Boston's Pilot Project to Measure CSO Flows Relies on New Technology and Scattergraphs to Detect Overflows

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ABSTRACT

In 2013, the Boston Water and Sewer Commission (Commission) initiated a pilot study of ten CSO structures to determine if current technology is reliable enough to measure overflow activation, duration and volume with a high degree of confidence for public notification on the Commission's web site. A hydraulic model is currently being used for regulatory reporting for volume, but a more immediate system is needed for public notification.

The strategy was to instrument all incoming and overflow pipes in nine of the ten regulators, which are all tidally-influenced. The Commission's goal for the pilot project was to determine 1) whether or not an overflow occurred, 2) the start and end times of a combined sewer overflow, 3) if these events and information can reliably be reported in real or near-real time in a practical manner to the notify the public.

ADS Environmental Services (ADS) was selected to measure depth, velocity and flow at the locations utilizing fifteen monitoring devices with twenty-five sensors measuring all incoming combined sewer flow and overflow to receiving water bodies. The selected structures are all different, but they contain typical components of overflow weirs, baffle walls to control floatables and tide gates. In addition to the ADS monitoring equipment a NOAA tide gauge installed in Boston Harbor is used for tide level verification and all depths in the ADS system are converted to elevation data on a common Boston datum. The use of elevation data in conjunction with traditional depth and velocity data in the outfall pipes has helped determine if motion in the overflow pipe is an actual overflow or flood and ebb tides. The use of traditional methods combined with elevation data and conditional algorithms for overflow confirmation have helped improve real-time data quality and confidence for eventual public notification.

The topic of this paper is an innovative method for understanding the regulator behavior and for identifying overflow events based upon repeatable patterns in scattergraphs. The incoming lines to all structures are metered with depth and velocity sensors and the scattergraphs of those data reveal patterns that, by themselves, can be used to identify and develop estimates of overflow volumes.

KEYWORDS: Combined Sewers, Combined Sewer Overflow, CSO, Flow Monitoring, Scattergraph, Tidal Influence

INTRODUCTION

The Boston Water and Sewer Commission (Commission) developed a pilot program to identify occurrences of combined sewer overflows (CSOs) and to provide the public with this information. Several years ago, a plan to notify the public about CSOs was submitted to the regulatory agencies as required by the Commission's CSO NPDES Permit. To complete this plan, the Commission is investigating whether current technology can be used to identify; (1) when overflows occur and (2) whether overflow information can be posted onto a web page within a reasonable time after the overflow.

In 2013, the Commission hired ADS Environmental Services (ADS) to conduct a two (2)-year, pilot program to identify overflows and develop a web page for posting overflow information. Currently, ADS collects data from ten (10) regulator locations (Figure 1) and stores the data on a web site maintained by FlowWorks. In addition to storing data, this site has the capability of performing calculations and logic tests which can identify overflow conditions. Over the past eighteen (18) months, the pilot program has analyzed data from six (6) significant storms; comparing the various calculations to gain confidence in identifying the beginning and end of overflow events. At many of the regulators, confidence in identifying the overflow is fairly high. However, more storms will be needed to increase the confidence at several locations.

Background

Almost twenty years ago (20), the Metro Boston regional water authority, Massachusetts Water Reclamation Authority (MWRA) developed a long term control plan to reduce overflows from the combined areas in Boston as well as Cambridge, Somerville and Chelsea. The overall goal of the plan was to eliminate overflows to receiving waters used for swimming and reduce overflows to the remaining receiving waters such as Boston Harbor to four times a year or less. The regulator locations in the pilot program can discharge into Boston Harbor or Fort Point Channel, an embayment of the harbor.

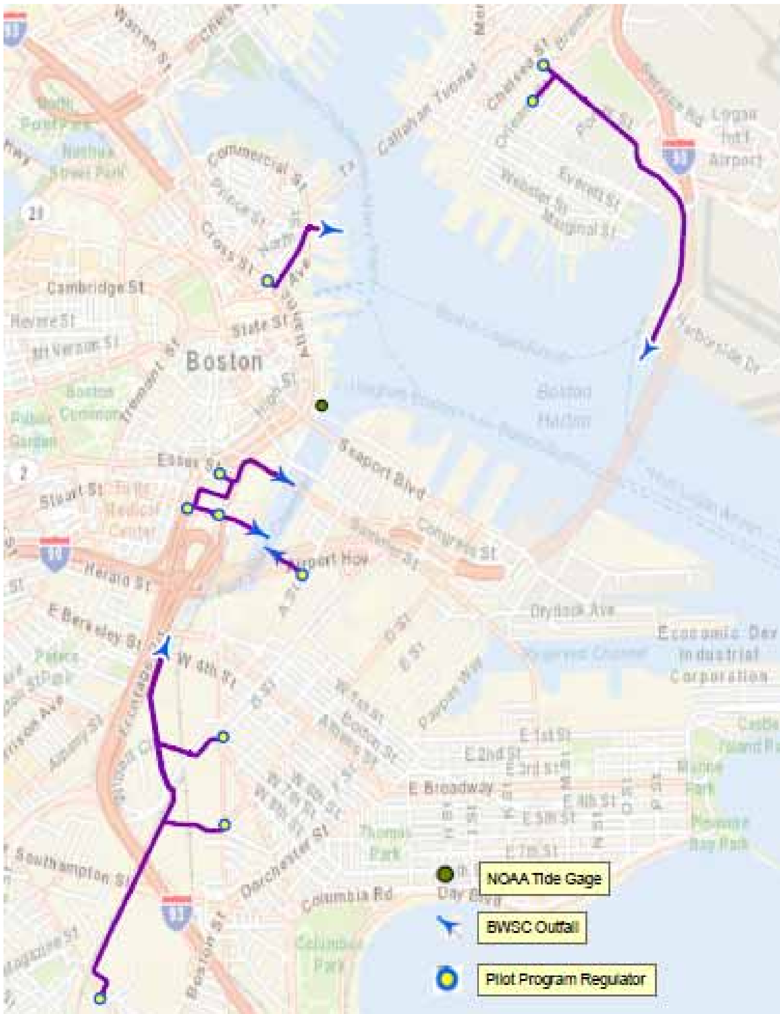

Figure 1 - Boston Water and Sewer CSO pilot location map

Many programs in the past attempted to identify overflows by focusing on measuring depth and velocity near the overflow weirs or in the outfall pipes. If stormwater or tidal water was present in the outfall pipe downstream of the regulator, the measurements at the overflow weirs were often not useful. This program approached data collection differently; depth and velocity sensors were installed in the inlet pipes and downstream of the weirs. Data was collected in five (5) min intervals so that we could observe the rapidly changing conditions during an overflow. The project monitors the tidal heights in Boston Harbor, since all of the regulators are impacted by the height of the tide. To compare water levels at the sensors to the water level in Boston Harbor, each location was field surveyed with elevations established for all of the sensors.

Six significant rain events from an inch and a half (1.5”) to nearly four (4”) inches have occurred during the project. During many of these events, stormwater or tidal water was present in the overflow pipes and affected the ability of the sensors near the overflow weirs to measure velocity with sufficient reliability; making it difficult to identify whether an overflow occurred.

Fortunately, the inlet sensors were not affected by tide or storm water and the full range of incoming combined sewer flows was measured. Depths and velocities from the inlet sensors were plotted onto scattergraphs to observe patterns in the data. During the initial stages of the storms, depth and velocity increased together as predicted by the Manning’s equation. However, as the storm progressed this relationship broke down. Depth continued to increase while velocity decreased. The scatterplot presented later (Fig. 3) show depth and velocity points generally following a line of constant flow (Iso-Q lines). This line of constant value represents the capacity of the regulator to convey flows to the nearby interceptor.

Regulator capacity is specific to a location and plays an important role in identifying an overflow. When the inlet flow exceeds the regulator capacity, the overflow begins and the excess flow discharges into the overflow pipe. After the storm ends the inlet flow recedes to a level that the regulator is able to convey to the nearby interceptor or high tide forces the tide gate shut.

We were able to determine with a reasonable amount of confidence the hydraulic capacity for many of the locations in the program. During the storm as the flows build in the interceptors, the regulator capacity is usually less than its initial value. The reduction in capacity can be seen on the scattergraphs shown later in this paper.

METHODOLOGY

The historical approach to measuring combined sewers has been to install meters in the overflow pipe to obtain an actual measurement of the overflow when it occurred. However, measuring in the overflow pipe is often affected by the conditions in the downstream portions of the overflow. In pipes with an invert below mean tide elevation, the flow meter will constantly register either positive or negative flows as the tides flood and ebb. For this work the Commission elected to measure all flows entering a regulator plus the overflow.

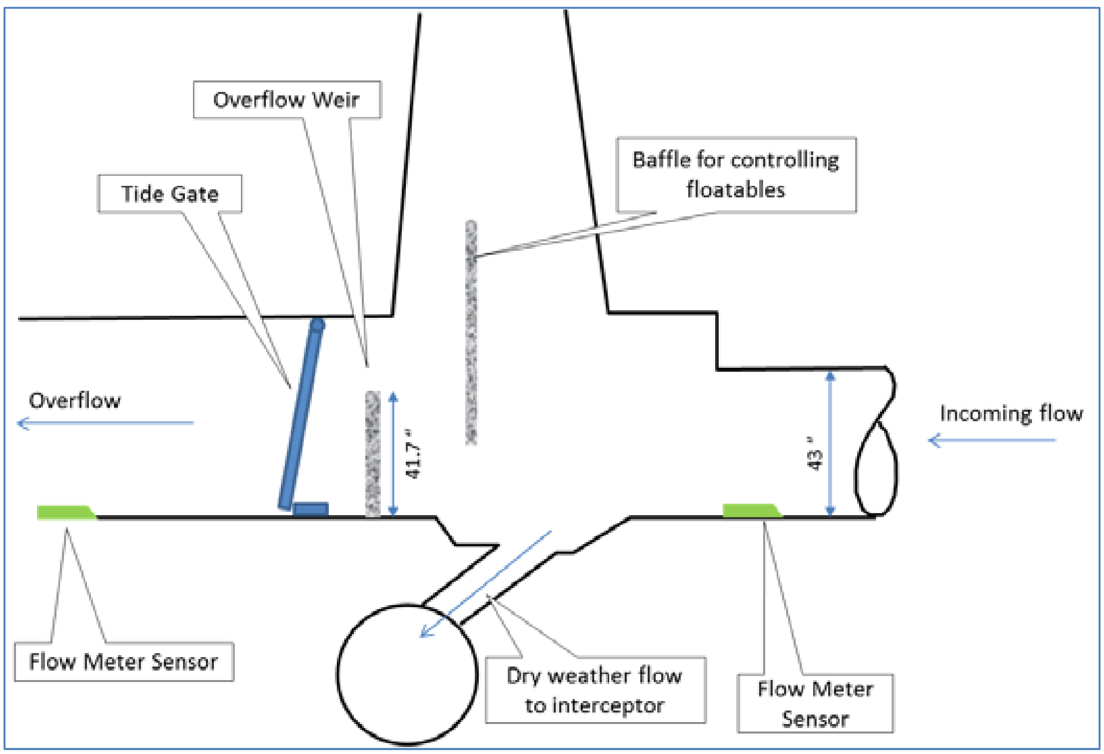

Figure 2 - Simple Schematic of Regulator RE070/8-3

Figure 2 is a simplified schematic of regulator RE070/8-3 showing that dry weather flow is diverted to an interceptor through a small connecting sewer. The incoming 1092 mm (43 inch) sewer conveys both dry and wet weather flow into the regulator and wet weather flow that exceeds the capacity of the 305 mm (12-inch) connecting sewer.

Wet weather flows that; a) exceed the capacity of the connecting sewer, b) exceed the 1060 mm (41.7 inch) height of the overflow weir and 3) exceed the elevation of the tide outside of the tide gate will cause and overflow event. Metering at all locations will provide the most information about how the regulator functions.

The study of scattergraphs is a relatively new discipline in flow metering and many people have not been exposed to it. More information is available at http://www.adsenv.com/scattergraphs .

Scattergraphs for CSO regulators are some of the most complex because the hydraulic conditions are combination of free flow and variable backwater conditions caused by changing tide elevations. But no matter how complex the hydraulic conditions, the rules of gravity flow must be adhered to and that behavior must be evident in scattergraphs.

RESULTS

As data were analyzed, interesting patterns were observed in the data and analysts attempted to understand the causes. A simple observation occurs during events in which no overflow occurs. Figure 3 shows a frequent pattern in which the flow rate during the ascending leg is at a higher flow rate than the descending leg. The key value from this graphic is the addition of Iso-Q lines or lines of constant flow rate. These lines are similar to the elevation contour lines on a topographic map where any point on an elevation contour line is at the same elevation. In this display any depth-velocity point along an Iso-Q line is at the same flow rate. The data shown in this example has a clockwise pattern.

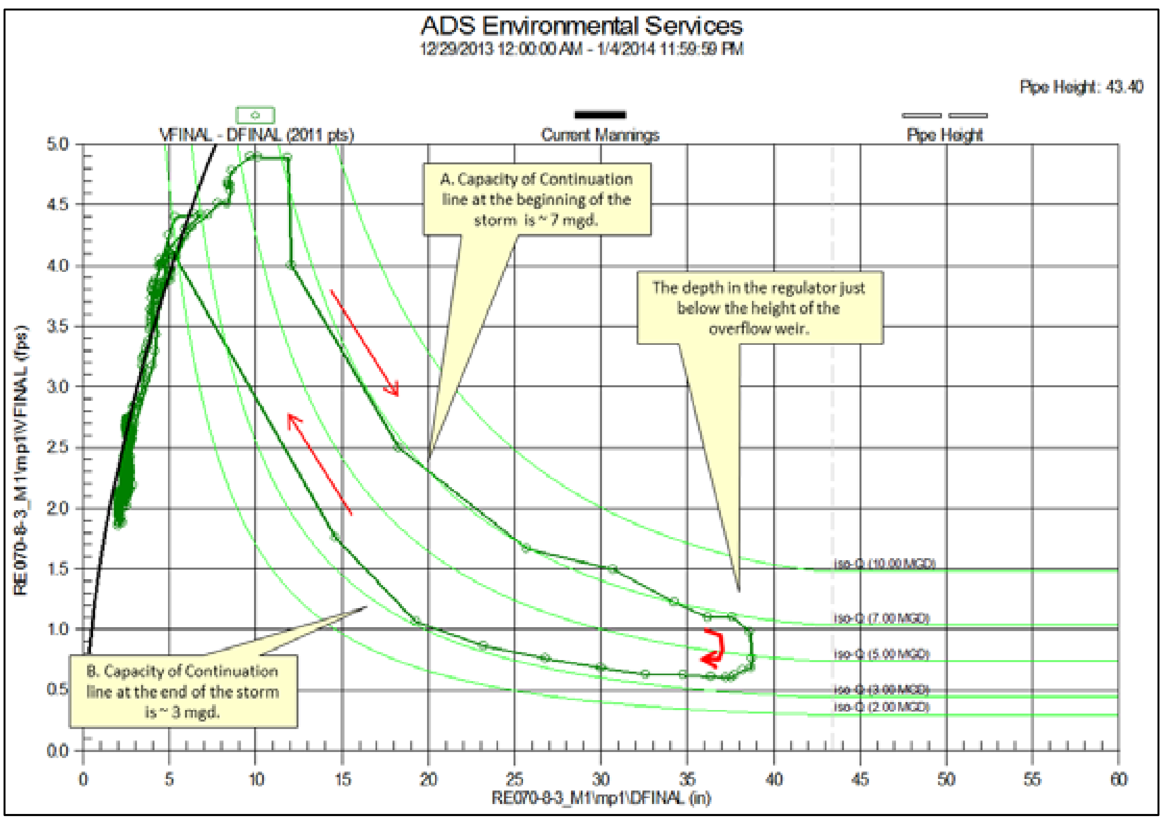

Figure 3 - Scattergraph of RE070/8-3 with Iso-Q lines

The presumed cause of this clockwise pattern is that the interceptor has more capacity during the first part of the storm and is surcharged or affected by downstream pump activity during the recovery period allowing less flow to enter. This has not been verified by any metering data.

A second example is a scattergraph from an event that just overtopped the weir with no downstream tidal influence. There is a telltale data pattern from a meter just upstream of a weir in this condition and it is a near-linear pattern as shown in Figure 4.

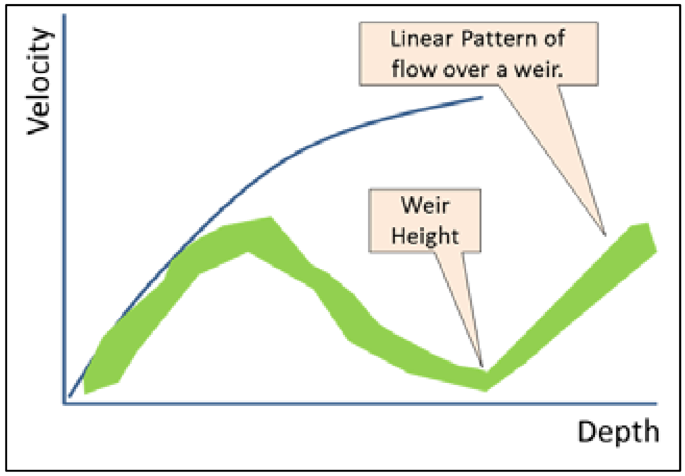

Figure 4 - Scattergraph with example of flow over a weir with no restriction

Figure 5 shows a scattergraph of the incoming meter and it shows the beginning of this linear pattern for just three data points that exceeded the weir height of 1060 mm (~41.7 inches). The flow rate to the continuation line as, as shown by the Iso-Q lines was 0.31 m^3/s (7 mgd) and as the depth over-topped the weir, flows increased to 0.37 m^3/s (8.5 mgd). The peak overflow rate can be calculated as [8.5 mgd-7.0 mgd= 1.5 mgd] 0.066 m3/s. The duration is approximately 15 minutes (three data points) and the overflow volume can be calculated as well.

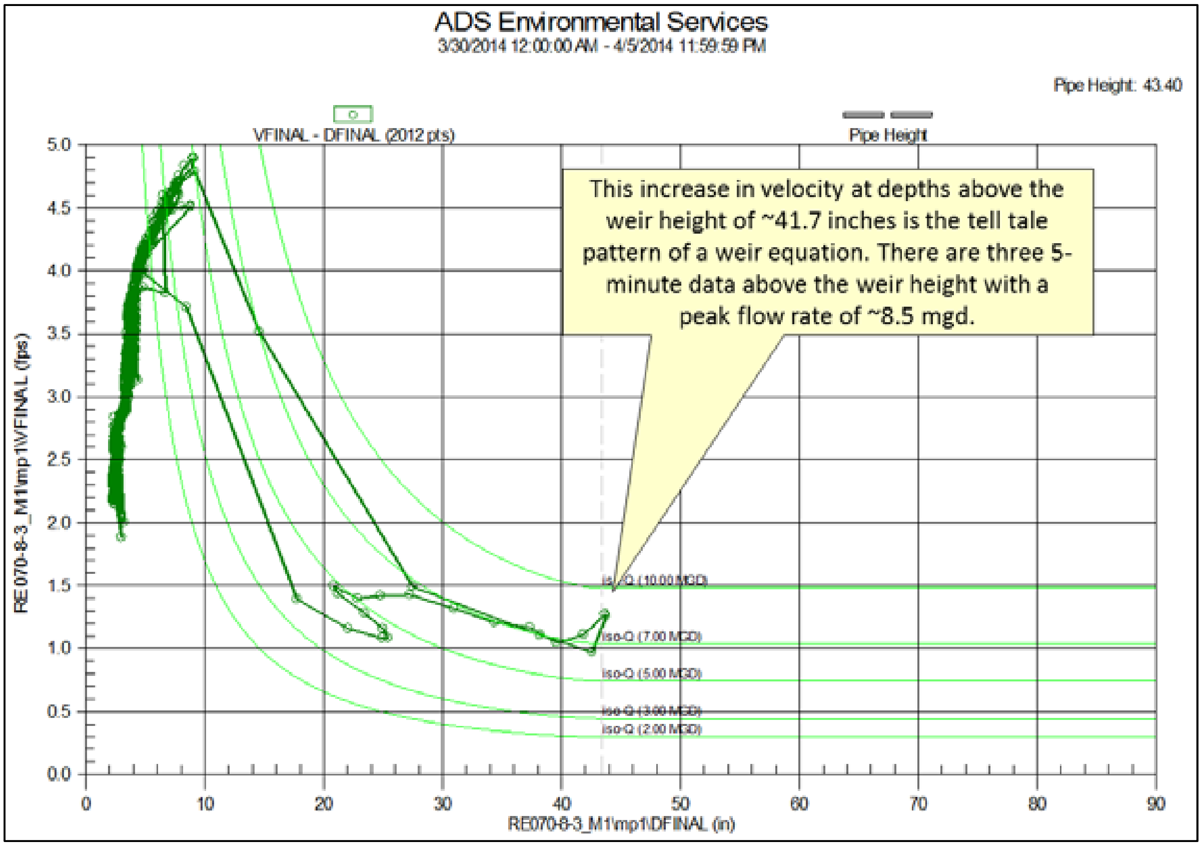

Figure 5 - Scattergraph RE070/8-3 (30 Mar 2014 Storm Event)

A more complex storm revealing a counter clockwise pattern was observed during a 9 Dec 2014 event shown in Figure 6. The overflow weir is around 1060 mm (41.7 inches) and both the ascending leg and descending leg of this scattergraph pattern show that the flow to the regional interceptor was approximately 0.13 m^3/s (3 mgd). In concept, any flow rate greater than this flow rate will be the overflow rate. The total overflow volume can be calculated by subtracting 0.13 m^3/s (3 mgd) from all measured data points during the event.

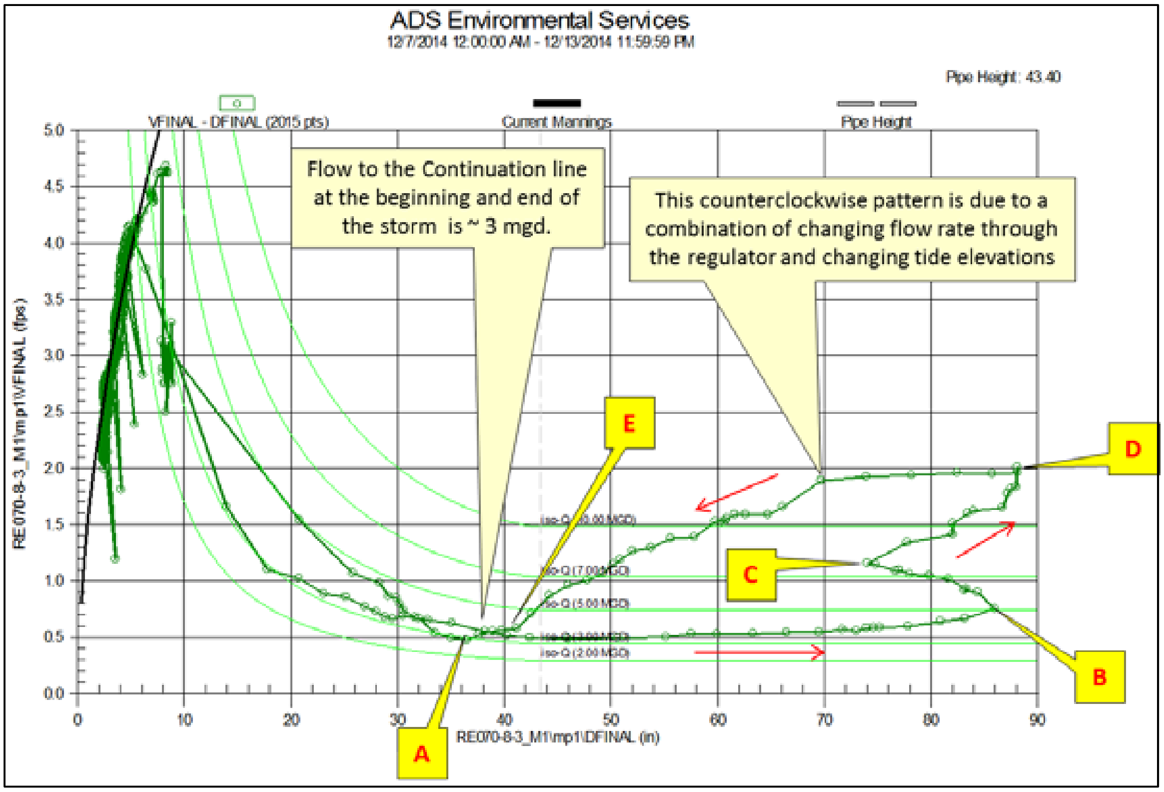

Figure 6 - Scattergraph RE070/8-3 (9 Dec 2014 Storm Event)

The corresponding hydrographs for events shown in Figure 7 and 9 provide a perspective most viewers are used to seeing. The hydrograph shows tide as measured in Boston Harbor in blue, incoming combined sewer depth converted to the same level datum in green and velocity shown in black. The overflow threshold (Weir) is red.

To help aid the reader we have placed red letters on both scattergraph and hydrograph at key points during the overflow event to serve as a guide. The initial storm flow (A) is following the 0.13 m^3/s (3 mgd) Iso-Q line up until (B) the flow peaks at 0.22 m^3/s (5 mgd), then subsides (C). There is an increase in the storm intensity creating a second, even higher, peak (D) at over 0.44 m^3/s (10 mgd) before receding back (E) into the interceptor post storm. This overflow event lasted approximately six (6) hours and the duration can be determined by observing all the 5-minute data points greater than the weir height of 1060 mm (41.7 inches).

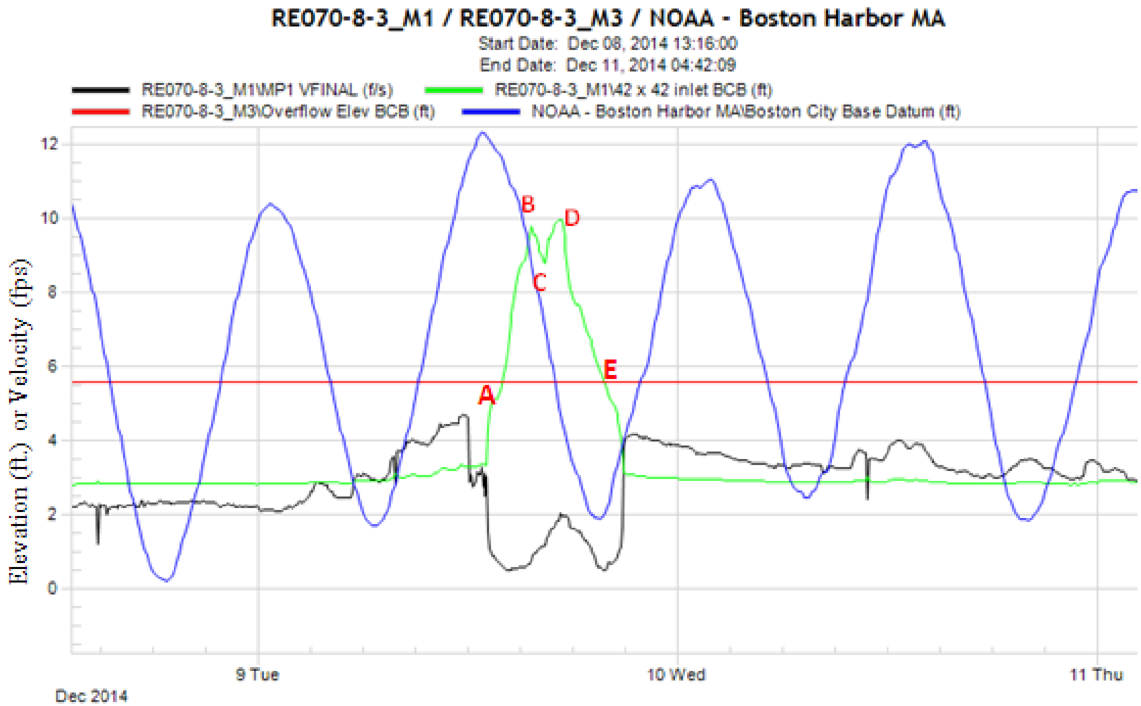

Figure 7 - Hydrograph RE70/8-3 (9 Dec 2014 Storm Event)

It was noted that these scattergraph patterns were both clockwise and counter clockwise and an attempt was made to determine if additional value or meaning could be extracted from these patterns. After some detailed review of the tide elevation and measured flow it was determined that the clockwise and counter clockwise patterns are due to two independent variables affecting the measurements.

In a sewer with no impact from a downstream sewer, the velocity must change when depth changes. In normal open-channel gravity flow, an increase in depth will result in an increase in velocity conforming to the Manning equation. If the sewer experiences a downstream restriction an increase in depth will result in velocity conforming to the Iso-Q line matching the capacity of the restriction.

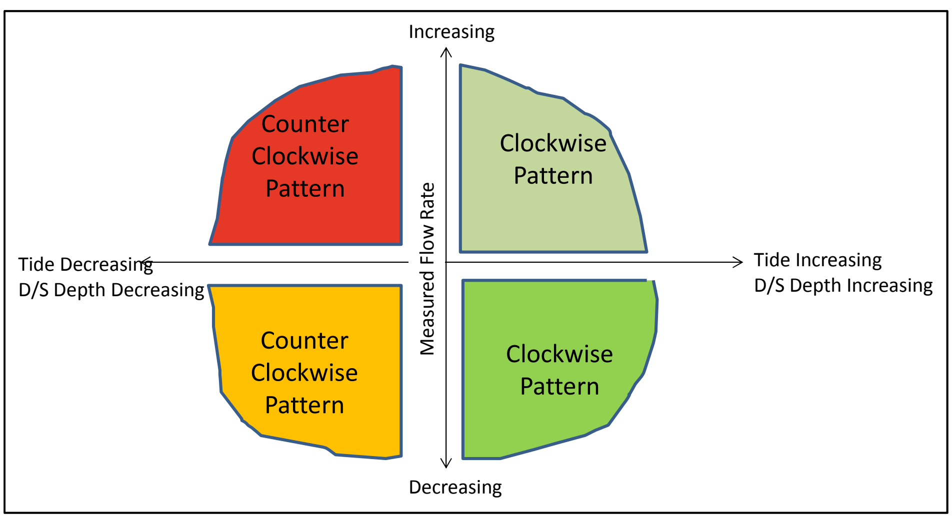

Figure 8 - Scattergraph rotation guide

If the downstream depth is controlled by some other factor such as tide, the rules change.

Figure 8 describes four conditions using flow rate entering the regulator and depth of the downstream pipe controlled by tidal elevation. This concept allows even more value that can be extracted from the scattergraph of data from the incoming pipe. The tidal changes can be deduced from the clockwise or counter clockwise pattern of the scattergraph.

Another more complex example occurred during an event on 23 October 2014. The hydrograph for this event is shown in Figure 9 and significant events are shown by letters A, B, etc. Figure 10 is the corresponding scattergraph on the incoming sewer and the significant events are labeled similarly.

In this example, a 01:00 am storm occurred near high tide and the depth in the regulator was not able to overcome the elevation of the tide and no overflow occurred (event B). A second storm occurred at 03:00 am near low tide and the depth and velocity of the incoming sewer clearly showed that an overflow occurred (event D) as shown by the increase in Iso-Q from 0.30 m^3/s (7mgd) to 0.44 m^3/s (10 mgd). There was not a noticeable clockwise or counter-clockwise pattern in either of these two events.

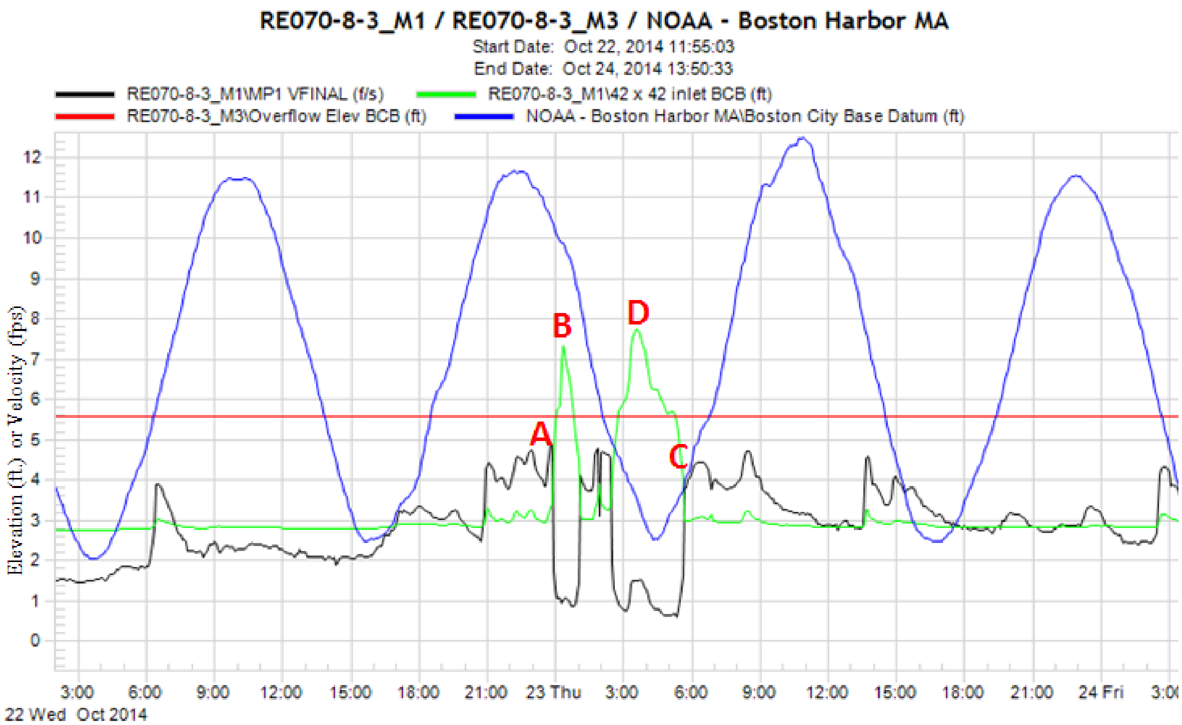

Figure 9 - Scattergraph for RE070/8-3 (23 Oct 2014 Storm Event)

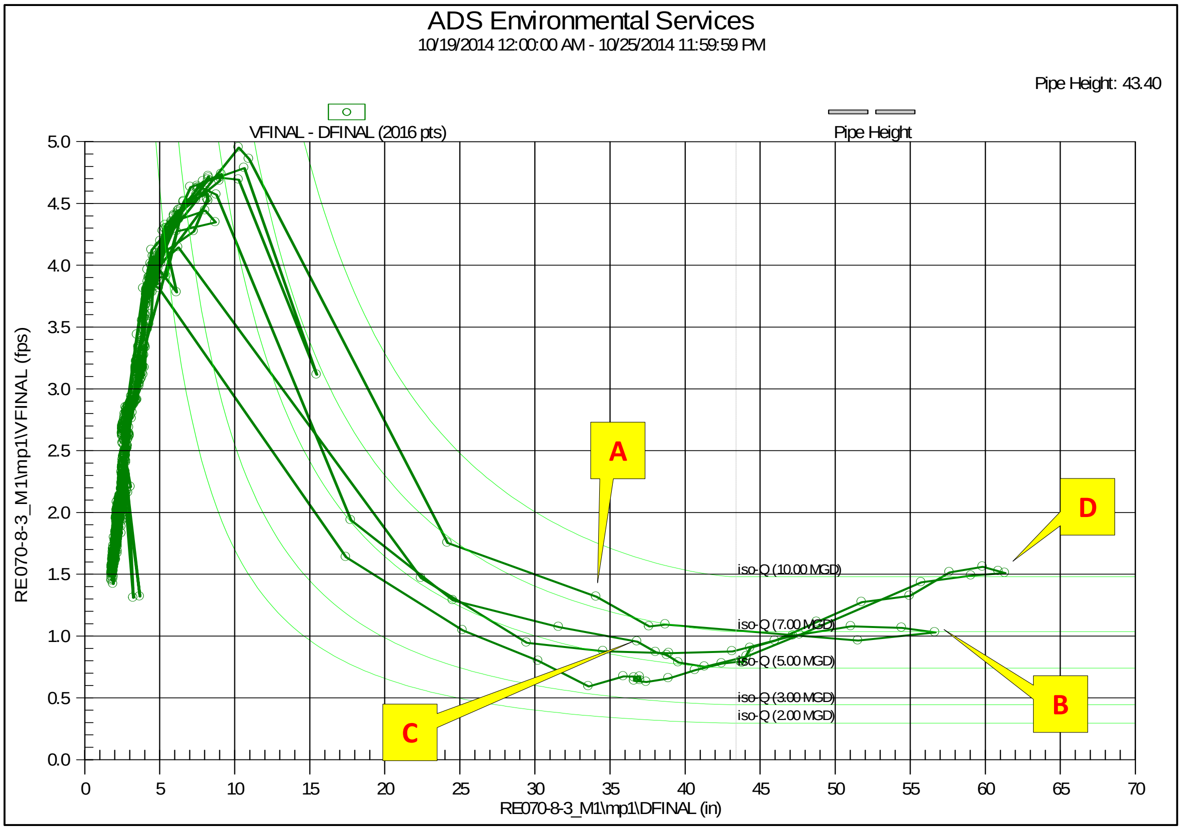

Figure 10 - Scattergraph RE070/8-3 (23 Oct 2014 Storm Event)

CONCLUSIONS

This project was designed to measure all flow entering each regulator and the overflow in a single outfall pipe. The purpose was to make sure we could completely understand how the regulators function and also to have sufficient data to calibrate hydraulic models if desired. Going into the project it was assumed that the primary source of CSO information would be data from the overflow pipe and other data collected would support or verify what was observed during the overflow. Great effort was taken to convert all depth data to a common elevation so that elevation comparisons between tides and regulator could be used as a test for an overflow. Ultimately, tidal elevations could not be compared to the water elevations in the overflow pipe. It appeared that the tide gates downstream or stormwater already in the overflow pipe influenced our measurements and minimized the ability to assume overflow activation from depth alone.

After examining data collected from entering and leaving the regulator it became apparent that incoming data was much more reliable and should be the primary source of information. The data from the outfall pipe should be used for support or verification of event. This is clearly reversed from traditional views of how to track CSO activity.

The Commission has been involved in flow measurement for over 20 years and has watched the technology improve steadily over that time. Improvements have occurred in the ability of the instruments to accurately and repeatedly measure depth and velocity and wireless communication can create an almost near-time access to the data. This advanced technology in the incoming sewers can now reveal both the subtle and dramatic hydraulic changes in the regulator. The advent of scattergraphs and knowledge that ADS has brought to scattergraph analysis now allows us to determine three separate flows (incoming flow, continuation flow and overflow) with a single meter.

The regulator used for examples in this paper has a single line in and a single line out and represents the simplest use of this new method. This technique is straight forward when the regulator has just a single incoming line, a fixed weir and a single overflow line.

If the regulator has multiple incoming lines this technique can predict the onset and duration of an overflow if the largest pipe is measured. But, the determination of the total overflow volume will require the summation of flows from all incoming lines. Also this method works well for only those regulators in which the continuation line is full prior to the onset of the overflow.

With the reliability of current metering technology and wireless communication, it is conceivable that both public notification of an overflow and quantification of overflow volume can be determined by a meter or meters in the incoming lines.

It was discovered that the capacity of the continuation line was a function of both the Commission's and MWRA's interceptors ability to accept flow. The variation in flow will cause some uncertainty in calculating overflow volume. If this project was repeated an interagency agreement between the MWRA and Commission would have provided more information on the interceptor performance which controls CSO activity.

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