Recognizing the Scattergraph Signature of an SSO

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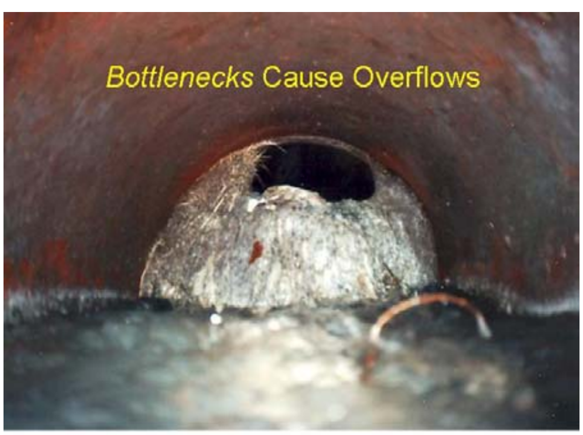
Ever since Congress prohibited overflows in the Clean Water Act[1], the regulated community has been wrestling with the challenge of preventing them. Overflows can cause serious impacts to the water environment. But they often occur in locations where they are not immediately apparent, or at times when they escape public attention. This can lead to recurrence or worsening, because utility administrators lack the information necessary to manage them. Advances in technology and engineering practice have now provided the technique to track and define unseen overflow events and causes. Progressive cities like Atlanta and San Diego have installed ADS' state-of-the-art IntelliScan® systems for, among other things, real-time monitoring and notification of potential overflows. Baltimore is embarking on an overflow monitoring effort that will rely heavily on expert interpretation of scattergraphs to detect and quantify SSOs.

The Causes of SSOs

Overflows are always caused by a unique group of sewer system stresses that ADS calls "bottlenecks". "Bottleneck" is a convenient term for a localized decrease in the slope of the hydraulic grade line that attains a slope less than required for proper operation. Sources of bottlenecks that cause overflows include:



- Acute wet weather overloading;
- Chronic overloading due to undersized pipe systems;
- Temporary or intermittent physical obstructions (especially under dry weather conditions)
- Catastrophic structural failures.

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[1] 33 USC §§ 1251-1387

Detection and Documentation

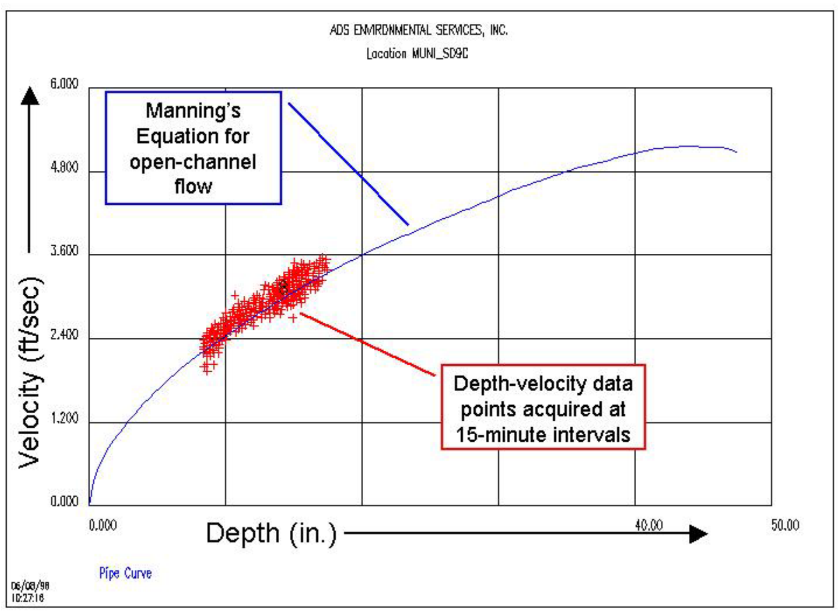
Is there a way to detect and quantify overflows? Is there a way to identify their threat before it manifests? Is there, perhaps, even a way to recognize and intercept overflow-threatening conditions as they develop? ADS includes scattergraphs in our flowView™ portfolios[2], because skillful interpretation of the scattergraph provides our clients with <u>all</u> this intelligence.

In order to extract overflow intelligence from a scattergraph, it must be supported by:

- The best hardware solution – High performance depth-velocity flow monitoring equipment;
- The best quality assurance program for installation and maintenance;
- The most skilled and experienced analytical staff and techniques.

Failure of any one of these supports will result in mountains of useless data, and no reliable overflow intelligence whatever.

Hardware is crucial because overflows always occur under conditions of maximum system stress. If the instrumentation delivers 98% of the time, but not when it's raining, the data are valueless for overflow monitoring purposes. Details of the equipment installation, and documentation of that installation, are critical. A single incorrect or inadequately documented measurement from the field will generate incorrect (and even convicting!) information about overflow conditions. Inadequate attention to sensor service needs always leads to data loss at the most critical times. Finally, interpreting the depth-velocity signature of the overflow requires experienced understanding of the data acquisition regime, the theoretical basis and practical details of sewer hydraulic behavior, and the perspective gained from studying similar overflow performance in comparable systems. These demanding elements make successful overflow monitoring a narrow discipline practiced only by experts.



What is a Scattergraph?

A Scattergraph is simply a graph of data in two variables. Wherever data in two variables are expected to exhibit a relationship that can be

[2] flowView™ - ADS' flow monitoring analysis and reporting programs

represented by a known equation, scatter plots have long been used for statistical analysis of data observations. The equation is plotted, and observed values are plotted along with it. Then, by testing the observations against the line of the equation, the analyst may distinguish between reliable and suspicious data. This "quality control" purpose was the initial application of scattergraphs for sewer flow monitoring data.

Alternatively, if the equation is unknown, suitable regression analyses may be employed to generate an equation that "fits" the data to an acceptable degree. This principle is the basis for the simplistic "curve fitting" lately practiced to "fill in" lost depth or velocity data; it is applicable in the cases where the regression curve is adequately established and the sewer is truly abiding by its historical pattern.

Observations of depth and velocity in sewers are amenable to plotting on a scatter plot. If an equation expressing the depth-velocity relationship for sewers is known, the depth-velocity data may be compared to it. Alternatively, these data may be regressed in an attempt to define an unknown depth-velocity relationship.

Mannings Equation

Enter Robert Manning, nineteenth-century Irish accountant and "hydraulician". Throughout the last century, civil engineers considered the depth-velocity relationship for unconstrained, uniform, steady-state, open channel flow to be well-understood. They thought that some empirical relationship, typified by Manning's Equation (1889) for open channel flow, was adequate for wide application. Whole generations of civil engineers learned this equation, and, ignoring Manning's own admonitions[3], designed sewers, and predicted sewer capacities, using this empirical relationship.

So, with the advent of precise computerized monitoring equipment to calculate sewer flow by the Continuity Principle[4], it was natural that civil engineers would assess the quality of that data by plotting it on the same chart with a plot of Manning's equation. With the data so plotted, they thought to judge data quality by correlating the data against the line mapped out by the equation. "Lines up?" – the data are considered reliable. "Doesn't line up"? – the data must be suspect. But the state of measurement technology was vaulting beyond the underlying empiricism, and finally, contradicting it…

Sewers Don't Behave Like They Taught Us

Some of these "quality" plots did indeed show the depth-velocity data to "line up" with the Manning curve. But for some monitoring sites, indeed many sites, the data plots obstinately refused to conform to the equation. Rigorous attention to equipment

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[3] Fischenich, C. (2000). J. Dooge, quoting Manning's address to the Institution of Civil Engineers of Ireland: "And now a few words, again addressed to the younger members…a formula is only a short memorandum (put in a shape fit for ready use) of the result arrived at after a patient consideration of the facts and principles upon which it is founded, and to use it without investigation is the merest empiricism."

[4] Continuity Principle: loosely, $Q=vA$, where Q is volume rate of flow, v is average velocity, and A is cross-sectional area of flow.

installation and quality control only confirmed that the data were plotting out a relationship different than the accepted one. Like the errant orbit of Uranus, crying out for the discovery of Neptune, the scattergraphs insisted there was "something else out there". Any or all of these problems persisted: the *Y*-intercept was negative, the slope was greater than Mannings curve, less than Mannings curve; the point of inflection was vastly different than that predicted, "curve-fitting" the data demanded high-order polynomial equations.

Engineers, determined to understand the practical hydraulics of open channel flow in sewers, struggled resolutely. They looked to the Space Program for new technology advances and redundancy concepts; they schooled hydraulic data analysts and subjected the analyses to endless cross-checking and quality control; they instituted disciplined field practices for installation and quality diagnosis; they established ISO9001 procedures for every process, for conduct of data analysis, for data management. And still many, perhaps most, of the more important flow monitoring sites refused to bow to the tyranny of the Manning curve.

Finally, the hydraulic engineers began to seek a new answer. Perhaps, they reasoned, Robert Manning himself was right, when he acknowledged that a mathematical understanding of open channel flow had proved "almost hopeless" in 250 years of hydraulics[5]. Perhaps the data from the field were correct if, when subjected to the most rigorous quality control, they still failed to "line up" with Manning's mathematical solution! The key was found in placing their trust in the data integrity – when the flow monitoring and data analysis were disciplined and trustworthy, they could be used to actually define the hydraulic operating regimes of the sewer. The data revealed discreet depth-velocity data regimes that could be identified on scattergraphs:

- Steady-state open channel flow with energy gradient equal to pipe slope;
- Steady-state open channel flow with positive *X*-intercept due to downstream sag;
- Transient conditions with energy gradient less than pipe slope, pipe backing up, storage occurring;
- Transient conditions with energy gradient greater than pipe slope, storage running out;
- Steady-state pressure flow with pipe surcharged;
- Steady-state and variable flow conditions with overflow relief.

In 1994, ADS engineers unveiled a new tool – depth-velocity scattergraph analysis! Actual sewer flow scattergraphs simply bore witness to the orderly transition of the data through a dynamic sequence of these hydraulic regimes, with several common sequences seen most frequently.[6] They found that these sequences left unique "signatures" that could be used to diagnose the operating modes and stresses to which the sewer was subject. Finally, the scattergraph from a precision flow monitor could be reconciled with Mannings Curve!

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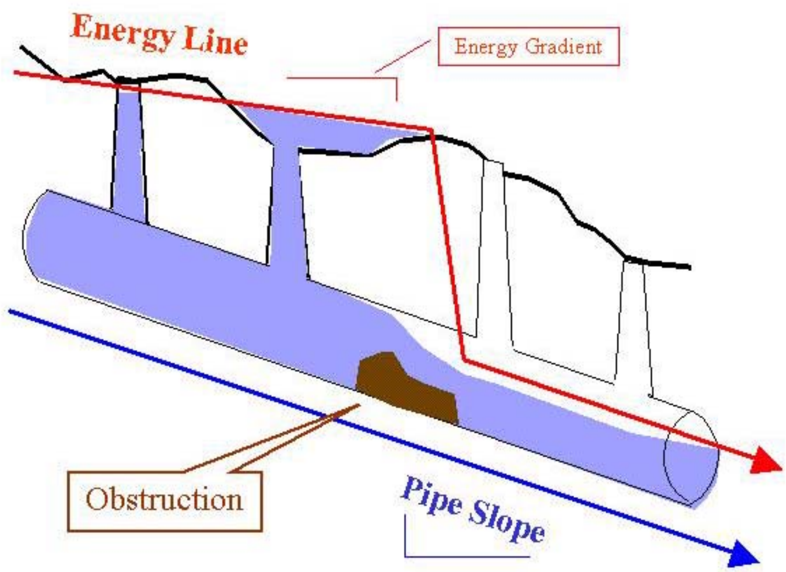
[5] Manning, R. (1889) "On the Flow of Water in Open Channels and Pipes"
[6] Stevens, P.L. (1997) "The Eight Types of Sewer Hydraulics", WEF Collection Systems Specialty Conference. Kansas City, Mo.

Manning's curve could now be used as a kind of "index curve", a baseline against which to compare, not data integrity, but rather sewer hydraulic performance. Understanding where the data would be, under simplified, controlled conditions, provides a baseline for identifying and characterizing complex dynamic performance.

The Energy Line Rules!

Anyone will tell you, "water flows downhill", "water seeks its own level". All that's necessary to diagnose sewer performance from a scattergraph is to express, understand and apply that common knowledge from the standpoint of fluid mechanics. The driving force that causes gravity sewer flow is expressed mathematically as the "energy gradient" or graphically as the "energy line". In Manning's equation, for any given sewer, the slope of the energy line will control the relationship between depth and velocity. Sewers with shallow energy gradients run deep and slowly; those with steep energy lines run shallow and fast.



The most fundamental principles of physics constrain the behavior of the energy line.[7] Its slope can never be steeper or gentler than the grade of the sewer itself - not in the long run. (unless energy is being added or mass removed just downstream[8]). But the energy line <u>can</u> be steeper or gentler than pipe slope for short periods (minutes or hours), those limits determined by the storage inventory available upstream. And the slope of the energy line can <u>also</u> be gentler than the pipe slope if an overflow is occurring downstream. In fact, scattergraphs of real sewers show them constantly storing and releasing flow, dynamically changing their energy gradient in continuous response to changes in loading; and scattergraphs from real sewers bear witness to developing and active overflows.

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[7] Conservation of mass and conservation of energy must always apply. So energy can be exchanged between the terms of Bernoulli's Equation, especially between elevation head and pressure head (velocity head is so small that it can absorb transfer of very little pressure or elevation head – velocity head is usually on the same order as the elevation head differential within a manhole section).

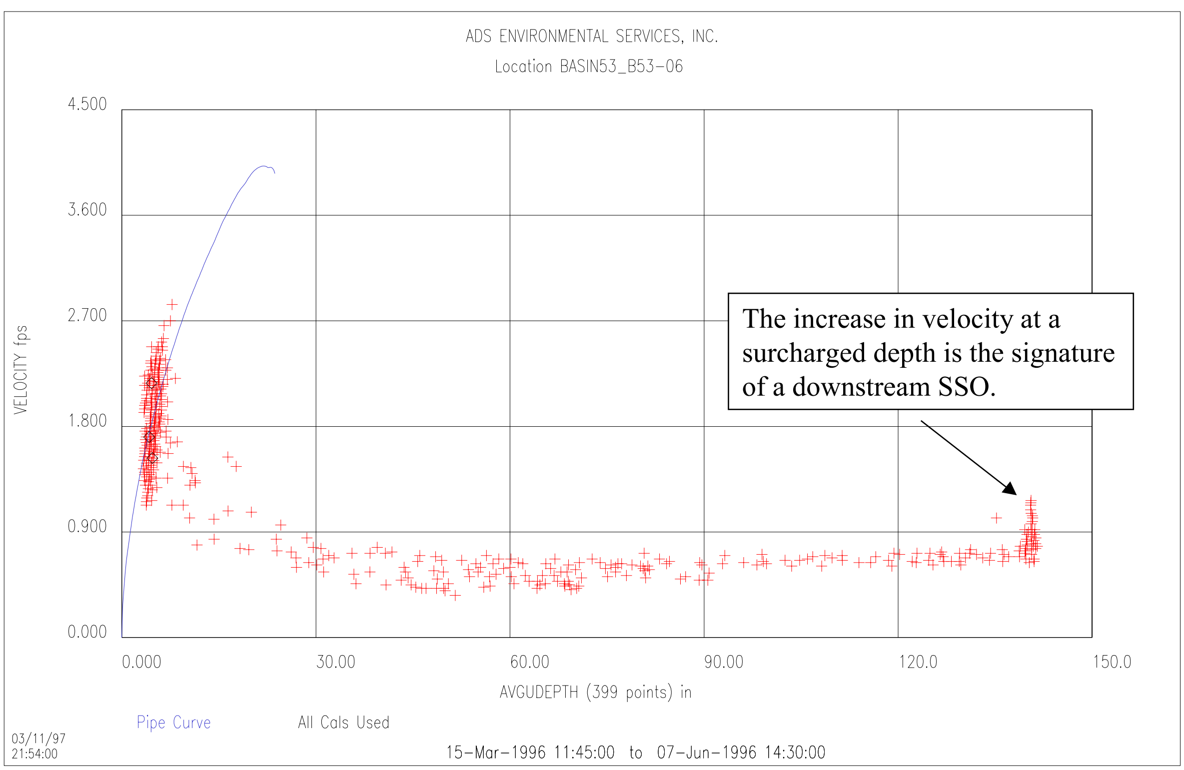
[8] Energy added as by a pump, or removed as by turbulence and waste caused by an obstruction or parasitic loss. As it turns out, these are very common conditions outside the laboratory.

Scattergraph of an Overflow

Therefore overflows can be identified and diagnosed by considering the energy line, as characterized by changes in the depth-velocity relationship, and easily seen on a scattergraph. When the relationship proceeds from shallower-faster to slower-deeper, the sewer is “backing up” – acting under influence of a downstream bottleneck; the energy gradient is gentler than the pipe slope. As this persists, increasing depth consumes all the storage capacity available in pipes and manholes upstream and the energy line rises, ultimately approaching the top of the lowest nearby manhole or nearby stormwater sewer overflow. The scattergraph shows the data points progressively becoming deeper and slower.

If the downstream obstruction is not overcome by the resulting pressure, the energy line finally attains the overflow elevation and an overflow ensues. When overflow initiates, the downstream end of the energy line becomes fixed at the overflow elevation, and the energy line will not rise any further (since the overflow manhole cannot surcharge any further). The depth-velocity relationship changes noticeably and instantly; with depth fixed, velocity (and hence discharge) continues to increase until the energy gradient stabilizes with discharge matching the upstream load.

An overflow scattergraph shows increasing velocity at a fixed depth. Scattergraph analysis is now a proven tool for identification and quantification of overflows in sewer systems. Successful application of the technique depends on application of the best flow monitoring hardware solution, yielding full-time, high quality depth-velocity data, a documented quality assurance program for installation and maintenance, and the most



skilled and experienced analytical staff and techniques.

Importantly, if the scattergraph is regularly reviewed and interpreted over weeks and months, the hydraulic engineer will perceive events trending towards, and approaching overflow. This advance warning provides adequate time for response and avoidance. Overflow consequences will then be avoided, through:

- short-term maintenance responses;
- medium-term operation optimization responses, and;
- long-term capital facilities responses.

Since overflows are always caused by bottlenecks, the warning signature from a developing bottleneck can be used to alleviate the pending overflow.

This progression of hydraulic behaviors is recognizable to ADS' experienced scattergraph analysts, only because the data are of adequate integrity to support the analysis. The flow monitor must function reliably throughout the backup and overflow event, while grease and floatables are rising in the pipe and manholes, solids are settling in the channel invert, and pressures are fluctuating rapidly, accompanied by severe changes in acoustic noise. If the instruments were installed properly and securely; if the monitor entered the event clean, operational and properly confirmed; if the sensors all remained functional; and the data analyst correctly interpreted all the fluctuating sensor data, the scattergraph will give a clear account of the onset and progress of the overflow.