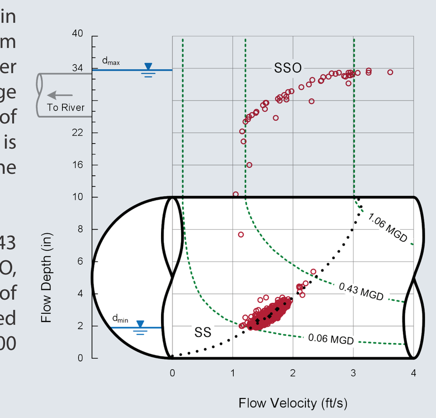
Note that the flow rate increased from 10.5 MGD to 13.3 MGD during the SSO, indicating that the maximum rate of overflow is 2.8 MGD. This SSO lasted for about six hours and discharged 331,000 gallons of wastewater to the environment.



15. Sanitary Sewer Overflow from Overflow Pipe

This 10-in sewer is equipped with an 8-in overflow pipe located in the downstream manhole. During a rain event, this sewer experiences backwater and surcharge conditions that limit flow to about 40% of the estimated full-pipe capacity. The SSO is activated when the flow depth reaches the invert elevation of the 8-in overflow pipe.

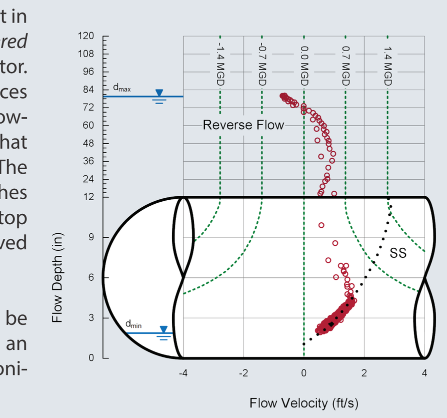
Note that the flow rate increased from 0.43 MGD to over 1.06 MGD during the SSO, indicating that the maximum rate of overflow is over 0.63 MGD. This SSO lasted about 10 hours and discharged 165,000 gallons of wastewater.



16. Reverse Flow

Reverse flow in a sewer system is rare, but in this situation a 12-in sewer is *overpowered* by a much larger downstream interceptor. 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.

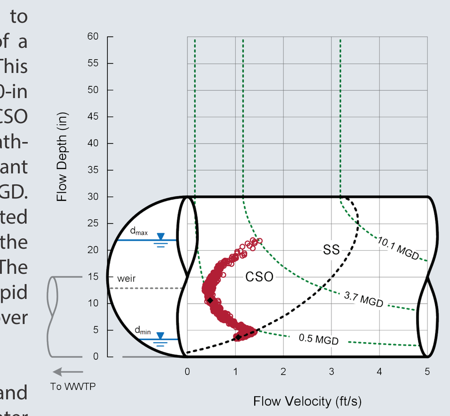
The reverse flow volume is estimated to be 46,000 gallons and might have caused an SSO somewhere upstream from the monitoring location.



17. Combined Sewer Overflow from End Weir

Flow monitor data provide a means to determine the duration and volume of a combined sewer overflow (CSO). This scattergraph displays data from a 30-in sewer located just upstream from a CSO regulator. A 15-in sewer conveys dry weather flow to the wastewater treatment plant (WWTP) and has a capacity of 0.5 MGD. Flow rates through the regulator are limited to this amount (hard restriction) as the regulator fills to the weir height. The overflow is characterized by a rapid increase in velocity as flow discharges over the weir.

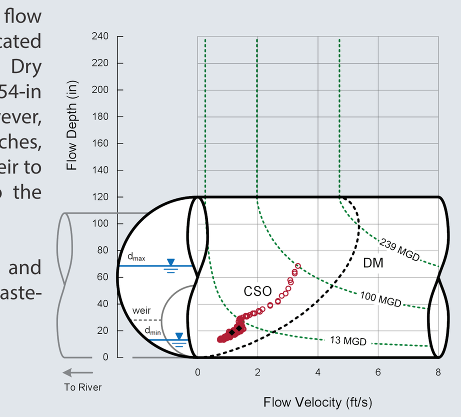
This CSO lasted for almost 22 hours and discharged 428,000 gallons of wastewater to the receiving water.



18. Combined Sewer Overflow from Side Weir

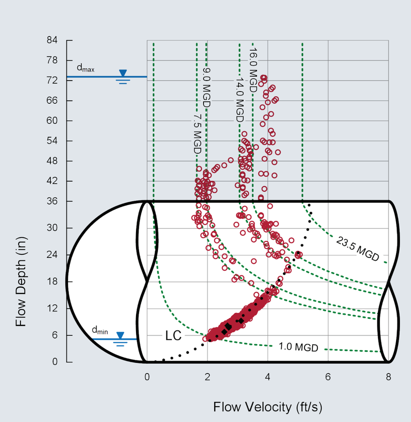
This scattergraph displays data from a flow monitor installed in a 120-in sewer located just upstream from a CSO regulator. Dry weather flows are funneled into a 54-in sewer and continue to the WWTP. However, when the flow depth exceeds 28 inches, additional flow is conveyed to a side weir to a 108-in sewer and is discharged to the receiving water.

This CSO lasted for over five hours and discharged over 7,400,000 gallons of wastewater to the receiving water.



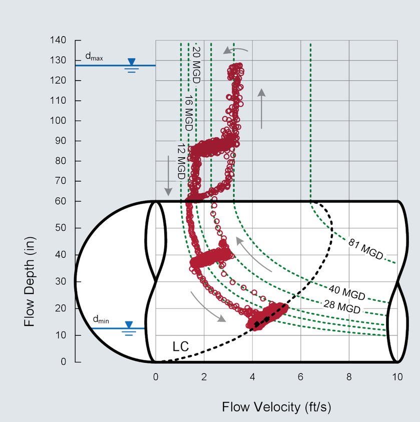
19. Constant Speed Pump Station

When operating in backwater conditions caused by a pump station wet well, flow monitor data follow an iso-Q equal to the pumping capacity. This monitor is upstream of a pump station with three constant speed pumps. Two pumps operate in a lead and lag role, with a third pump in reserve, and each pump alternates roles to equalize wear and tear. Each pump has a capacity of 9 MGD, and two pumps together have a capacity of 16 MGD. One of the pumps has a worn impeller and can pump only 7.5 MGD by itself and 14 MGD when paired with a second pump, a condition revealed by iso-Qs. This scattergraph alerted the Owner to the problem.



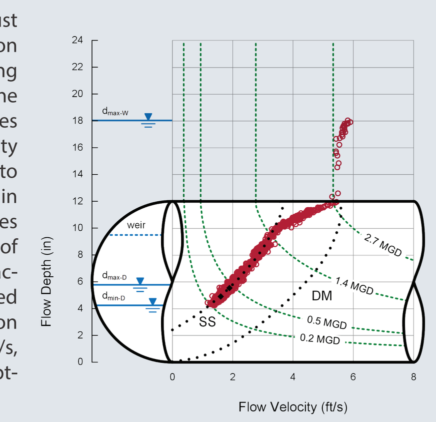
20. Variable Speed Pump Station

This scattergraph displays data from a sewer located upstream from a pump station with five variable speed pumps in which the pumping rate of each pump is varied to keep the wet well level within defined set points. These observations were made during a rainfall event in which all five pumps were placed in service. Four groups of data are observed in order of ascending flow depth as additional pumps come online. Movement of the data is counterclockwise. Note how the spacing between data points ascending the iso-Qs is greater than those descending, indicating a rapid response to and a slow recovery from this rainfall event.



21. Inverted Siphon

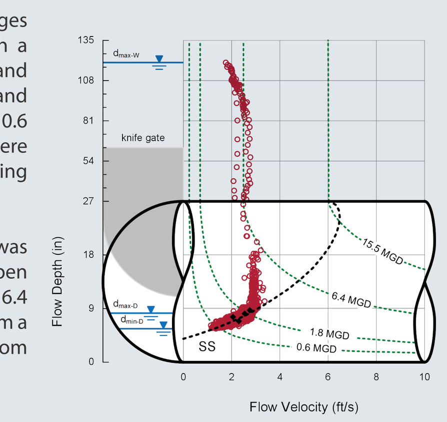
This flow monitor is installed in a sewer just upstream from an inverted siphon comprised of two 8-in barrels. The incoming sewer has a design capacity of 2.7 MGD. The velocity increase observed at 9 inches indicates that the first barrel has a capacity of 1.4 MGD. Additional flow is conveyed to the second barrel by a side weir located in the inlet structure. This pipe handles additional flow up to the design capacity of the incoming sewer. At the observed capacities of 1.4 MGD and 1.3 MGD, it is calculated that the two barrels of the inverted siphon have flow velocities of 6.20 and 5.76 ft/s, respectively – well within generally accepted guidelines for self-cleansing velocities.



22. Knife Gate

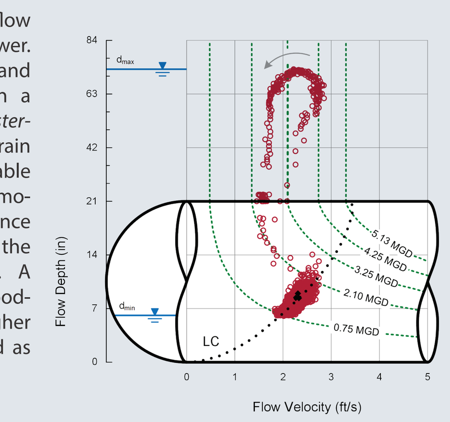
A satellite collection system discharges wastewater to another agency through a 27-in sewer for subsequent conveyance and treatment. The observed minimum and maximum dry weather flow rates are 0.6 MGD and 1.8 MGD. Greater flows were observed during wet weather, creating problems for the receiving agency.

To regulate peak flows, a knife gate was installed and positioned at a partially open setting, limiting the incoming flow to 6.4 MGD. This scattergraph displays data from a flow monitor located just upstream from the gate.



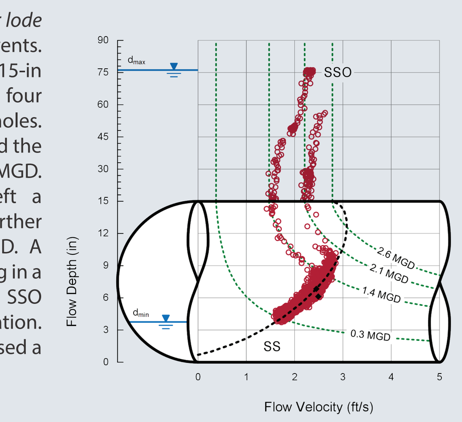
23. Hydraulic Hysteresis

This scattergraph displays data from a flow monitor installed in a 21-in trunk sewer. During wet weather, backwater and surcharge conditions are observed in a distinct manner defined as *hydraulic hysteresis*. During the initial response to this rain event, downstream storage is available within the system, allowing it to accommodate flows up to 4.25 MGD. However, once this storage is used, the throughput of the system is reduced to about 2.50 MGD. A similar condition is often seen in river flooding when the channel velocity is higher during the ascending part of the flood as flood waters fill the flood plain.



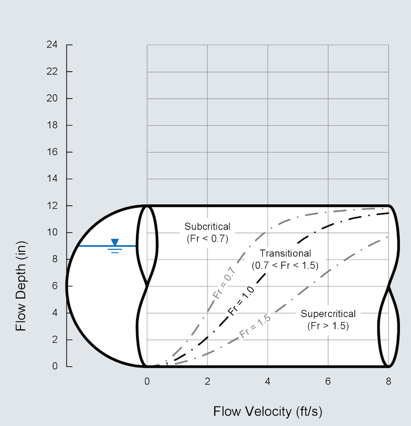
24. Sewer in the News

This scattergraph is a hydraulic *mother lode* showing three distinct hydraulic events. This flow monitor was installed in a 15-in sewer located just upstream from four consecutive 90-degree turning manholes. The head loss from this routing reduced the sewer capacity from 2.6 MGD to 2.1 MGD. Later, a contractor inadvertently left a concrete block in the channel, further reducing the sewer capacity to 1.4 MGD. A large rain event then occurred, resulting in a surcharge of 75 inches and an SSO upstream from the monitoring location. The SSO entered a small pond and caused a fish kill that made the evening news.



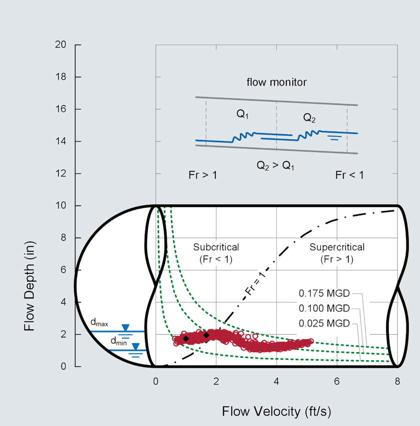
25. Iso-Froude Lines

Flow conditions within a sewer are directly related to the Froude number (Fr). If Fr < 1, conditions are classified as *subcritical* and are often described as tranquil or streaming. If Fr > 1, conditions are classified as *supercritical* and are often described as rapid or shooting. Hager and others have modified and expanded the traditional classification of flow conditions, introducing a region of *transitional* flow (0.7 < Fr < 1.5) between subcritical and supercritical flow where unstable conditions may be observed. These conditions are denoted on a scattergraph by constructing *iso-Froude lines* as shown here.



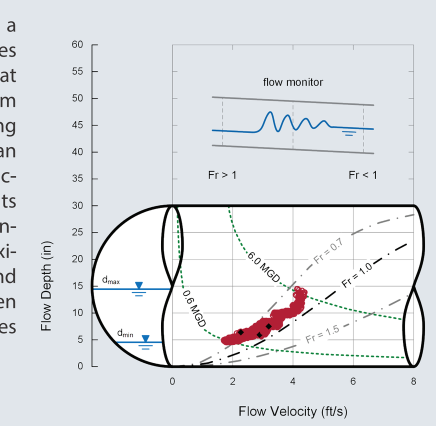
26. Hydraulic Jump

This scattergraph is from a site that experiences a *hydraulic jump*. This condition occurs when flow transitions from supercritical to subcritical flow. In this example, the hydraulic jump is located upstream from the monitor at lower flow rates, and the subcritical side of the hydraulic jump is observed (Q_1). As the flow rate increases, the hydraulic jump is *pushed* through the monitoring location, and the supercritical side of the hydraulic jump is observed (Q_2). Flow monitors can operate well in either subcritical or supercritical conditions, but accuracy may deteriorate during the transition. Therefore, a hydraulic jump should be avoided, if possible.



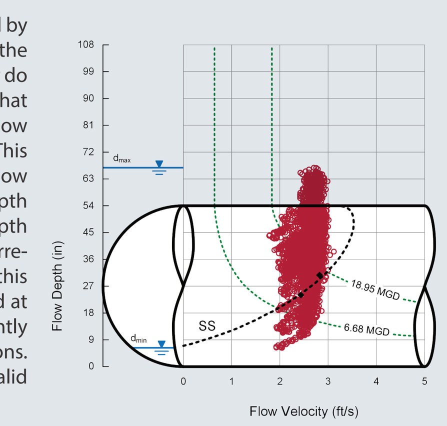
27. Undular Jump

An *undular jump* is different from a traditional hydraulic jump and includes surface undulations and disturbances that extend some distance downstream from the jump. A scattergraph depicting near-critical conditions resulting from an undular jump is shown here and is characterized by a *stair step* pattern that results from surface undulations on the downstream side of the undular jump. The maximum distance between wave crest and trough is nearly five inches and occurs when the beginning of the undular jump reaches its closest approach to the flow monitor.



28. Drifting Depth

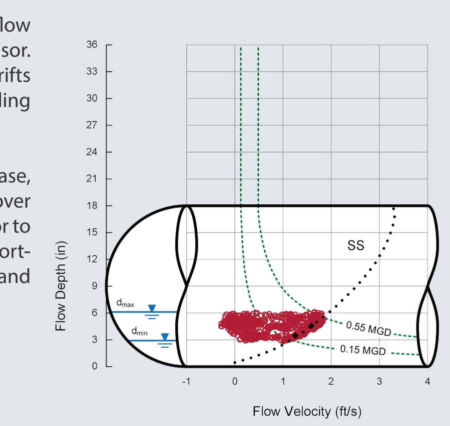
Most flow monitor data can be described by the Manning Equation using one of the methods previously described. Data that do not lie on a pipe curve indicate either that the hydraulics are different or that the flow monitor is not working correctly. This scattergraph displays data from a flow monitor with a drifting pressure depth sensor. Note that the reported flow depth drifts over a wide range without a corresponding change in flow velocity. In this case a series of pipe curves are observed at multiple depths and deviate significantly above and below the manual confirmations. The data from this flow monitor are invalid and should be disregarded.



29. Drifting Velocity

This scattergraph displays data from a flow monitor with a drifting velocity sensor. Note that the reported flow velocity drifts over a wide range without a corresponding change in depth.

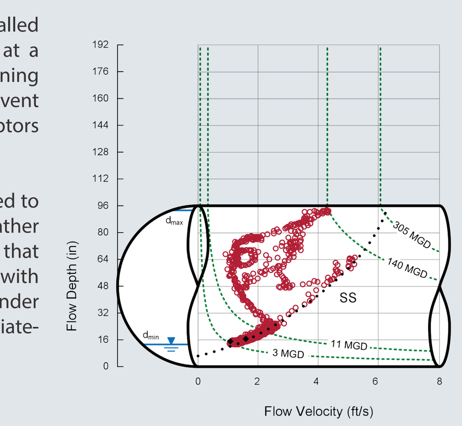
This velocity sensor was fouled by grease, and sensor performance deteriorated over time, eventually causing the flow monitor to record negative velocities. The data reported by this flow monitor are invalid and should be disregarded.



30. Sewer Entertainment

These data are from a flow monitor installed in one of three interceptors arriving at a WWTP. This unusual and entertaining pattern was created during a rain event when one of the larger interceptors *overpowered* this one.

The Stevens-Schutzbach Method is used to define a pipe curve based on dry weather data (between 3 and 11 MGD). The fact that subsequent wet weather data coincide with this pipe curve at greater depths under similar conditions validate the appropriateness of this method.



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