The Seduction of Depth-only Measurement for I/I Work
He Who Forgets the Past is Doomed to Repeat It

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ABSTRACT

Since the beginning of time people have attempted to quantify flow of water by measuring its depth. One of the most famous devices is the Nilometer in ancient Egypt used by the Pharaohs to estimate arable land and crop production.

It has been the same for thousands of years with several improvement along the way. A significant improvement was offered by Robert Manning in the late 1800's as a simple equation using depth to calculate velocity (and flow) in an open channel. The Manning Equation is still used today in most open channel hydraulic models, but the advent of the Infiltration/Inflow discipline in the United States in the 1970's revealed the serious shortcomings of its application to flow measurement in sanitary sewers. Too many unusual hydraulic conditions made the Manning Equation invalid as a method to measure flow in sanitary sewers.

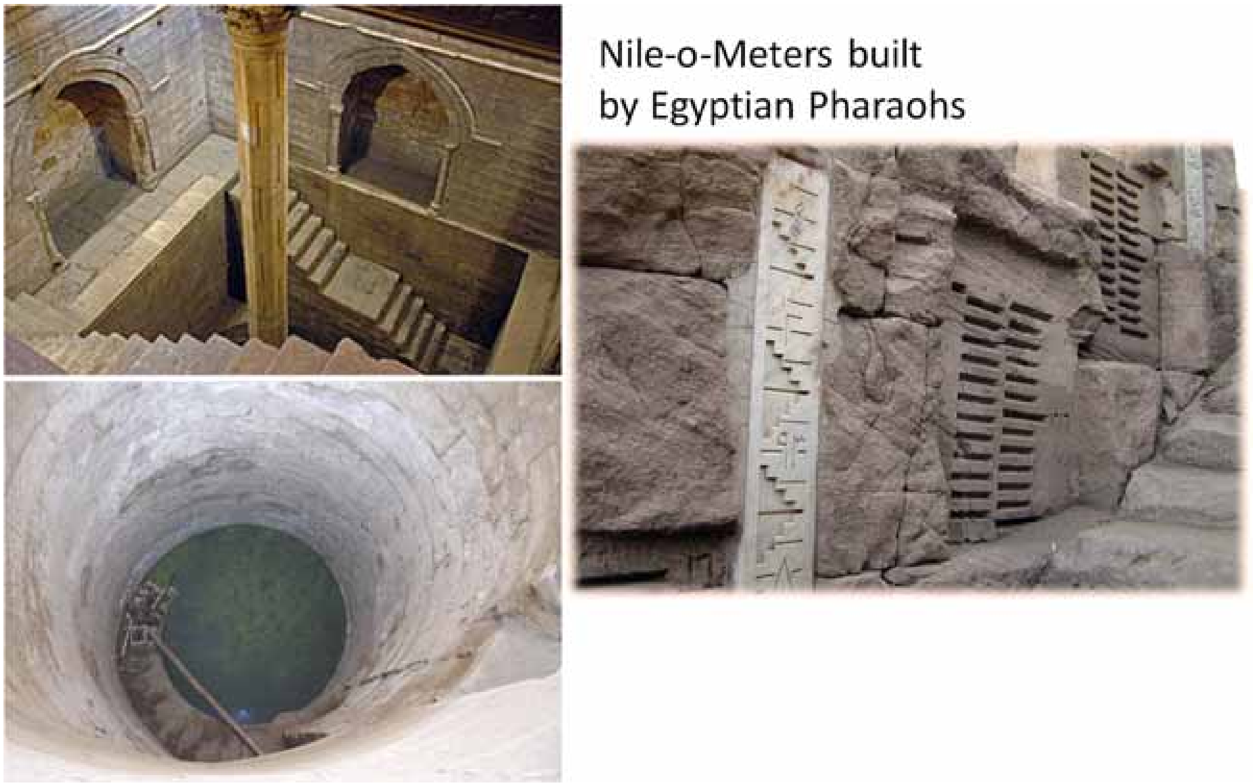
KEYWORDS

Depth-only Device, Manning Equation, Chasing I/I, Area-Velocity Meter

BACKGROUND

The need to understand the level of a water surface has been around for millennia. Perhaps one of the most famous ancient devices for measuring the level of a water surface is the Egyptian Nile-O-Meter to determine the annual flood levels of the Nile River. Figure 1 shows two examples of measurement structures on the left side and on the right side is a photo of the scale used to record the flood level each year. The data were used to predict the crop production and probable tax revenue for the upcoming year.

Figure 1 Nile-O-Meters



The same concept is still used today by the USGS in their stream gage network as shown in the diagram in Figure 2.

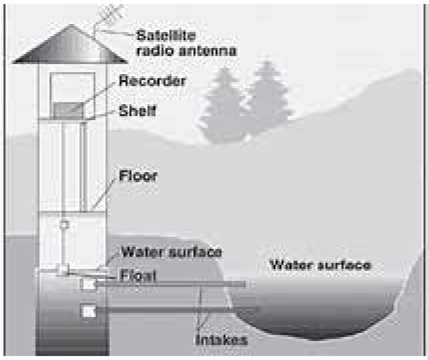


Figure 2 USGS Stream Gage

Figure 3 displays a timeline of flow measurement from the Egyptians to the present day. Throughout the 1700's and 1800's several hydraulic equations were developed to estimate the velocity of water in a channel using various terms for a friction factor or roughness. Robert Manning in the late 1800's developed a simplified empirical equation to predict velocity (and rate of flow) in an open channel and it became widely used in the United States.

Figure 3 Timeline of flow measurement since Egyptians

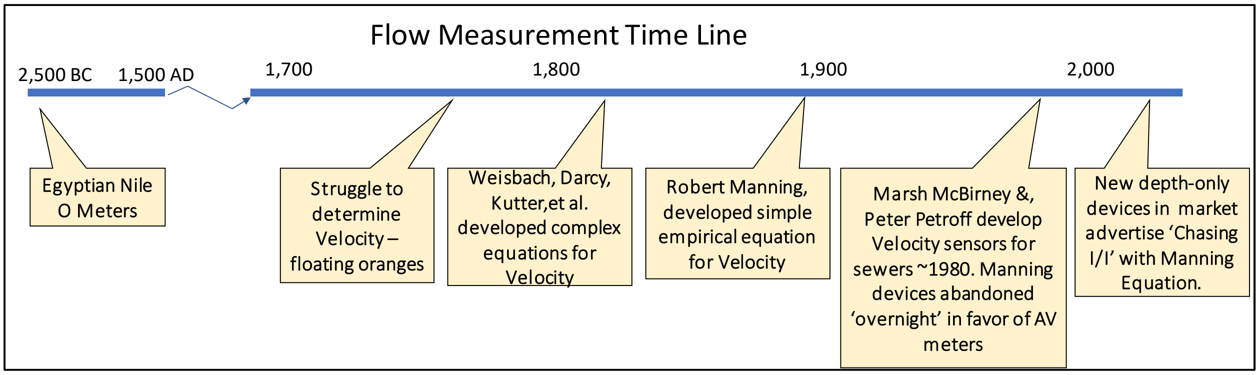
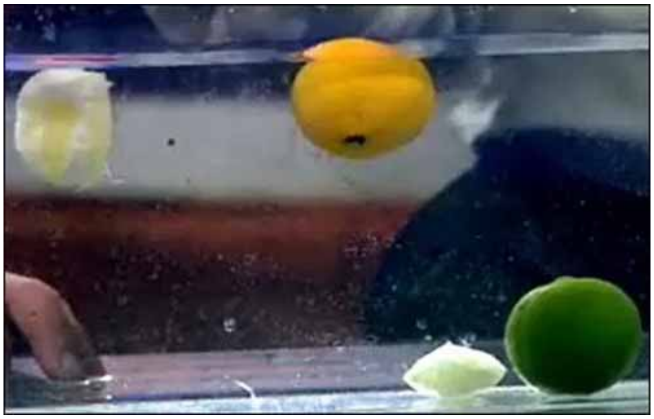


Figure 4 Oranges for velocity measurement



It has always been understood that the key to measuring the rate of flow of water in an open channel was to determine its velocity. Determining depth is straightforward, but velocity is difficult. One simple method that has been used and is still used today is the floating orange technique shown in Figure 4. Oranges have the characteristics of having a specific gravity slightly less than water (barely floats) and being very visible in water. After determining the cross-sectional area of a stream or channel, an orange is thrown in at one bridge and its time of travel to the next bridge is determined.

In the mid-1900's the Manning Environmental Corporation developed the Manning Dipper that relied on the Manning equation to calculate a flow rate in channels and sewers. Figure 5 shows how the device got its name; it relied on a float that was regularly lowered or 'dipped' to the water surface to record the level and calculate a flow rate. It was used in sewers that were large enough to accommodate the device and the dipping float mechanism. A flow rate was printed on a circular chart.

Figure 5 The Manning Dipper

By 1980 two technologies were developed to measure velocity in sanitary sewers. Larry Marsh, founder of Marsh-McBirney Inc., developed a small non-mechanical sensor that could be installed in sanitary sewers to measure velocity. It relied on the Faraday Principle. Peter Petroff, founder of ADS Environmental Services, invented an ultrasonic sensor that relied on the Doppler Principle.

Both devices included a depth sensor and together they ushered in the use of the Continuity Equation or Q (flow rate) = **A**rea x **V**elocity. Flow meters that use this method of calculating flow are commonly referred to as AV meters and that reference is used in this paper.

Gone were the classic Manning Dippers, now displayed as museum pieces. Today, nearly every open channel sewer flow meter in the market is an AV meter and nearly all rely on the Doppler principle using acoustic, electromagnetic or Laser technology for measuring velocity.

New Depth-Only Devices

Within the last decade or so manufactures have been producing ultrasonic depth-only or level-only devices that are intended primarily to monitor water elevation/depth to spot the formation of blockages. The devices are packaged with cellular or satellite communications with real-time web data delivery. In general, these devices will rapidly notify the Collection System Manager that a blockage is developing or has occurred. To many people these devices appear to be 'new technology'.

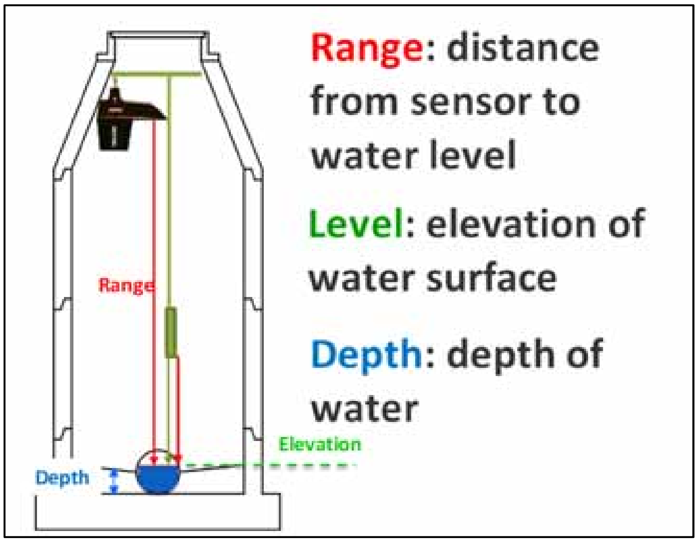
Depth-only devices in the market come in two basic forms; 1) an ultrasonic sensor suspended near the water surface by a cable attached near the top of the manhole and 2) an ultrasonic sensor mounted at the top of the manhole. The terms Range, Level and Depth are often used interchangeably, but they have the definitions shown in Figure 6.

Range is the actual measurement made by these devices- it is the distance from the sensor to water surface.

Level or elevation is derived by knowing the elevation of the manhole rim minus the distance to the face of the sensor minus the Range.

Depth of water is derived by knowing the distance from the face of the sensor to the invert of the flow channel minus the Range.

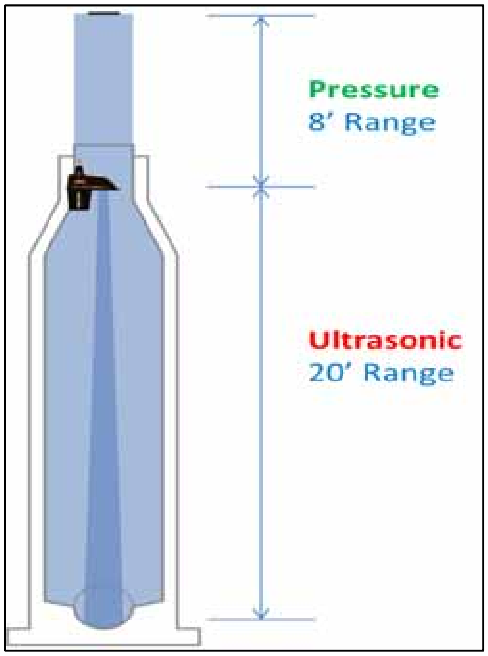
Figure 6 Definitions in depth-only devices



The type of depth-only device that most manufacturers produce is one with the sensor suspended on a cable so that the sensor is just a few feet above the water surface. This hanging design is necessary because of the relatively short range of a single ultrasonic sensor and its wide beam angle.

In 2015 ADS developed a unique ultrasonic depth-only device shown in Figure 7, with a 20-foot range below the sensor and pressure sensor with an 8-foot range above the sensor. The device (ECHO) was intended to monitor sewer depth/elevation to spot developing blockages before it becomes a full-fledged blockage. In that use it performs extremely well.

Figure 7 ECHO depth-only device



Around the same time the concept of micro-metering was frequently discussed as a way to isolate sources of RDII into smaller 'micro-basins' and the authors considered the ECHO device would be good micro-metering tool to be used in conjunction with Area Velocity meters. Some manufacturers are promoting the devices as an I/I tool using the Manning Equation. Engineers tend to reject this application of the devices, but there is a growing cottage industry of '***Chasing I/I***' or '***Scouting for I/I'*** among agencies looking for a quick and easy way to detect I/I sources.

The concept of Chasing I/I involves installing several of these devices in manholes to monitor the level/depth of water in the manhole invert channel. At least one manufacturer advertises that the device's depth readings can be converted to a flow rate by the Manning equation and knowledge of the house count upstream. One of the fundamental reasons why the Manning equation was abandoned as a sewer flow measurement method in the 1980s is that it is prone to false positive and false negatives.

Figure 8 depicts the most common false-positive incident with the Manning Equation. During normal dry weather conditions, the flow is, say 1 inch deep in this sewer, but a partial blockage downstream (roots here) that will cause a backwater condition. During a storm, the depth in this sewer increases to 2 inches and a depth-only sensor in the left manhole could measure a valid flow increase. However, a sensor in the center manhole would measure an increase from 1 inch to 6 inches and would indicate a very large increase in I/I between these two manholes. This is a false positive and could induce the manager to launch a detailed physical inspection of the pipe segment or upstream basin.

Figure 8 Depth-only device delivers a false positive result in presence of downstream restriction.

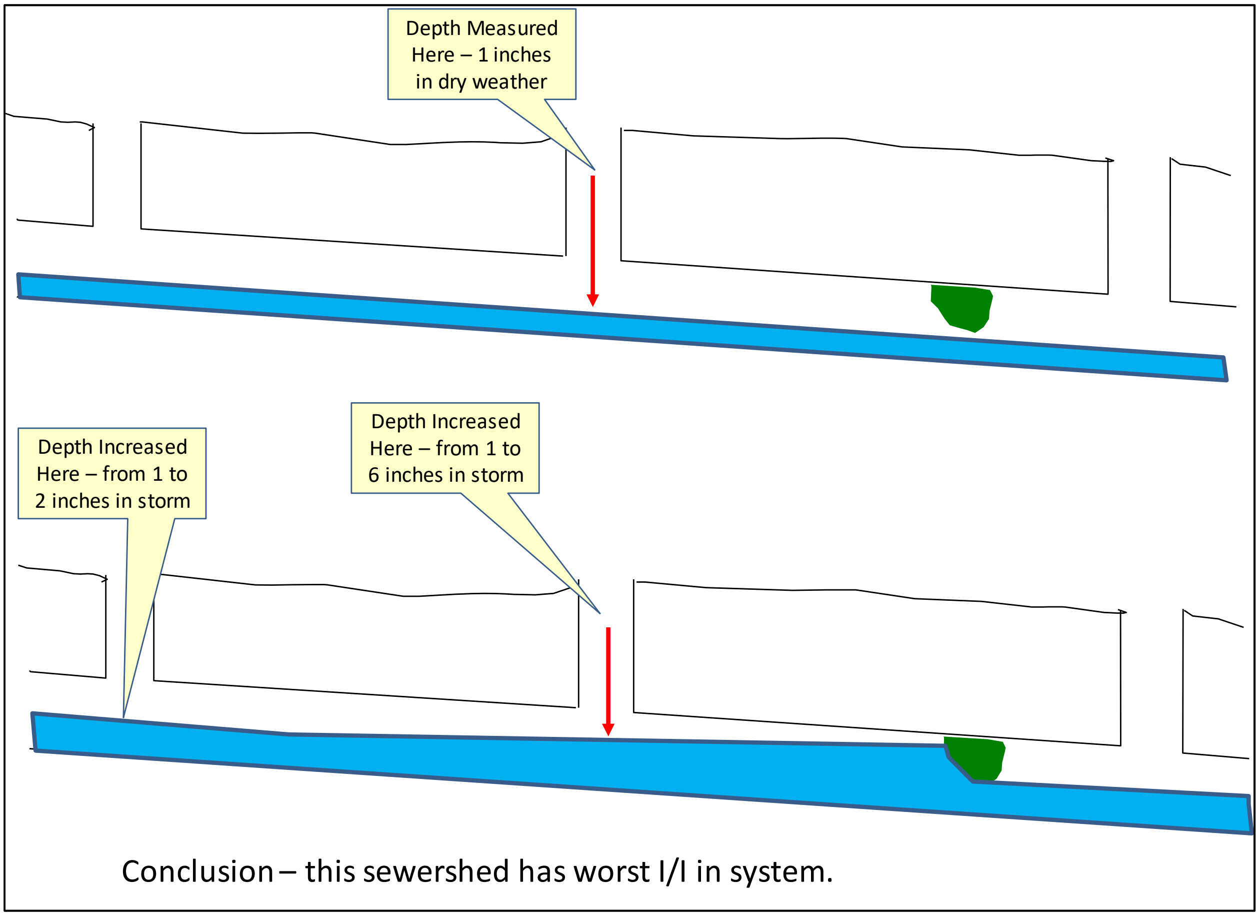
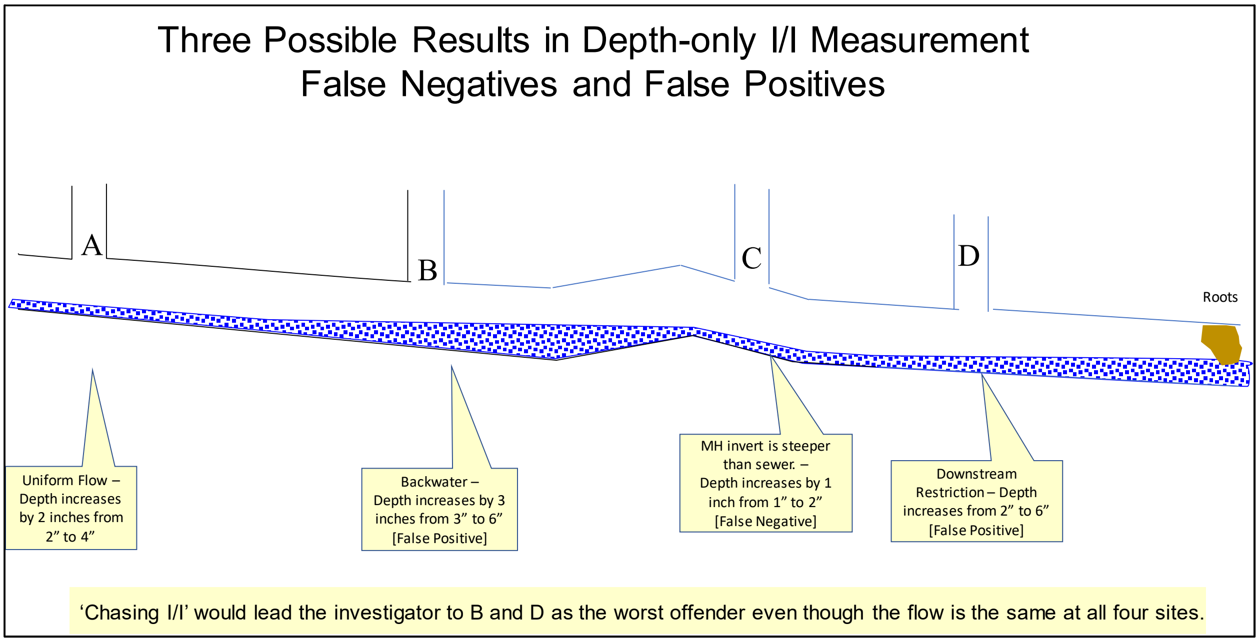


Figure 9 shows several common conditions in which both false positive and false negative indications can occur. The devices are installed from the surface and they rely on the published slope of the pipes for setting up the Manning equation. In the case of Manhole C, in which the slope is steeper than the design slope, the calculated Manning flow would be incorrectly low – a false negative.

Figure 9 Causes of false positives and false negatives with depth-only devices.



Three Possible Results in Depth-only I/I Measurement
False Negatives and False Positives

Uniform Flow – Depth increases by 2 inches from 2" to 4"

Backwater – Depth increases by 3 inches from 3" to 6" [False Positive]

MH invert is steeper than sewer. – Depth increases by 1 inch from 1" to 2" [False Negative]

Downstream Restriction – Depth increases from 2" to 6" [False Positive]

'Chasing I/I' would lead the investigator to B and D as the worst offender even though the flow is the same at all four sites.

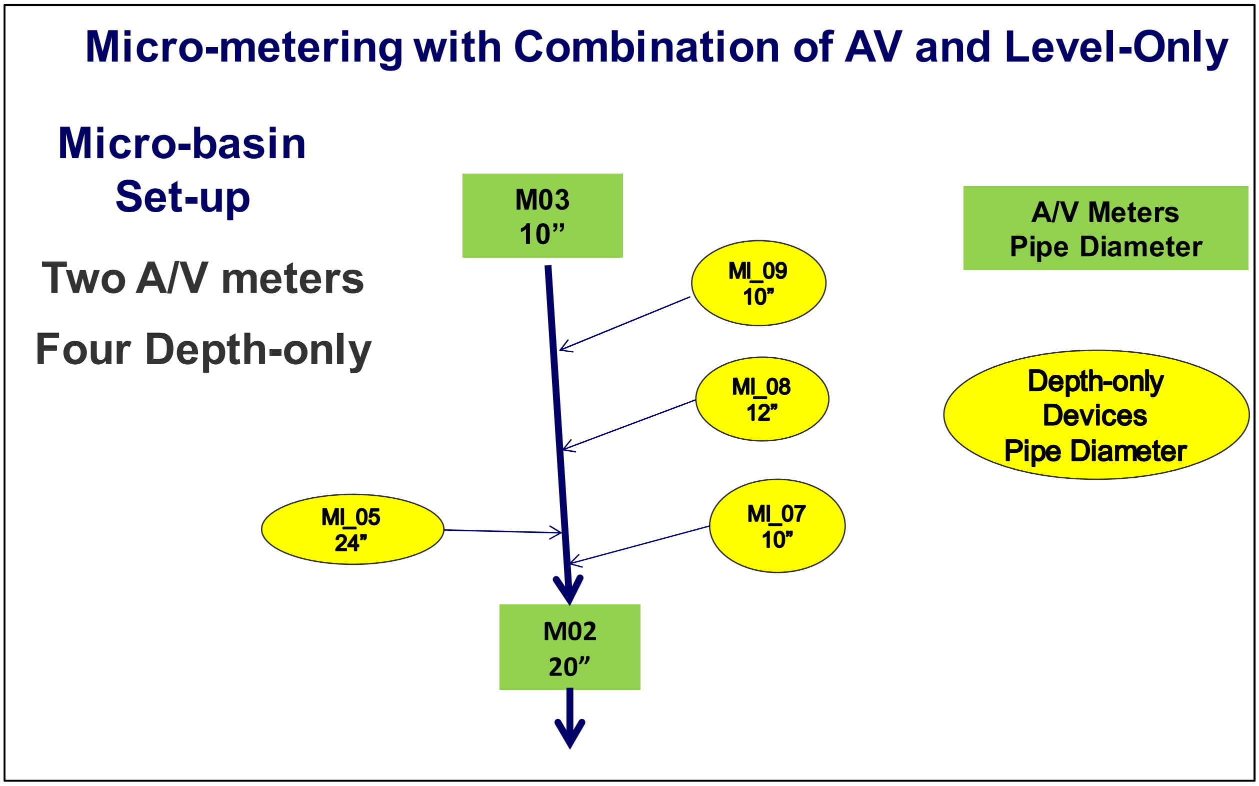
CASE STUDIES

Study 1: Micro-metering with a Combination of Depth-only and AV meters
Study 2: Side-by-Side Comparison; Depth-only vs. AV meters
Study 3: Converting a Network of AV meters to Depth-only Devices

Case Study 1 Micro-metering with a Combination of Depth-only and AV meters

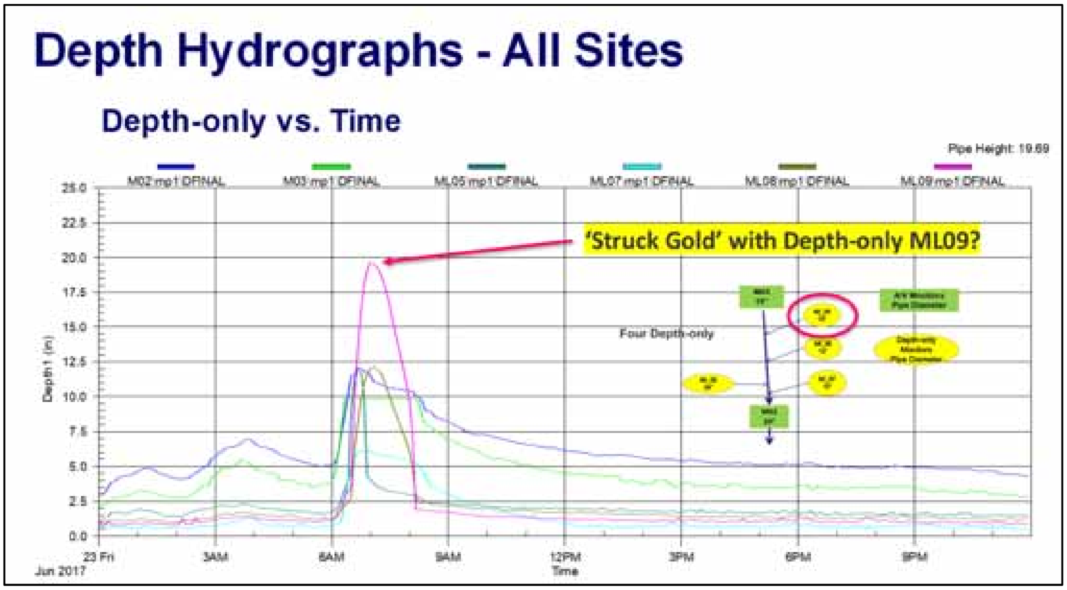
A sewer agency had conducted flow metering as part of an I/I study looking for sources of I/I. Area-Velocity (AV) meters had been in place for a year measuring I/I in 'Mini-basins' of around 10,000 to 20,000 LF of sewer. The Agency decided to try the 'Micro-basin' concept of breaking down the mini-basins into even smaller micro-basins. Figure 10 shows the location of the original mini-basin meters in green and the location of four depth-only devices on four of the major side branches in the M02 mini-basin. The plan was to let the results guide the follow-up work of smoke testing, CCTV and perhaps house inspections. The goal was to demonstrate that the combined cost of the micro-metering and the anticipating reduced cost of physical inspection costs would be less than the cost of simply doing physical inspection of the entire M02 mini basin.

Figure 10 Meter Layout, 1 inch = 25.4 mm.



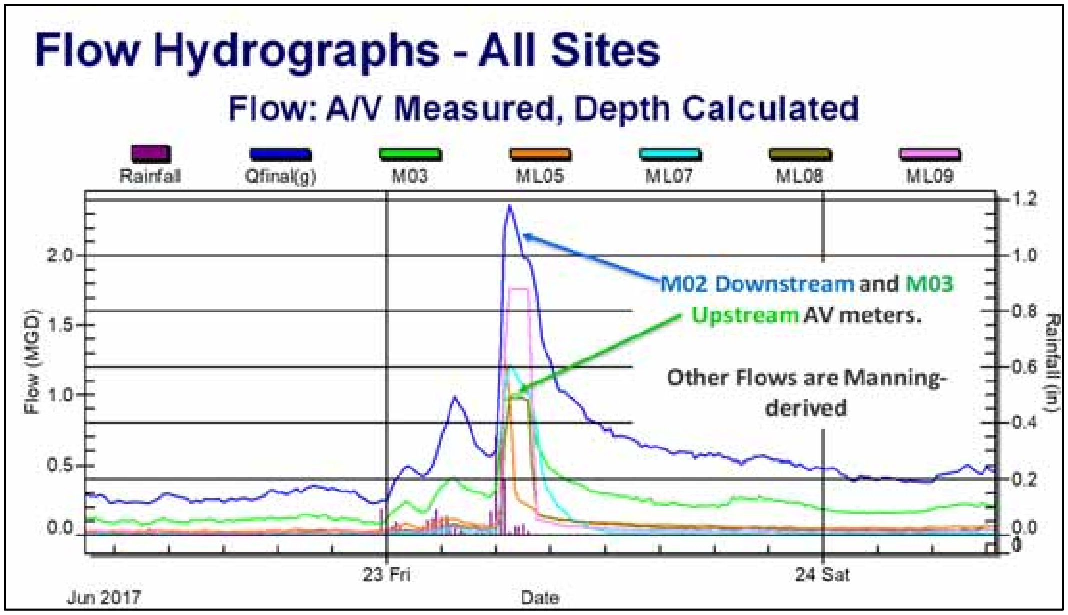
After a couple of rains and review of the depth data for these sites (Figure 11) it appeared that they ‘struck gold’ by seeing the dramatic depth response from ML09.

Figure 11 Depth hydrographs, 1 inch=25.4 mm.



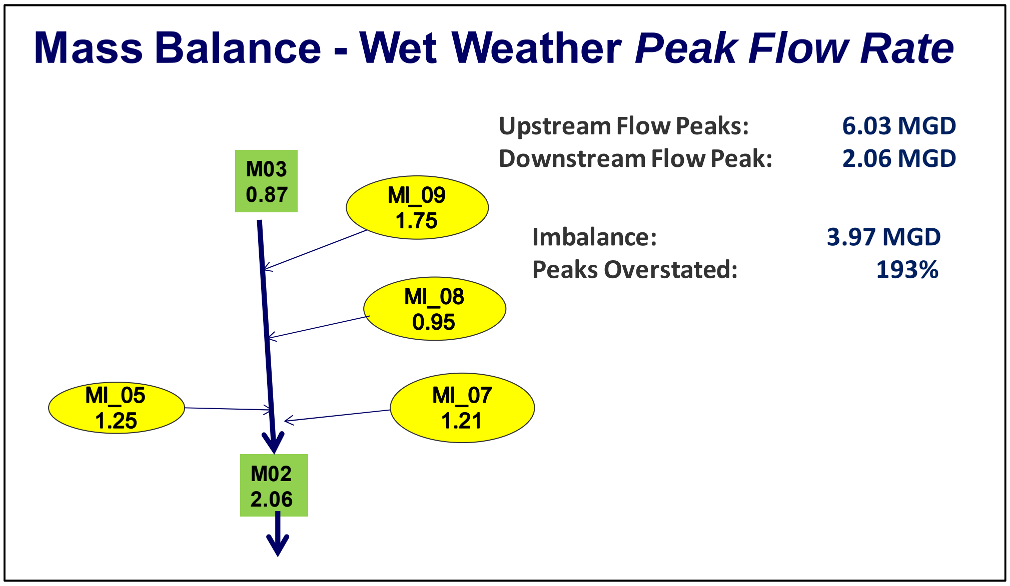
The engineering staff did due diligence and calculated flow rates from the depth-only devices and generated the combined set of hydrographs in Figure 12.

Figure 12 Flow rate hydrographs, 1 MGD=43.8 L/s.



A standard practice in the wastewater business is the mass balance exercise that assures the numbers in a process are valid. In this this case, mass balances were conducted on both peak flow rates and total RDII volumes. Even though mass balancing peak flows (Figure 13) is not a precise exercise, it can still yield useful results. The sum of upstream peaks is nearly double the measured downstream peak flow.

Figure 13 Peak Flow Balance 1 MGD=43.8 L/s.

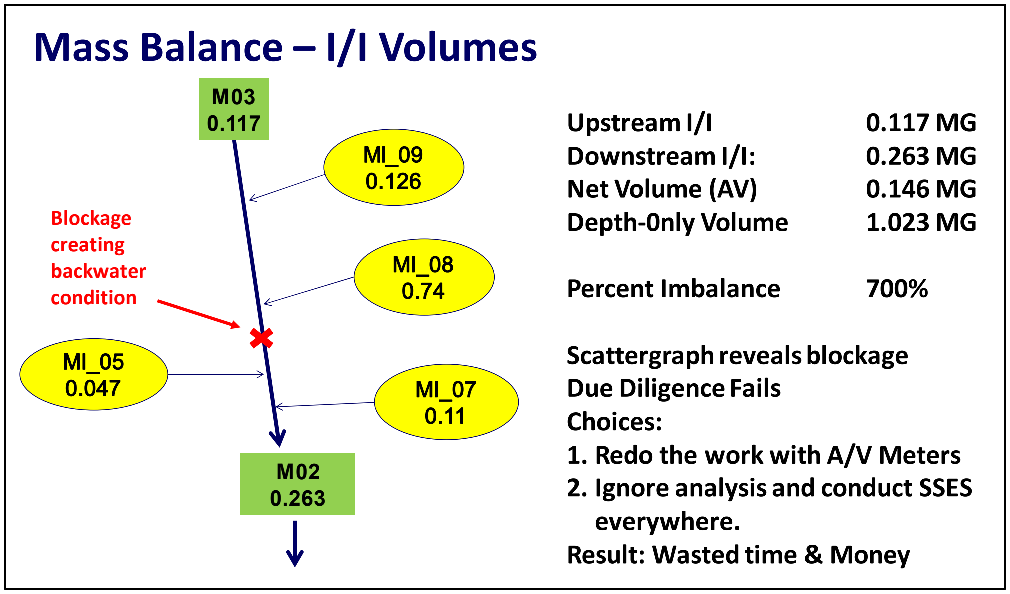


Mass Balance - Wet Weather *Peak Flow Rate*

Upstream Flow Peaks:	6.03 MGD
Downstream Flow Peak:	2.06 MGD
Imbalance:	3.97 MGD
Peaks Overstated:	193%

Figure 14 is the traditional mass balance of volume showing that 0.146 MG originated in the basin, but the depth-only device measured 1.023 MG, a seven-fold mistake.

Figure 14 Volume Mass Balance



Mass Balance – I/I Volumes

Upstream I/I	0.117 MG
Downstream I/I:	0.263 MG
Net Volume (AV)	0.146 MG
Depth-0nly Volume	1.023 MG
Percent Imbalance	700%

Scattergraph reveals blockage
Due Diligence Fails
Choices:
1. Redo the work with A/V Meters
2. Ignore analysis and conduct SSES everywhere.
Result: Wasted time & Money

CASE STUDY 2: SIDE-BY-SIDE COMPARISON; DEPTH-ONLY VS. AV METERS

The Westfield, Indiana collection system is managed by the Citizens Energy Group (CEG). Co-Author Derek Sutton from CEG worked for several years managing flow metering programs in the pursuit of I/I without any ‘big wins’. In Derek’s words; *We would typically place area velocity meters in locations where we suspected large wet-weather responses or R-values and would monitor the location for 3-6 months and see what the data suggested. It can be an expensive program for a smaller utility to have 3 or more A/V meters in service year-round searching for I/I. We also placed these meters in specific locations to successfully build a hydraulic model for the collections system.*

At WEFTEC one year, ADS showed me a less-expensive depth only flow monitoring technology (ECHO). They talked about the ability to deploy more meters in a smaller space and effectively isolate I/I at the street or block level by micro-metering. We were intrigued by the idea and had a location within our system in which we wanted to use this technique to get a better understanding of the wet-weather response.

We selected an area of the system that is isolated to one downstream discharge location. The discharge location happens to be a 12” interceptor that runs right through the historic portion of Main St. and modeling shows a significant tendency to surcharge during rain events. The area that we had targeted was metered previously using AV meters and we had a good understanding of the total and peak flow from the area. We were hoping to find areas within this portion of the collections system that showed higher wet-weather responses and we could focus on theses streets or sections with rehabilitation or identifying potential illicit connections.

ADS suggested that we again place AV meters with the depth only meters to help interpret the data. In the end, the depth only meters didn’t tell us enough of the story by themselves and the AV meters were necessary to interpret the data. We could have made the wrong conclusions based only on the depth-only data. Depth increases but does velocity increase or stop? Is there surcharge or blockage downstream? These questions were difficult if not impossible to answer correctly without actual velocity and flow data.

We didn’t see a way forward using depth-only meters without AV meters in coordination for our purposes. This can be an expensive proposition for a smaller utility.

Figure 15 is the layout of the AV meters and the Depth-only devices in Westfield. The yellow symbols are on the manhole being monitored and the red triangles on the pipe being measured. The Manning equation was set up at all sites to match the most common slope that was determined during the installation of the AV meters.

Figure 15 Layout of Westfield Meters

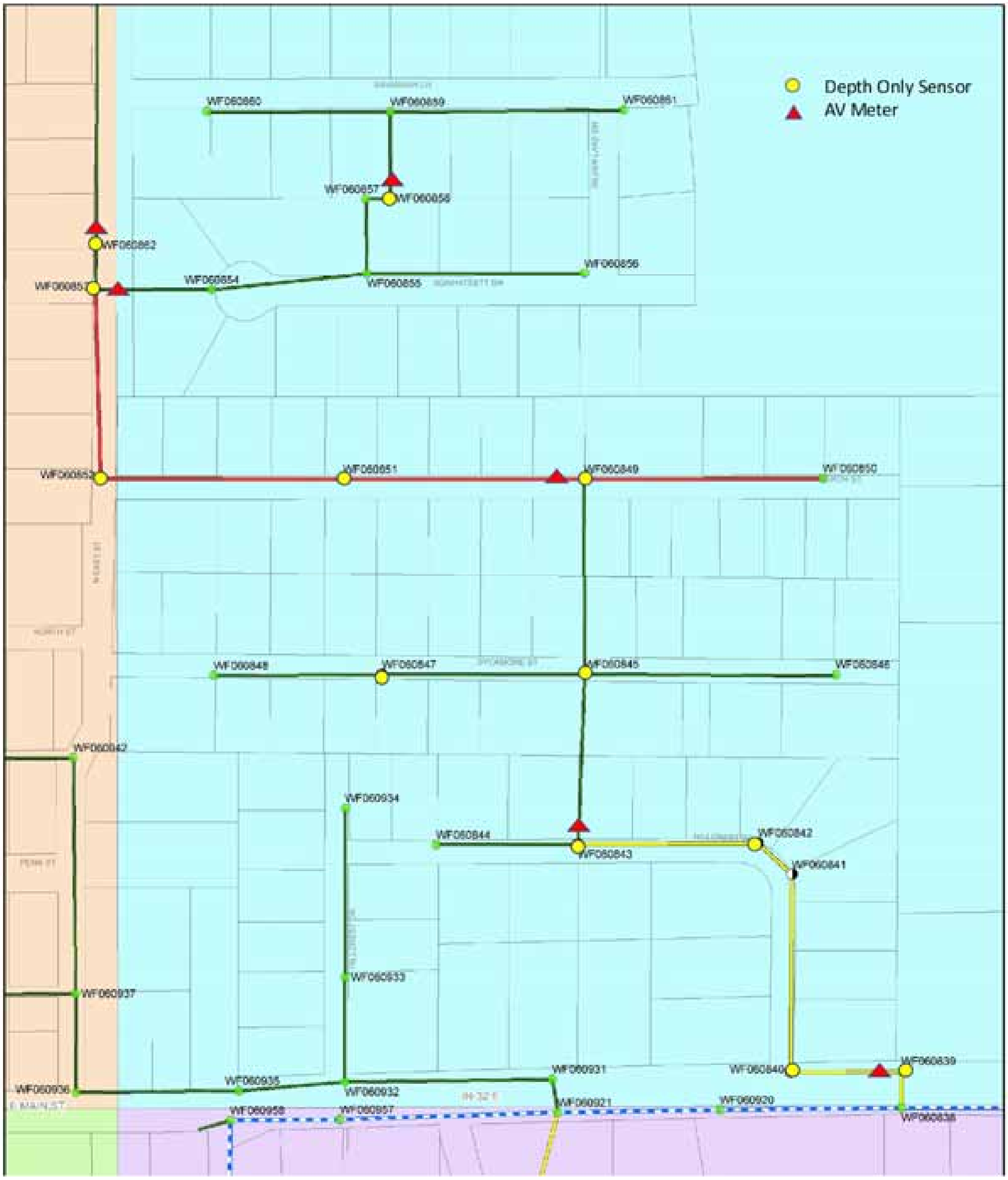


Figure 16 shows the meter sheds formed by the AV meter. The label within each of the six (6) meter shed polygons is the Net I/I volume for the October 31, 2019 storm. The values are in million gallons for the storm event. The total Gross volume of I/I in this sewershed at the lower right corner is 0.37 MG and a volume of 0.2 MG enters from the upper left. The Net I/I produced within this sewershed is 0.17 MG.

Figure 16 RDII Volume with AV Meters, 1 MG=3,785 M^3

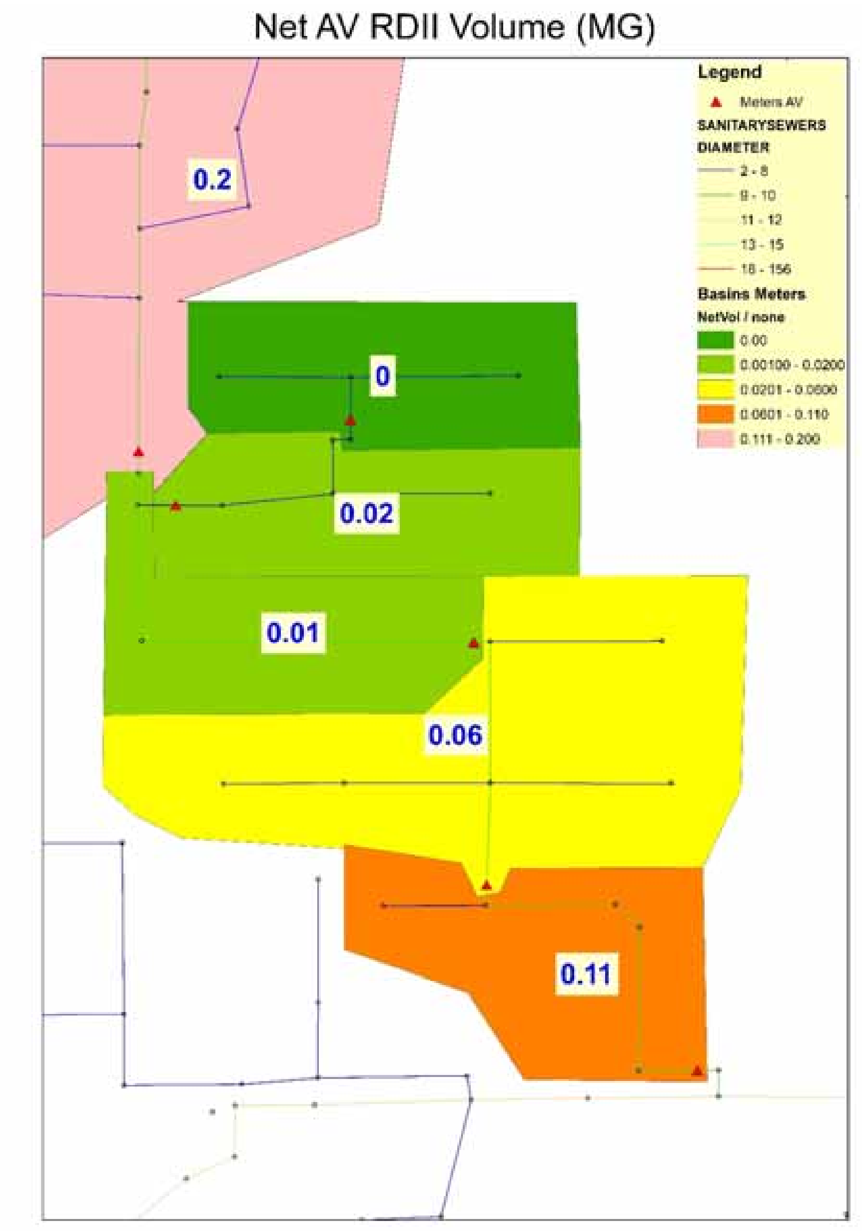
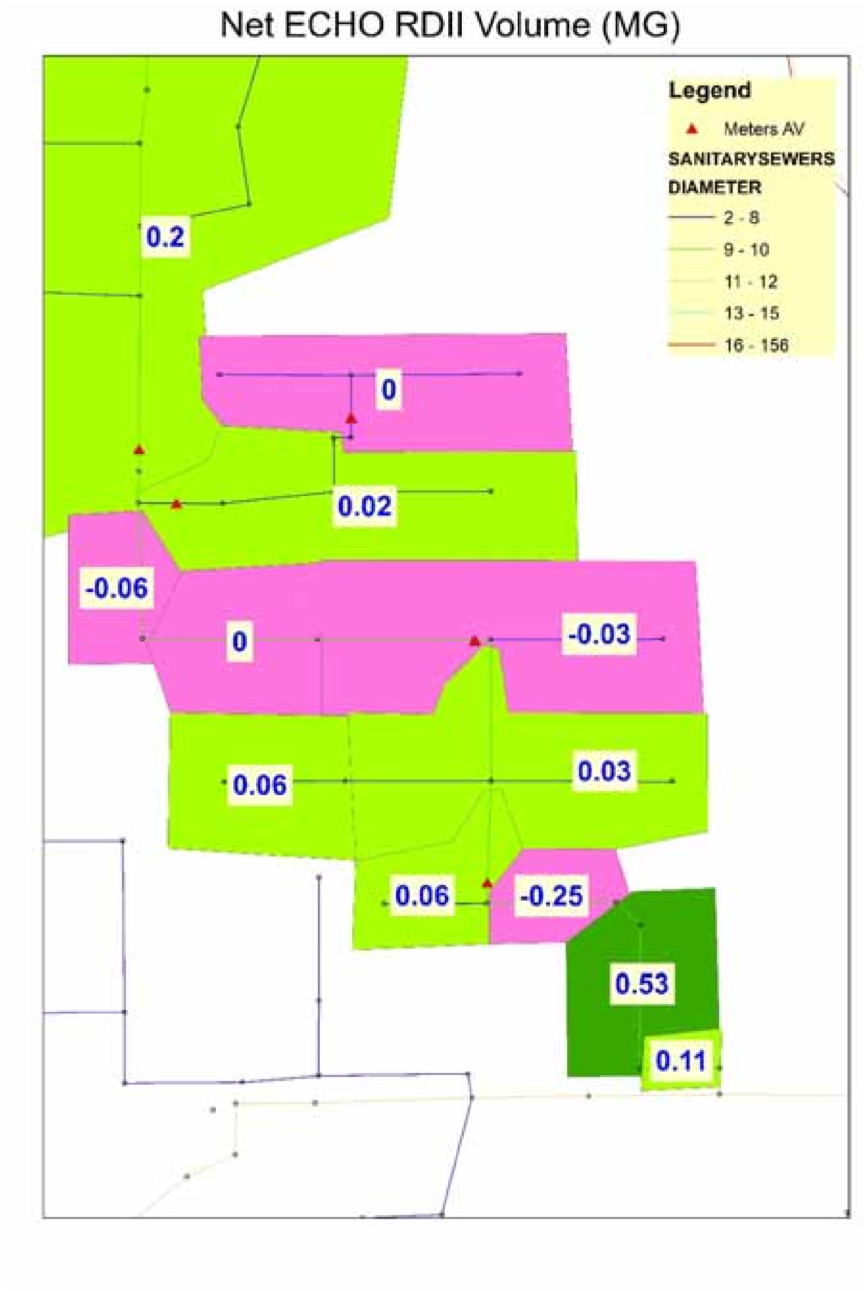


Figure 17 shows the meter-sheds formed by the 12 depth-only sensors and the value in each polygon is the Net I/I volume calculated using the Manning equation. Note that there are both negative values (false negatives) and very high values (false positives). The sum of the positive values is 1.02 MG and the mathematical sum of all values is 0.31 MG. Both values are greater than the measured volume of 0.17 MG in this sewershed. What is alarming here is to think about what your next step would be if presented with each of the two sets of results. The manager would be in a quandary if the goal was to develop a scope of work for a physical inspection contractor.

Figure 17 RDII Volume using Depth-only devices, 1 MG=3,785 M^3



What is the Cause of Such Disparate I/I Values?

Figures 18 through 21 include detailed photos of the manholes and the flow channels. They reveal that many of the flow channels are poorly formed or have non-uniform flow conditions such as changes in grade and turns. The physical condition in most of these manhole flow channels completely rule them out as candidates for the use of the Manning equation. Some collection system managers may claim their system is free of these conditions, but the author's observation is that these conditions tend to be the rule, not the exception.

Figure 18 Manhole 845

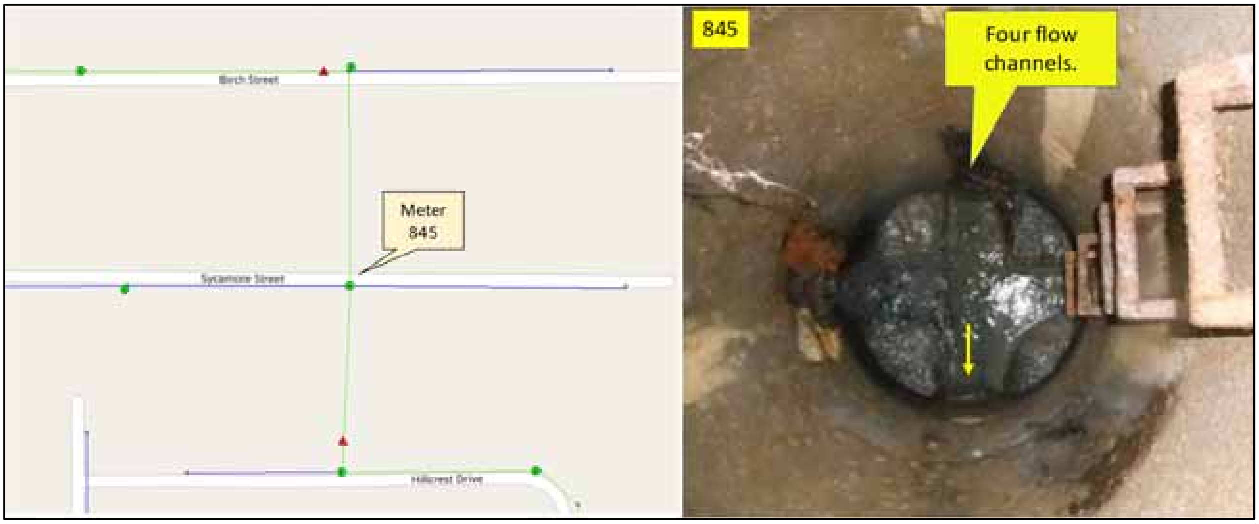


Figure 19 Manhole 842

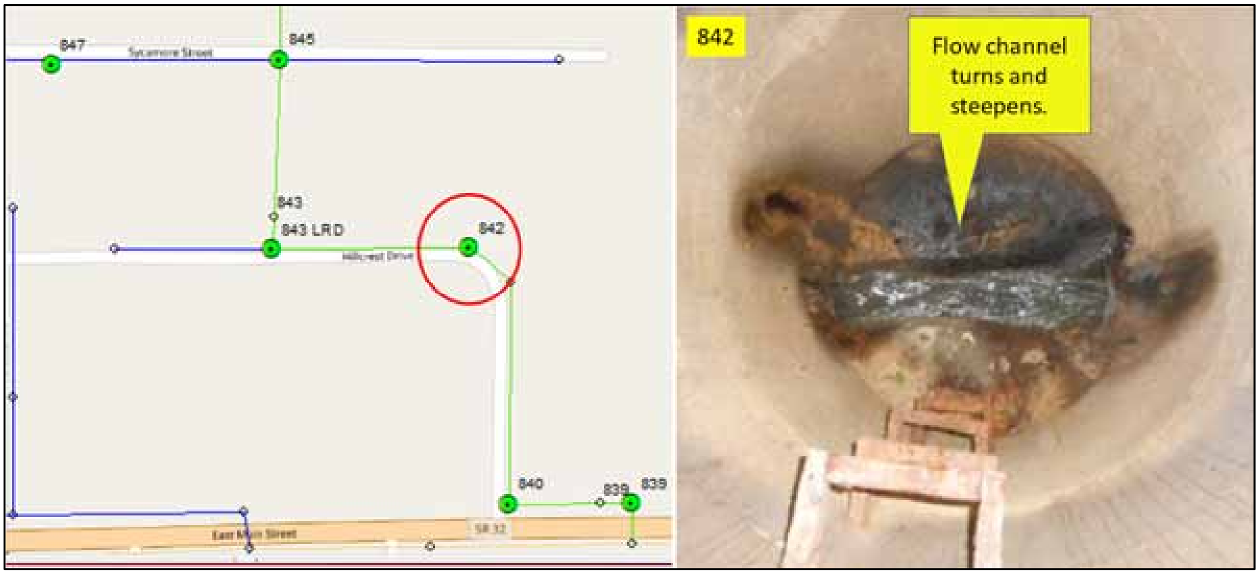


Figure 20 Manhole 843

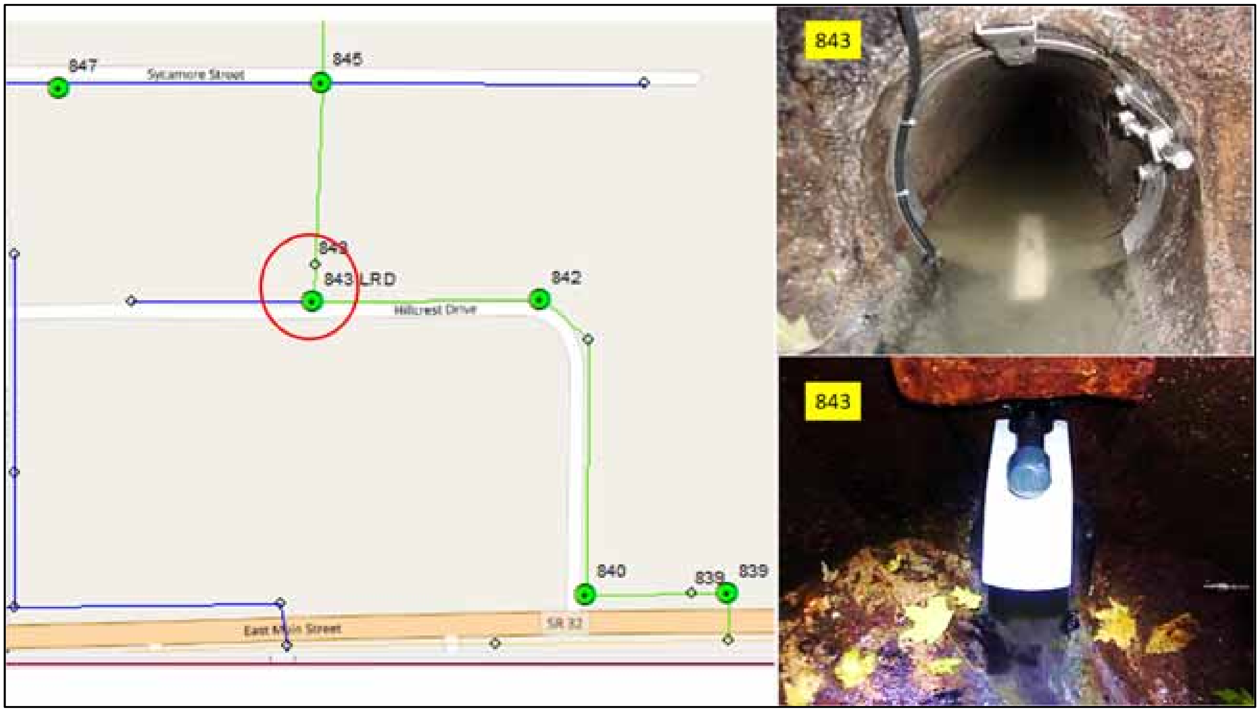


Figure 21 Manholes 847, 849 and 840

Three poorly-formed flow channels render Manning Equation invalid.

This experience revealed to Derek Sutton and Westfield that the depth only meters didn't tell enough of the story by themselves and the AV meters were necessary to interpret the data. Depth-only data would have led to the wrong conclusions. Clearly the flow balances are very wrong, and Westfield's only option would have been to abandon the entire depth-only program and re-do the work with AV meters. Not only is that an expensive proposition, but it can set back the program until the following wet season.

CASE STUDY 3: CONVERTING A NETWORK OF AV METERS TO DEPTH-ONLY DEVICES

An agency with several years of data from ten (10) AV meters decided to switch to ECHO depth-only meters. The belief was that depth-only devices using the Manning equation could deliver just as accurate information as AV meters, but at a lower cost. Prior to the switch, an evaluation was conducted to determine if the metering site was likely to deliver reasonably accurate flow data. The evaluation was based largely on an analysis of the depth-velocity scattergraphs from each of the AV meters. Out of the 10 meters there were 3 ‘Yes’ recommendations and 1 ‘Perhaps’ recommendation. Items noted were:

- Dead Dog – any obstruction or unusual conditions at bottom of pipe that interferes with the Manning equation.
- Backwater – did the pipe enter backwater and at what depth.
- Surcharge – did the pipe surcharge and how deep during wet weather.
- Operational Capacity as percentage of Theoretical Capacity.

Some other considerations that were not included in this evaluation are:

1. Is slope of MH channel close to that of incoming pipe? Can the same pipe curve be used?
2. Is pipe large enough and flow deep enough so that any slope change in the manhole channel has minor effect?
3. Is the shape of the invert channel close to shape of a round pipe so that the Manning equation is proper representation of the cross section?
4. Is benchwall of MH channel close to 80% of pipe height so that flow does not ‘spread out’ within the manhole?

Table 1 lists the items of the evaluation and the recommendation as to whether the site may be suitable for depth-only measurement with the Manning equation.

Table 1 Site Evaluation for suitability for depth-only devices

	Evaluation based on Hydraulic Conditions with AV Meters					
Meter	Pipe Size	Dead Dog	Backwater Begins (in)	Operational Capacity	Surcharge	Recommend?
ABE1200	36	nil	20	50%	175	perhaps
ABE6750	54	6	28	25%	110	orifice
ABE9877	36	nil	20	na	no	shifting debris
BER0345	36	nil	22	60%	64	no
BER3433	31	nil	none	na	no	yes
CMD7760	42	5	20	40%	150	yes
MLE5540	30	5	12	10%	120	yes
MLE8723	37	nil	25	25%	57	no
PCT2022	24	nil	10	40%	90	no
TIN1285	33	nil	12	20%	105	no

Table 2 displays the results of the Average Dry Day Flow (ADDF) comparison. The ADDF values were based on a year of data prior to the switch to a year of data after the switch. The Wastewater and Base Infiltration estimates were produced by ADS' Sliicer.com software. The key observation here is the Percent Change of the ADDF values. Values were as low as 22% and as high as 169% of the original AV values.

Table 2 Comparing AV and Depth-only values with percent change. 1 MGD = 43.8 L/s

	With AV Meters			With Depth-only Devices			Percent Change		
Meter	Average Dry Day	Waste Water	Base Infilt.	Average Dry Day	Waste Water	Base Infilt.	Average Dry Day	Waste Water	Base Infilt.
ABE1200	3.013	2.338	0.675	0.675	0.476	0.199	22%	20%	29%
ABE6750	5.618	4.370	1.248	3.010	2.205	0.806	54%	50%	65%
ABE9877	3.536	2.816	0.759	4.591	3.018	1.573	130%	107%	207%
BER0345	3.283	2.524	0.759	2.346	1.701	0.645	71%	67%	85%
BER3433	1.652	1.310	0.342	2.146	1.355	0.791	130%	103%	231%
CMD7760	4.629	3.431	1.198	3.180	2.240	0.940	69%	65%	78%
MLE5540	3.523	2.636	0.887	2.565	1.683	0.882	73%	64%	99%
MLE8723	1.284	0.735	0.549	0.792	0.415	0.377	62%	56%	69%
PCT2022	1.414	1.117	0.297	2.388	1.836	0.552	169%	164%	186%
TIN1285	1.864	1.487	0.377	0.708	0.510	0.198	38%	34%	53%

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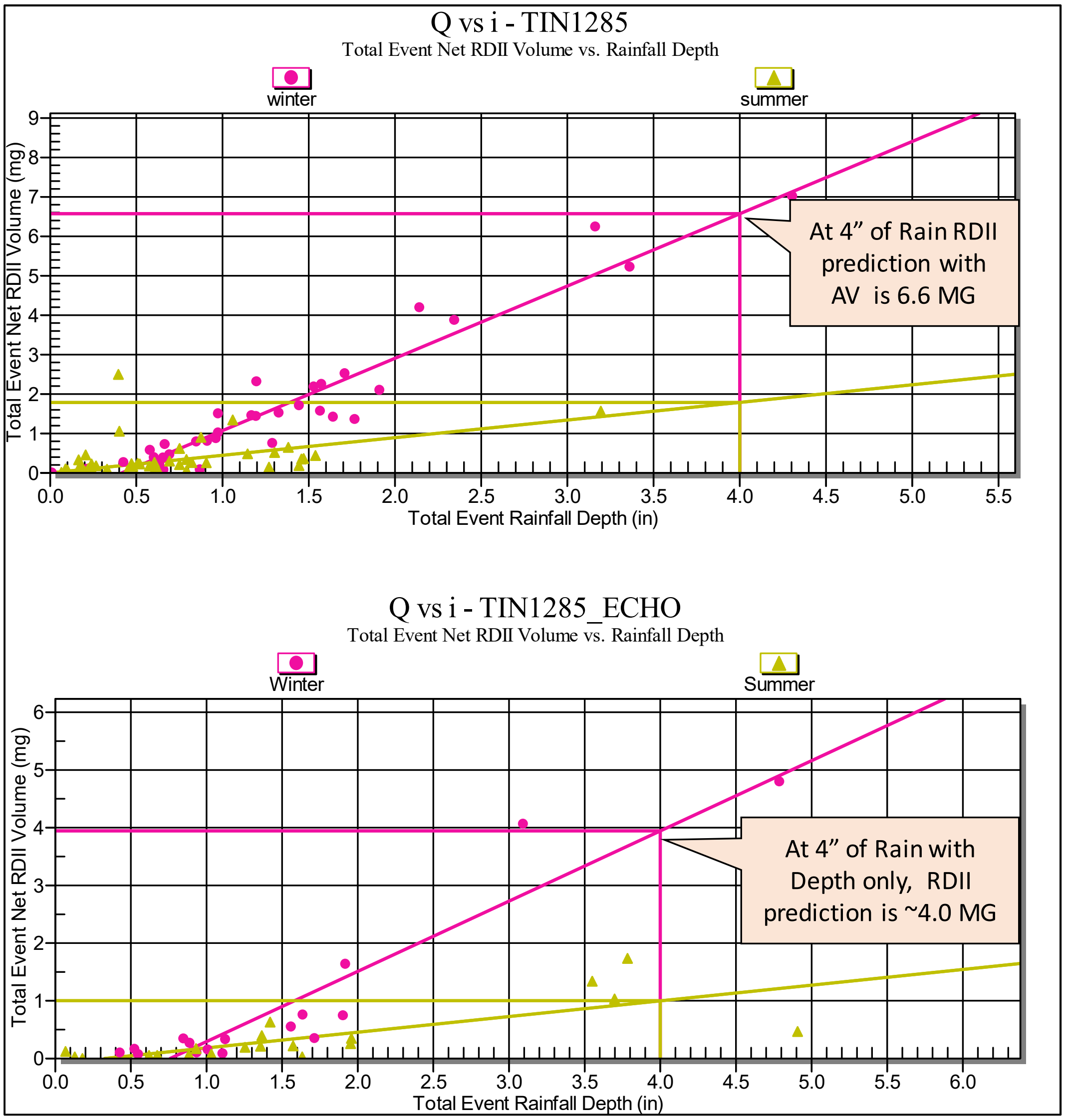
Wet Weather Comparison

RDII values were calculated for each of the ten (10) sites with AV meters and Depth-only devices. Storms were grouped into Winter and Summer storms and Q vs i regression lines were generated for each season. Winter in this case is defined by the period from November through April. A 4-inch design storm was applied to the regression line and the RDII value was predicted as shown in Figure 22. In this example the AV meter produced a projected volume of 6.6 MG while the Depth-only device produces a projected 4 MG. The same process was used to project the Peak RDII flow rate from the same design storm. This analysis was conducted by Sliicer.com software.

Figure 22 Q vs i plots and Design Storm projections, 1 MG=3,785 M^3



At 4” of Rain RDII prediction with AV is 6.6 MG

At 4” of Rain with Depth only, RDII prediction is ~4.0 MG

Table 3 displays the projected RDII values for all ten sites for both Peak Flow and Volume. The results are highly variable, and the spread of values is similar to the spread of the Average Dry Day results.

Table 3 Comparison of Design Storm Projections, 1 MGD = 43.8 L/s and 1 MG = 3,785 M^3

	Peak Q (MGD) - 4-inch Design Storm			Volume (MG) - 4-inch Design Storm		
Meter	AV Meter	Depth only	Percent change	AV Meter	Depth only	Percent change
ABE1200	7.57	2.95	39%	6.23	1.84	30%
ABE6750	24.82	29.8	120%	21.02	14.64	70%
ABE9877	12.82	8.29	65%	10.99	5.43	49%
BER0345	8.54	6.86	80%	6.9	3.81	55%
BER3433	5.27	7.18	136%	3.67	3.44	94%
CMD7760	19.2	13.2	69%	13.62	18.97	139%
MLE5540	10.68	12.82	120%	8.05	16.11	200%
MLE8723	5.02	5.1	102%	3.76	3.76	100%
PCT2022	3.89	6.08	156%	3.13	4.21	135%
TIN1285	8.58	9.89	115%	6.57	3.94	60%

If the purpose of an Agency's flow metering network to manage trends and to quantify changes that may have resulted from operational changes or sewer rehabilitation projects, it is observed here that the error/uncertainty/biases that exist in the depth-only data can easily be greater than the trend or magnitude of changes that are trying to be quantified. For example, sewer rehabilitation projects seldom demonstrate a reduction in RDII of more than 30% to 50%. Such improvements will be difficult to quantify with depth-only data with inaccuracies that are greater than the system improvement.

There may be conditions in some sewers that are suitable for depth-only metering using the Manning equation (no surcharging, no backwater, constant slope through manhole, well formed channel in manhole, etc.), but a careful evaluation must be conducted prior relying on the technique.

CONCLUSIONS.

Depth only devices do not provide the reliability and accuracy to serve an agency that uses flow metering data for engineering applications such as planning for capital improvements and hydraulic modeling.

Depth-only devices do not provide the reliability and accuracy to locate and quantify RDII sources for guiding physical inspection programs. The presence of false positive and false negative indicators create confusion.

The use of the Manning equation in sanitary sewers is plagued by false negatives and false positive indications of flow. When a mass balance exercise is conducted, it appears that the magnitude of false positive indications is much larger than the magnitude of false negative indications. In other words, it leads to *looking for flow in all the wrong places*.

The depth only devices that are marketed as a tool for 'Chasing I/I' or 'Scouting for I/I' are probably useful as replacement for the 'raincoat and flashlight' technique used by operations staff in searching for I/I during rainstorms. They drive around in a known problem area during a storm (raincoats on) lifting manhole lids and trying to make judgements about the location and cause of RDII problems by noting the height of water in a manhole (with flashlights).

Both authors of this paper approached the use of depth-only technology for I/I work with optimism. Westfield was looking for a lower cost option for identifying sources of I/I. ADS was looking for a new application for its unique and successful ECHO product. In the end it is believed that we have re-learned and re-documented why the sewer flow measuring industry abandoned the depth-only Manning equation 40 years ago.