Scattergraph Principles and Practice

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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 the 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 designed as 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 scattergraph tools are presented and discussed throughout this poster, including the Design Method, the Lanfear-Coll Method, and the Stevens-Schutzbach Method, along with iso-Q™ lines and iso-Froude lines. The combination of these tools makes it easy to determine the Operational Capacity of a sewer.

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

Additonal Resources

A growing body of educational information on the scattergraph is available at www.adsenv.com/scattergraph, including technical publications, additional examples, and other reference materials.

Acknowledgements

The authors acknowledge the contributions that others have made to the development and application of the scattergraph, including the Water Research Centre, Peter Keefe, Jim Schutzbach, Burt Curry, David Butler, Willi Hager, and Hubert Chanson.

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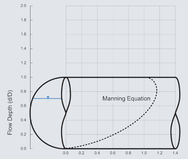
1. Manning Equation

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.

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

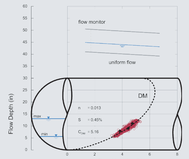
This relationship is depicted here as a *pipe curve* and provides a convenient reference to evaluate flow monitor data. The Manning Equation is an important component of the scattergraph and can be applied using three methods.



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 ( ).

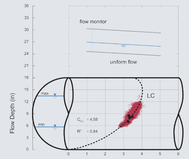
The fact that these data coincide with the pipe curve is evidence that this sewer operates as designed. Three manual confirmations (•) are also shown and demonstrate the accuracy of the flow monitor. Note that the Design Method results in a pipe curve that is constrained to the origin (0,0).



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).

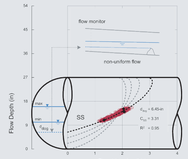
This method is demonstrated here. Under ideal conditions, the Design Method and the Lanfear-Coll Method generate the same pipe curve. Note that the Lanfear-Coll Method results in a pipe curve that is constrained to the origin (0,0).



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, debris, and other related conditions.

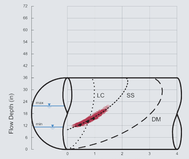
This method is demonstrated here using four iterations. The magnitude of the *dead dog* (d_{dog}) is varied until the Manning Equation best fits the observed data. Note that the Stevens-Schutzbach Method results in a pipe curve that is not constrained to the origin (0,0).



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*.

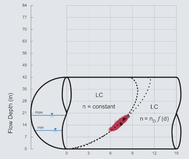
This example illustrates this concept and demonstrates the effect of a *dead dog* on sewer capacity. The predicted full-pipe velocities range from 1 ft/s to 3 ft/s, a three-fold difference among these methods.



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.

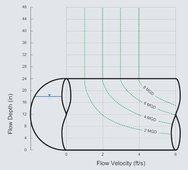
All three methods can be modified to use a varying roughness coefficient. The use of a constant or varying roughness coefficient can result in estimates of sewer capacity that differ by 20% or more. Both versions are used in the following panels and are identified using dashed or dotted lines as shown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

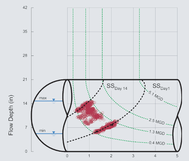
Simply put, an iso-Q is a line of constant flow rate and is analogous to a contour line on a topographic map. Iso-Qs play an important role in evaluating sewer capacity and are incorporated in the following panels.



8. Debris Accumulation

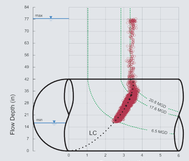
Silt and debris can cause a significant reduction in sewer capacity. This example displays flow monitor data from a 14-day period. Observed conditions become deeper and slower as debris accumulates downstream from the monitoring location. What is the impact on sewer capacity?

The Stevens-Schutzbach Method is used to estimate the actual capacity on Day 1 and Day 14. These values, along with the minimum and maximum dry weather flow rates are denoted using iso-Qs. The debris caused a capacity loss of 51% (2.5 MGD vs. 5.1 MGD).



9. Surcharge

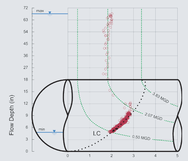
Surcharge conditions are common in sewer systems, especially during wet weather events. The flow monitor data shown here indicate that this sewer operates as expected up to its rated capacity of 20.8 MGD. This value is shown using an iso-Q. Although surcharge conditions are common, it is uncommon to find a surcharged sewer that actually accommodates 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

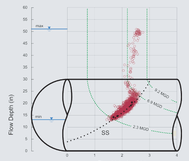
Most surcharge conditions result from downstream restrictions that reduce sewer capacity. The flow monitor data shown here indicate that this sewer operates as expected up to a depth of about 9 inches. However, backwater conditions are observed above this point and result in surcharge conditions at a lower capacity than expected.

The effect of a downstream restriction on sewer capacity is readily identified using iso-Qs. A capacity loss of 46% (2.07 MGD vs 3.83 MGD) is observed in this example.



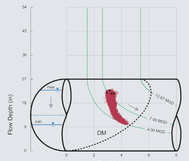
11. Backwater and Surcharge with Orifice Flow

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 nearly 9.2 MGD as the flow depth increases during surcharge conditions. 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

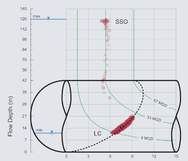
This scattergraph displays data obtained during dry weather from a flow monitor installed in a 27-in sewer just upstream from a 12-in Parshall flume. By design, the flume causes the upstream sewer to operate under continuous backwater conditions. This flume is no longer used for flow measurement. What 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 (Upstream)

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.

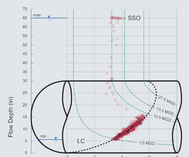
Viewing these data in a hydrograph reveals that this SSO lasted for almost eight hours. However, since the SSO occurred upstream, the overflow volume cannot be estimated.



14. Sanitary Sewer Overflow (Downstream)

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.

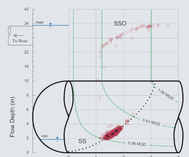
Note that the flow rate increased from 10.5 MGD to 13.3 MGD during the SSO, indicating that the maximum rate of overflow is 2.8 MGD. This SSO lasted for about six hours and discharged 331,000 gallons of wastewater.



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.

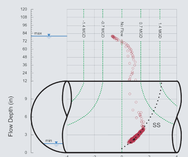
Note that the flow rate increased from 0.43 MGD to over 1.06 MGD during the SSO, indicating that the maximum rate of overflow is over 0.63 MGD. This SSO lasted about 10 hours and discharged 165,000 gallons of wastewater.



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.

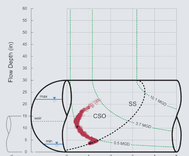
The reverse flow volume is estimated to be 46,000 gallons and most likely caused an SSO somewhere upstream from the monitoring location.



17. Combined Sewer Overflow (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 flow monitor installed in a 30-in sewer located just upstream from a CSO structure. This structure is equipped with an end weir that diverts dry weather flow to the wastewater treatment plant (WWTP) through a 15-in sewer. When the flow depth exceeds the weir height, additional flow is carried over the weir and is discharged to the receiving water.

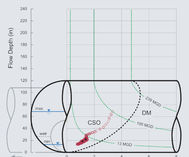
This CSO lasted for almost 22 hours and discharged 428,000 gallons of wastewater to the receiving water.



18. Combined Sewer Overflow (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 carried over a side weir to a 108-in sewer and is discharged to the receiving water.

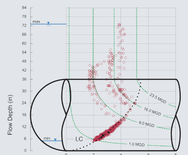
This CSO lasted for over five hours and discharged approximately 7,423,000 gallons of wastewater to the receiving water.



19. Pump Station

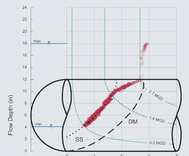
When operating in backwater conditions caused by a pump station wet well, flow monitor data follow an iso-Q equal to the pumping capacity. This monitor is located upstream from a pump station that alternates between two lead pumps, each with a rated capacity of 9 MGD. The station has a total rated capacity of 16 MGD.

This scattergraph indicates that one lead pump is operating below capacity. However, the total capacity of the pump station exceeds its nominal rating under observed conditions. If needed, this pump station could be upgraded to a capacity of 23.5 MGD, the capacity of the incoming sewer.



20. Inverted Siphon

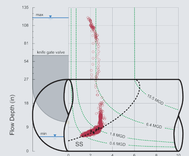
This flow monitor is installed in a sewer just upstream from an inverted siphon comprised of two 8-in barrels. The incoming sewer has a design capacity of 2.7 MGD. The velocity increase observed at 9 inches indicates that the first barrel has a capacity of 1.4 MGD. Additional flow is conveyed to the 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.



21. Knife Gate Valve

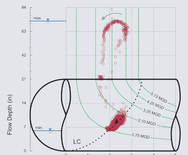
A satellite collection system discharges wastewater to another agency through a 27-in sewer for subsequent conveyance and treatment. The observed minimum and maximum dry weather flow rates are 0.6 MGD and 1.8 MGD. Greater flows were observed during wet weather, creating problems for the receiving agency.

To regulate peak flows, a knife gate valve 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 valve.



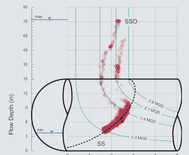
22. Hydraulic Hysteresis

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.



23. Sewer in the News

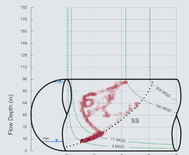
This scattergraph is a hydraulic *mother lode* showing three distinct hydraulic events. This flow monitor was installed in a 15-in sewer located just upstream from four consecutive 90-degree turning manholes. The head loss due to this routing causes a capacity loss of 0.5 MGD. Later, a contractor inadvertently left a concrete block in the channel of one of the manholes, resulting in a further capacity loss of 0.7 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.



24. Sewer Amusement

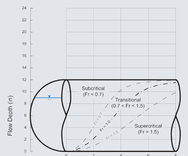
These data are from a flow monitor installed in one of three interceptors arriving at a WWTP. This unusual and entertaining pattern was created during a rain event when one of the larger interceptors *overpowered* this one.

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.



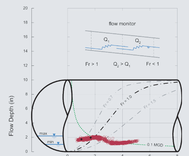
25. Iso-Froude Lines

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 illustrated on a scattergraph by constructing *iso-Froude lines* as shown here.



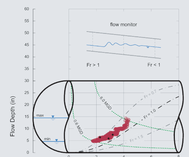
26. Hydraulic Jump

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.



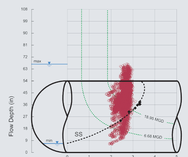
27. Undular Jump

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 believed to depict 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 Sensor

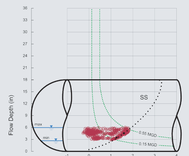
Most flow monitor data can be described by the Manning Equation using one of the methods previously described. Data that do not lie on a pipe curve indicate either that the hydraulics are different or that the flow monitor is not working correctly. This scattergraph displays data from a flow monitor 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 Sensor

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



30. Official Bird of Collection Systems

Patrick Stevens has long proposed that the sewer industry adopt the American Robin as the Official Bird of Collection Systems. Think about the similarities between the Robin and sewer folks. The Robin lives in every state and province in North America and is found where people live and congregate. It spends the day with an eye on the ground looking after things unseen by others. The Robin makes a living doing things with holes in the ground that most people find disgusting, and (most importantly) the scientific name of the Robin is a fitting description of our industry's mission - *Turdus migratorius*.

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