BE WARY OF WEALLY WOUGH WAVES

Identifying and Quantifying the Impact of Standing Waves on Flow Measurement

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ABSTRACT

The authors discuss the effect of waves on the accuracy of flow monitoring. Most people are familiar with waves in streams and channels, but likely don't think about waves in "out-of-sight" sewers. Waves and hydraulic jumps are close cousins and can reduce the carrying capacity of sewers and junction structures if they occur in nearly full-pipe conditions. Even when flow monitors are working correctly, localized variation in depth and velocity from standing waves can cause an incorrect calculation of flow rate. Because waves in sewers are out of sight, users of flow monitors may be unaware of the effect on data quality. Deviation can be on the order of ±25% of calculated flow rate.

The authors encountered standing waves during a flow monitor test conducted by EPA's Environmental Technology Verification (ETV) field test. Subsequent research has lead to the classification of three types of hydraulic jump phenomena and a methodology for identifying the presence of waves by reviewing depth and velocity flow monitor data.

KEYWORDS

Dead Dog**,** ETV, Flow Meter Accuracy, Flow Monitoring, Froude Number, Hydraulic Jump, Iso-Froude Line, Sewer Bore, Standing Wave, Undular Hydraulic Jump

INTRODUCTION

Purchasers and users of flow monitors typically want to know "how accurate" the instrument is. Manufacturers offer lab-based numbers such as "±2%" or "±5%" and users readily rely on these accuracies for the final calculated flow rates produced by the monitor when installed in sewers. As it turns, out sewers offer several sources of error in the calculated flow rate and many of these sources far exceed the published accuracy of the instrument. Sources of error in the calculation include such things as an incorrect measurement of the pipe's cross-sectional dimensions, measuring depth and velocity in different longitudinal locations and not accounting for silt. However each of these sources can be overcome with sufficient fieldwork and selection of monitoring sites.

One source of error that often goes undetected, regardless of the amount of fieldwork, is the presence of waves in the flow. Nearly all sewers experience small waves or ripples, but these typically have no or little effect on accuracy of the flow calculation. It is the larger waves that cause problems and these waves usually show up at higher flow rates in fuller pipes when inspection is difficult or dangerous.

The authors gained experience with standing waves and undular hydraulic jumps while setting up two flow monitors for EPA's Environmental Technology Verification (ETV) field test. The field test called for the installation of two flow monitors close to each other in a 1-meter (41.7 inch) diameter sewer with a reference monitor downstream. Dramatic differences in depths recorded by the two monitors during a trial run lead to the discovery of standing waves at high flow rates. The discovery has provided the ability to quantify the magnitude the standing waves as well as the deviation or miscalculation in flow rates caused by the waves.

Figure 1 below shows two views of the test pipe, one at low flow and one at high flow. To a monitor installer, the conditions seen in low flow make it appear to be a good monitoring site. However at high flow, standing waves with amplitude of approximately 15 cm (6 inches) appear near the down-looking ultrasonic depth sensor. The photograph on the right was taken by a person suspended over the flow; an unorthodox field practice not likely to be performed in real life. Waves and swales with amplitude of approximately 6 inches resulted in deviations of -15 to +25% in flow rates compared to the reference monitor.

Figure 1 Test pipe in low and high flow conditions. Standing wave is visible at high flow.

The paper will discuss the observations that led to the discovery of the waves, demonstrate the magnitude of the resulting miscalculation of flow rate and guide flow monitor users in the technique for spotting the tell tale signature of standing waves in scattergraphs.

DISCUSSION

A common view of waves in sewers is that they are the result of imperfections in the flow channel including offset joints, changes in slope, changes in direction, manhole transitions, etc. While these are contributory causes, significant waves due to the motion of flow cannot occur unless the flow is supercritical. Supercritical flow is flow whose Froude number is greater than 1. There are many similarities between the Froude number concerning gravity waves in non-compressible flows and the Mach number concerning pressure waves in compressible flows. In flight dynamics, stability exists in either supersonic or subsonic conditions, but instability occurs in the transition between subsonic (Mach number <1) and supersonic (Mach number >1). Similarly, instability in water flow occurs in the transition between subcritical (Froude number < 1) and supercritical (Froude number > 1). The hydraulic jump is commonly understood to be the phenomenon in water that occurs when flow transitions from supercritical to subcritical flow (Froude number =1) similar to the sonic boom in air.

Hydraulic Jump Theory

The Froude number (Fr) is named after British civil engineer William Froude who developed innovative methods in the late 1800's for developing full sized ship design based on models in tow tanks. His work, along with his son Robert, led to the design of some 175 British warships including the famous "Dreadnought". The Froude number is a function of velocity and a characteristic length, which was the beam of a ship. Further work has allowed the Froude number to be calculated for flow in a sewer.

$Fr < 1$:	Subcritical flow
$Fr = 1$:	Critical flow
$Fr > 1$:	Supercritical flow

$$\text{Froude Number} = Fr = \frac{v}{\sqrt{gL}}$$

where:
- v = flow velocity, ft/sec
- g = acceleration of gravity, ft/sec^2
- L = characteristic length, ft

In open-channel flow, the characteristic length (L) is defined as the hydraulic depth, which is the wetted cross sectional area divided by the breadth of flow. The term "breadth of flow" is a British term. Some texts refer to this as the "width of the free surface."

Severity and Type of Jumps and Waves

Hydraulic jumps in sewers are not always the distinct transition commonly discussed in textbooks, but more frequently occur as "undular hydraulic jumps". Montes and Chanson (1998) and others have classified undular hydraulic jumps based on the Froude number of incoming flow. In general the classifications are:

Fr < 1.2 - No cross-waves, two-dimensional structure.

Fr < 1.7 – Cross-waves develop, but no wave breaking at their intersection.

Fr < 2.4 - Wave breaking and air entrainment at the first cross-wave intersection.

At Froude number higher than 2.6 the undulations diminish.

Figure 2 demonstrates the concept of cross-waves and cross-wave intersections. The schematics on the left show profile and plan view of a sewer with fully developed waves. The diagonal cross-waves are diamond shaped. The photo on the right captures small diamond cross-waves as water passes over a plywood board used to simulate silt in a sewer.

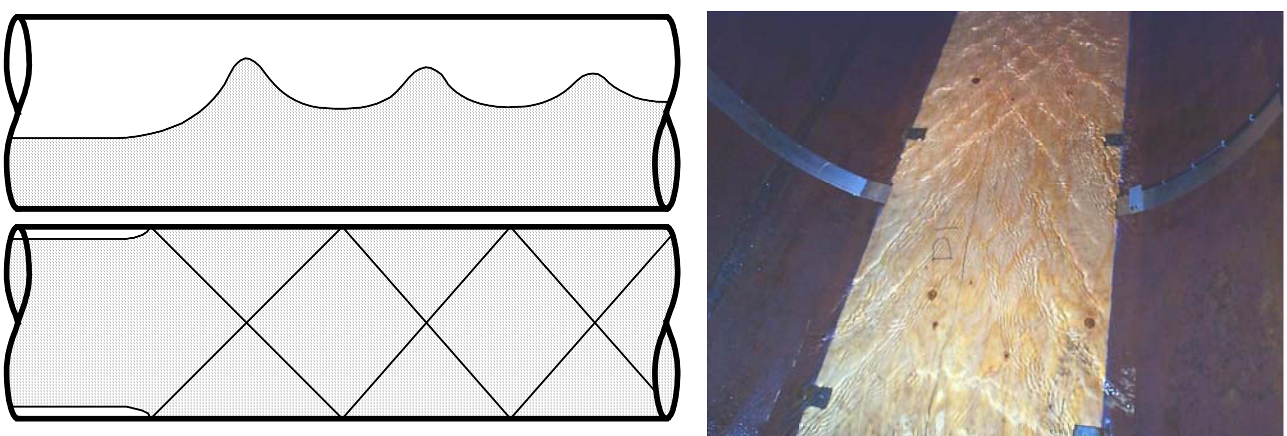


Figure 2 Schematic of undular waves and cross wave pattern. Cross-waves are visible in photo as waves pass over plywood used to simulate silt in a sewer.

The largest of these waves are "standing waves" that tend to hold their position in a channel at a fixed flow rate. These waves are often referred to as "undular hydraulic jumps" and as the name implies, are associated with flows at or above the critical velocity. Undular hydraulic jumps are commonly recognized as rapids in fast rivers. Figure 3 is a picture by Chanson (2000) showing an undular hydraulic jump of a meter or so in height in a concrete channel. The stain on the wall just ahead of the surfer indicates that the wave is in that position regularly.

Figure 3 Stationary undular hydraulic jump in a concrete channel. Jump is suitable for surfing.

Most research on undular hydraulic jumps is empirical and based on controlled laboratory facilities similar to Chanson's shown in Figure 4. Often the experimental channels are flat or on a very slight slope. Undular waves are three dimensional in nature and this paper will generalize the results to observations at the centerline of the channel. Although there are minor differences in what various researchers found, there are a few observations that provide guidance to flow monitor users.

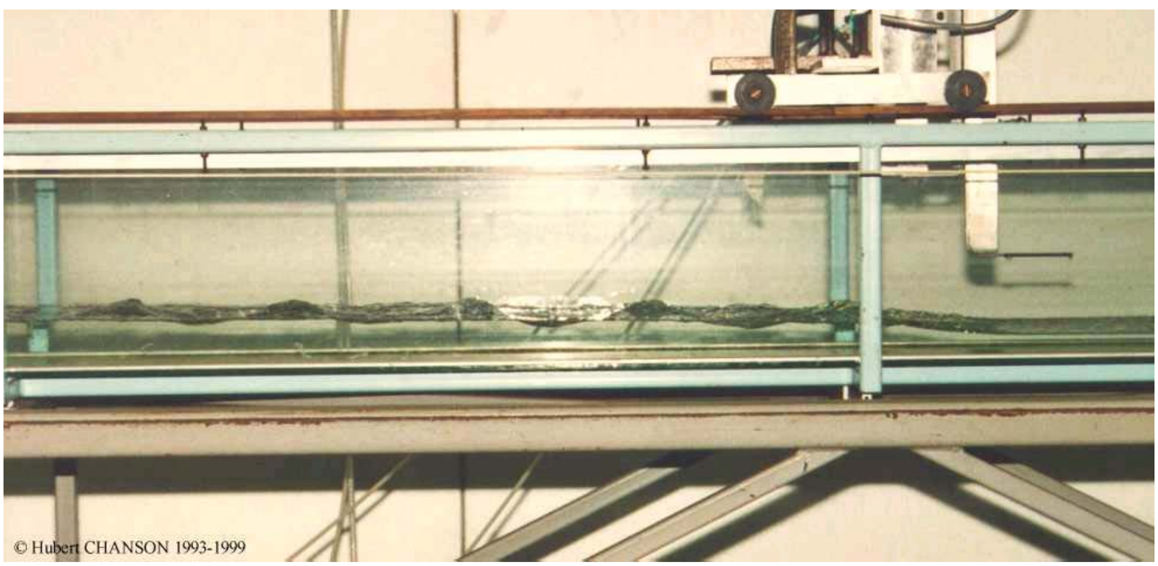


Figure 4 Channel used to create and study undular hydraulic jumps. The waves appear in the absence of defects of channel walls.

No Imperfections Needed for Wave Formation

Many engineers believe that waves in sewers are the result of some type of channel imperfection. Offset joints, wall roughness, slope change and debris are thought to create waves. Chanson (1998) and Ohtsu (2001) used smooth panels of glass or plastic and found that the waves form without the presence of imperfections and discontinuities in the surfaces. They report that pressure and velocity differentials in the boundary layer between the flow and wall are sufficient to initiate the undulations and shock waves. Surface imperfections may contribute to wave severity, but are not necessary for undular hydraulic jumps to form.

Wave Amplitude and Incoming Flow

The amplitude, attenuation, velocity profiles and hydrostatic pressure profiles of waves are all subjects of continuing research, but this paper is focusing primarily on the magnitude and effect of the waves. Figure 5 is a simple schematic showing the relationship of incoming flow to wave formation.

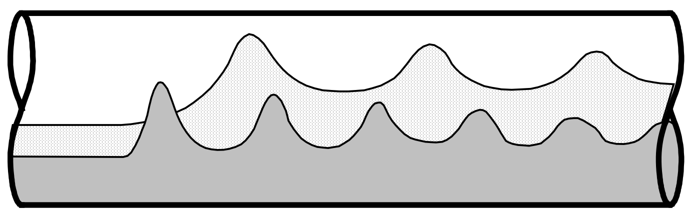


Figure 5 Schematic showing that wave amplitude and wave length are function of both incoming depth and Froude number.

As a general rule higher Froude numbers in the incoming flow will result in waves with greater amplitude and shorter wavelength. The highest wave crest and lowest wave trough usually appear at the center of the channel at the intersection of the first cross-wave or shock wave. Waves attenuate in amplitude after the first wave crest.
Wave crest amplitude can range from 13 to 75 mm (1/2 to 3 inches) in small to medium sewers and from 75 mm to over 1 meter in large channels and sewers. Large waves in nearly full pipes can result in sewer “choking” and designers are cautioned to avoid sewer velocities in the critical range.

Classification of Waves and Jumps

For this paper we have we have classified waves and jumps into three categories, undular hydraulic jumps, sewer bores and jumps due to fixed downstream conditions. Although the science may be similar for each type, the effect on flow monitors will be different. Undular hydraulic jumps have been discussed earlier and the other two categories are discussed below.

"Sewer Bores"

A "Sewer Bore" is similar to a tidal bore in which a rising tide will cause a hydraulic jump to migrate upstream on a flat, but supercritical river. Figure 6 shows a tidal bore formed as tidewater from the Bay of Fundy advances (towards the viewer) up the Kennetcook River in Nova Scotia. The advancing hydraulic jump is approximately 200 mm (8 in) high and is trailed downstream by several undular hydraulic jumps. Tidal bores occur in many locations around the world and several of the bores are surfable at heights on the order of a meter or more.

Figure 6 Tidewaters from the Bay of Fundy advancing up the Kennetcook River as a tidal bore in Nova Scotia.

This condition can exist in a sewer if flow in a larger downstream sewer or a downstream wet well controls the depth of an incoming sewer. Figure 7 is a schematic showing how this can occur at a flow monitor located near a larger downstream sewer. If the depth of the downstream sewer rises sufficiently, the "sewer bore" hydraulic jump will advance past the monitor. From a monitor's perspective the hydraulic jump may not occur at a specific flow rate or specific depth, but will occur any time the downstream depth is sufficient.

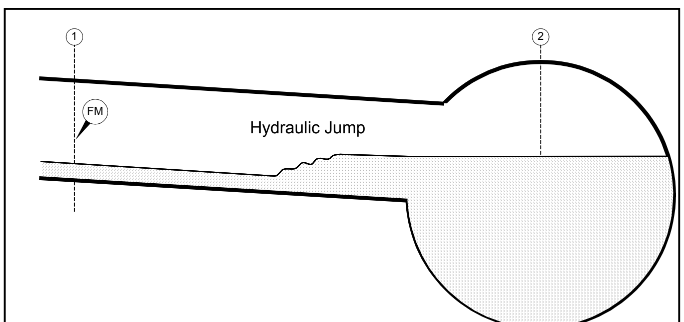
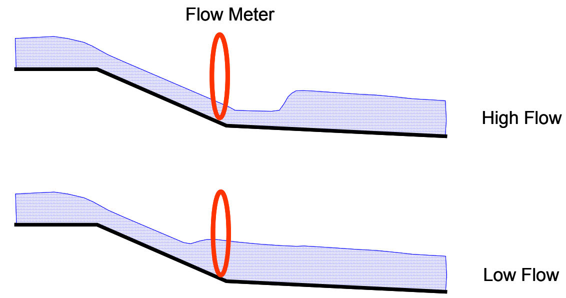


Figure 7 Depth in a downstream sewer can create a "sewer bore" moving upstream past a flow monitor.

Fixed Downstream Condition (Dead Dogs)

Many types of stationary conditions can cause a hydraulic jump to occur. Downstream stationary conditions include a flat slope, as shown in Figure 8, diversion structures, offset joints or other obstacles. Obstacles such as debris, silt, bricks or any object that would form a pool of water at low flow are often collectively described as "Dead Dogs". The common characteristic of this type of jump is that it moves downstream at higher flow rates and upstream at lower flow rates as shown in Figure 8. A monitor located within this range of travel will see a distinct and repeatable shift in the depth-velocity relationship at a specific depth and a specific flow rate.



A hydraulic jump moving back and forth, upstream and downstream of the sensors.

Figure 8 Hydraulic jump resulting from a change in slope of a downstream pipe.

Figure 9 is a photo of a jump that was created by inserting a wooden "Dead Dog" in the bell of the pipe. This setup simulated the backwater condition that formed in the manhole during high rain-induced flows. It confirmed that the meters was calculating flow using the greater depth of the jump with the higher velocity of the incoming flow. Notice upstream that the flow is shallow (~ 1 inch deep) and is 2 to 3 inches deep after the jump the jump is formed under the down looking ultrasonic sensor and the depth reading would certainly be affected.

Figure 9 Hydraulic jump created by inserting the wooden "Dead Dog" in the bell of the pipe. The faster and shallower flow is visible upstream of the jump.

Monitoring Configuration During Field Test

An opportunity to quantify undular wave heights occurred during the ETV field test in 2001. The test was being conducted in a 1-meter (41.7 in.) diameter sewer between an upstream storage facility and a downstream gate. The combination allowed the creation of various flow rates and backwater conditions. The test facility was able to produce simulated wet weather flow rates on demand by releasing stored flow and could create backwater conditions by restricting the downstream gate.

During the test, two ADS monitors equipped with identical quadredundant ultrasonic depth sensors were placed a few feet apart in the same pipe as shown is Figure 10. The two test monitors were in different pipe sections with slightly different slopes resulting in depths being different by approximately 25 mm (1 inch). Figure 9 also shows a possible configuration of suspected undular hydraulic jumps.

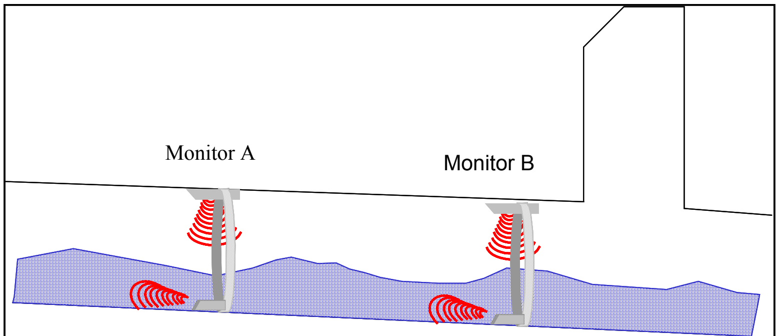


Figure 10 Configuration of two test monitors located a few meters apart.

Magnitude of Monitoring Deviation

During the initial setup and test run with the monitors in place, ADS installation crews noticed that depths reported by the two monitors were in consistent agreement (within 25 mm) during normal flow conditions, but varied dramatically (170 mm) during simulated wet weather when flow was released. A crewmember was suspended over the flow during a second test run and captured the standing waves in the photograph shown in Figure 1. The testing contractor and the ETV coordinator recognized that the waves would affect the reported accuracies, but it was agreed that the test should continue.

The hydrograph in Figure 11 plots the ultrasonic depth measurements from the two monitors during one of the test cycles. The first half of the test, prior to 15:00, was conducted in partial backwater at different depths and flow rates. The second half begins at 15:00 and is simulating wet weather at high flow rates with no backwater (free flow condition). During the backwater condition the depths differed by approximately 25 mm (1 inch) due to the different slopes. During the high flow rates the depths differed by as much as 170 mm (~7 inches) due to the apparent presence of undular hydraulic jumps.

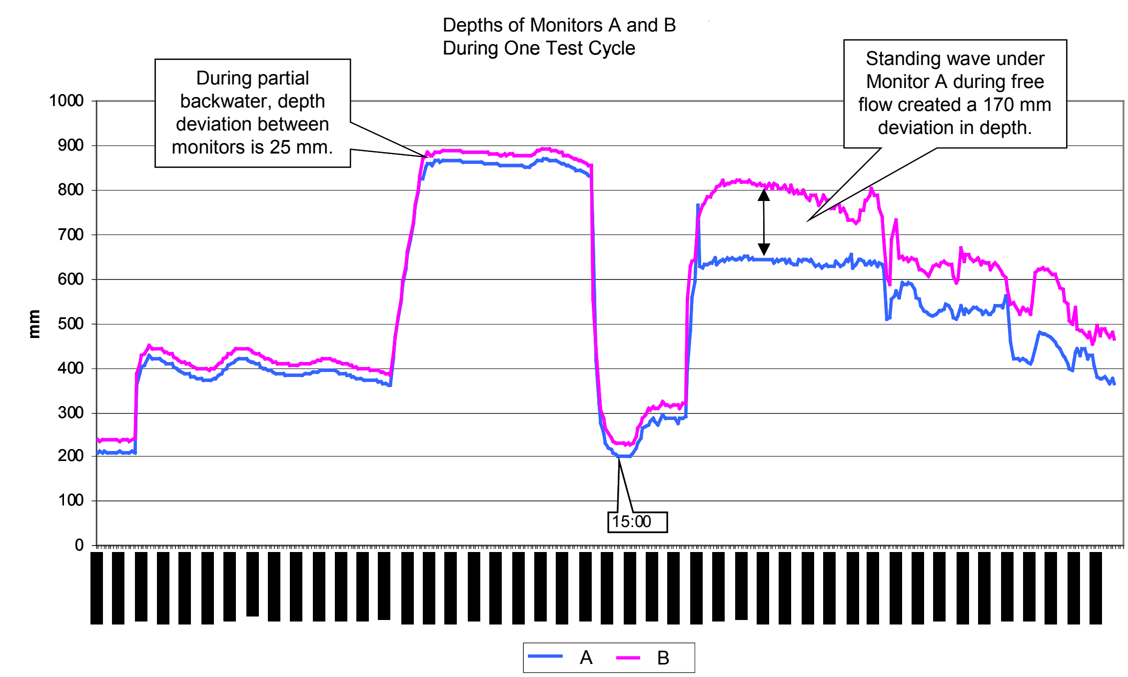


Figure 11 First half of test cycle was in partial backwater and second half was in free flow at high flow rate.

Displaying the two depth readings in a scattergraph, shown in Figure 12, reveals the distinct difference in depth relationship between partial backwater conditions and free flow conditions. Depth data collected during backwater conditions prior to 15:00 are plotted as blue diamonds. The linear regression line reveals consistent measurements ($R^2 = 0.9972$) and an offset of 26 mm (~ 1 inch) due to different slope at each meter location.

Free flow depth data after 15:00 are plotted in violet squares. At depths under 300 mm the monitor depths were consistent and plot on the regression line, similar to flow in backwater. At depths greater than 300 mm the relationship in depth between the two monitors varies dramatically. Depths differed by approximately 170 mm and a definite clustering pattern appears in the data. It is believed that the clustering effect is a combination of steady flow rates and standing wave peaks or troughs situating themselves for a period of time under the ultrasonic depth sensors. The test protocol called for the flow rate to stabilized at several values during the test cycle.

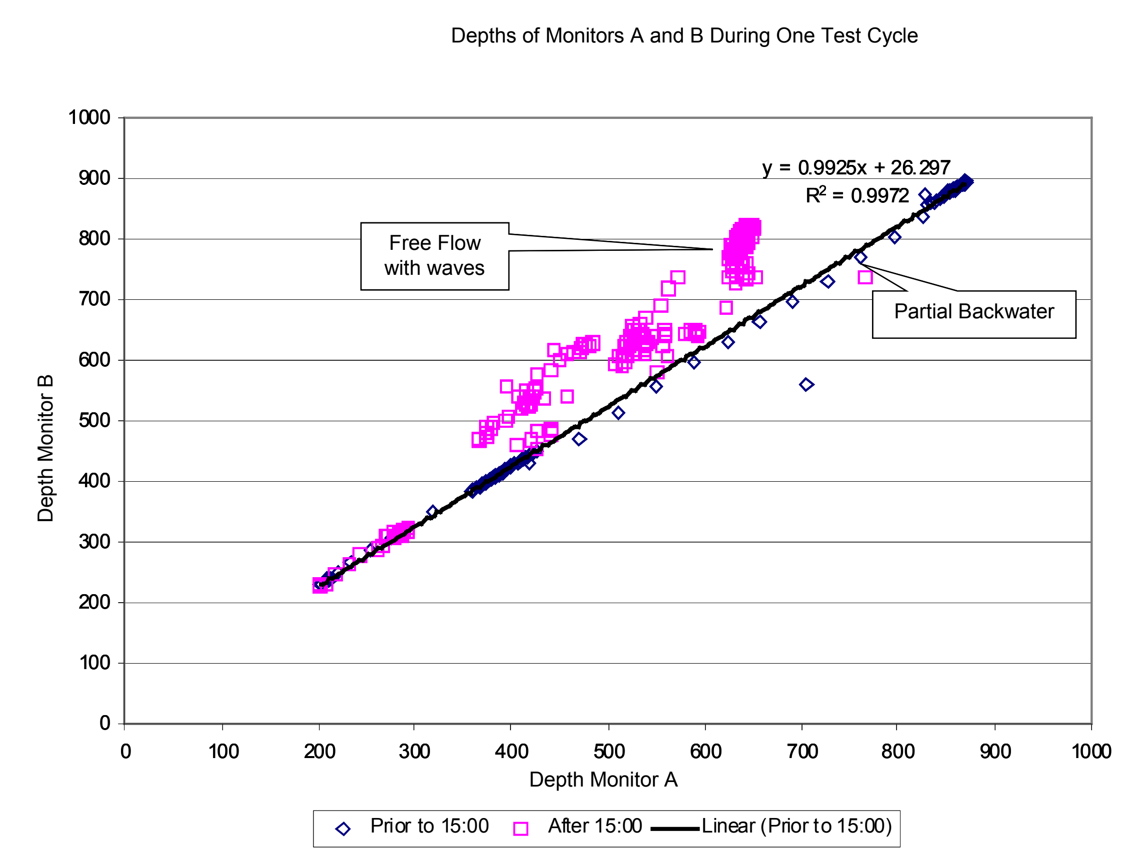


Figure 12 Scattergraph of depths from test monitors shows consistent relationship below depth of 300 mm, but wide deviations at greater depths in free flow conditions.

Comparison to the reference monitor shows that the test monitors were exposed to both wave crests and troughs. Analysis was able to identify periods when the test monitors experienced either crests or troughs and flow rates calculated during those periods were separately compared to the reference meter. Figure 13 displays the percent deviation separated into periods of crest and trough influence. There is a clear bi-modal separation in the data. Crests appear to cause a greater deviation than troughs and can be on the order of 25%. The temptation is to call this deviation metering error, but in reality the meter was performing correctly.

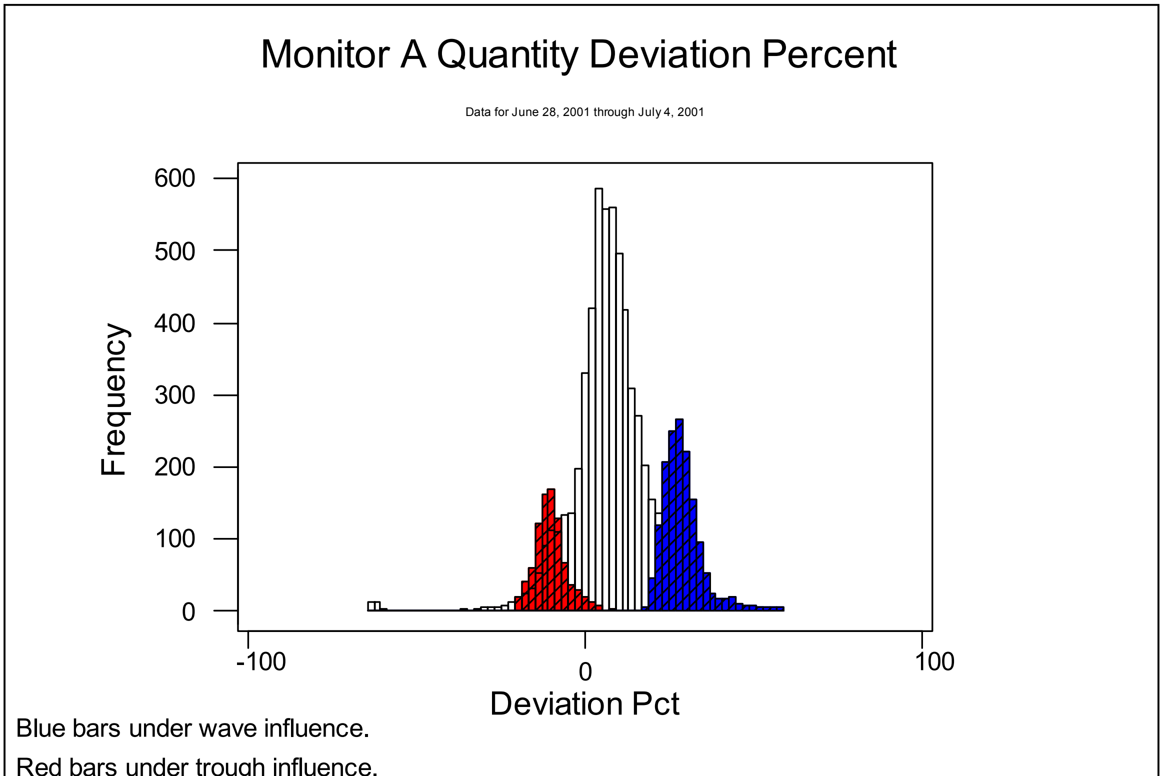


Figure 13 Display of percent deviation in calculated flow rate from reference monitor. Bi-modal pattern is due to influence of wave crests and troughs.

Spotting Hydraulic Jumps

An effective way to evaluate the performance of the flow monitor as well as the hydraulic condition in the pipe is through a depth-velocity scattergraph. Initially scattergraphs were merely a plot of depth and velocity to verify acceptable monitor operation. As the use of scattergraphs has developed over the years several additions have brought increased value.

- The Manning pipe curve compares the monitor to theoretical depth and velocity values
- The manual confirmation points reveal if the data are accurate
- The Iso-Q™ Lines provide a visual indication of flow rate for each data point.

This experience with the waves has inspired an additional feature, the use of lines of constant Froude Number, informally called Iso-Willies™ in honor of William Froude. The Iso-Willie lines allow the user to determine if flow is subcritical, supercritical or has transitioned between them. Figure 14 is a scattergraph showing data from a site that is influenced by some type of fixed downstream condition. The graph includes the Iso-Willie lines of Fr = 1.0, 1.2 and 1.7, which are the numbers offered in the literature as points of significant hydraulic change.

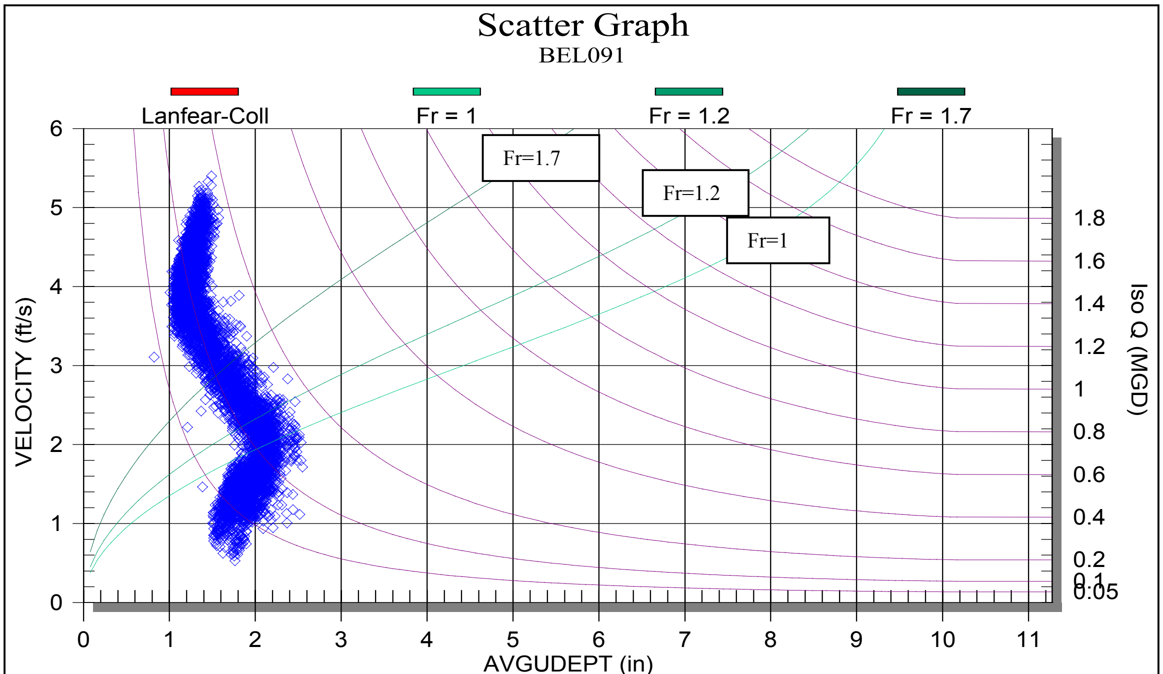


Figure 14 This scattergraph is from a site with a fixed downstream obstacle. The transition from sub- to supercritical flow consistently occurs at the same depth and approximately follows an Iso-Q line of 0.1 mgd. Ten weeks of data are plotted here.

The characteristic that indicates this is due to a fixed downstream condition is the distinct and repeatable pattern as the flow transitions from subcritical to supercritical. The second characteristic is that the flow rate during the transition approximately follows the Iso-Q line of 0.1 mgd. The depth during the transition drops from approximately 2 inches to 1 inch.

The Froude numbers plotted on the scattergraph are those key values discussed above and identified in the literature from experiments in test stands with known incoming conditions. The upstream or incoming condition at flow monitoring site is not known so the incoming Froude number is not known with certainty. The Froude numbers in the scattergraph are those at the meter location not the necessarily the incoming value. The user should take this difference into account when interpreting results.

Example of A “Sewer Bore” Hydraulic Jump

The characteristic of a hydraulic jump from a sewer bore is that the jump will likely occur at varying depths at the meter site. The diurnal pattern of the controlling down stream depth sewer may not correlate with the timing of diurnal pattern at the metering site. Figure 15 shows two distinct depths at which the jump occurs.

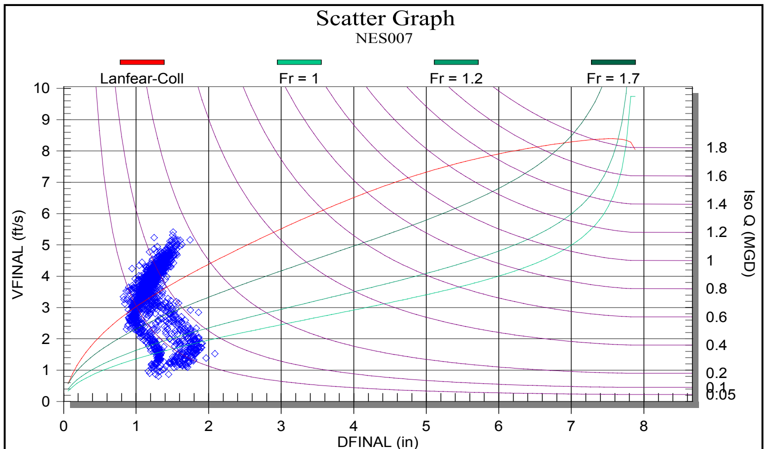


Figure 15 Depth of hydraulic jump controlled by varying downstream condition.

Scattergraph from Standing Waves

Figure 16 is a depth-velocity scattergraph of one test meter during one of the test cycles. The clustered and stair step pattern in the scattergraph is observed to correlate with presence of undular hydraulic jumps. Much of the clustering here may be due to the test protocol which calls for flows to be stabilized at fixed flow rates during the test cycle.

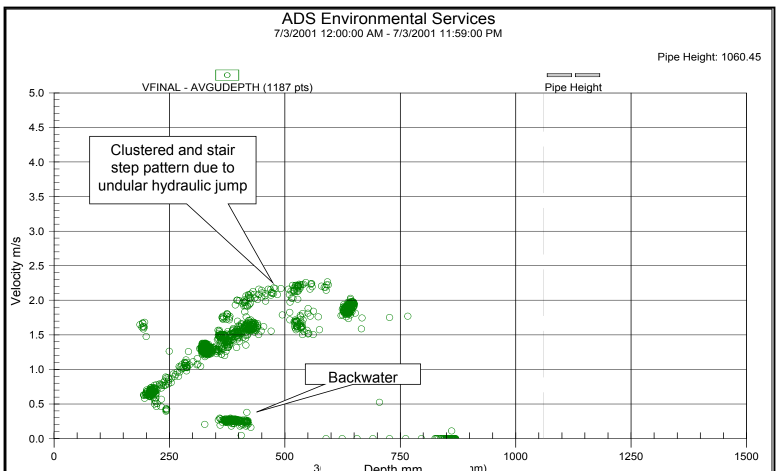


Figure 16 Clustered and stair step pattern appears to be associated with presence of undular hydraulic jumps.

Figure 17 shows the entire data set with data from one test cycle highlighted in violet. The Iso-Willie™ lines show that the undular hydraulic jump pattern is present at or near Fr number = 1. The characteristic pattern believed to be associated with waves is the stair step shape.

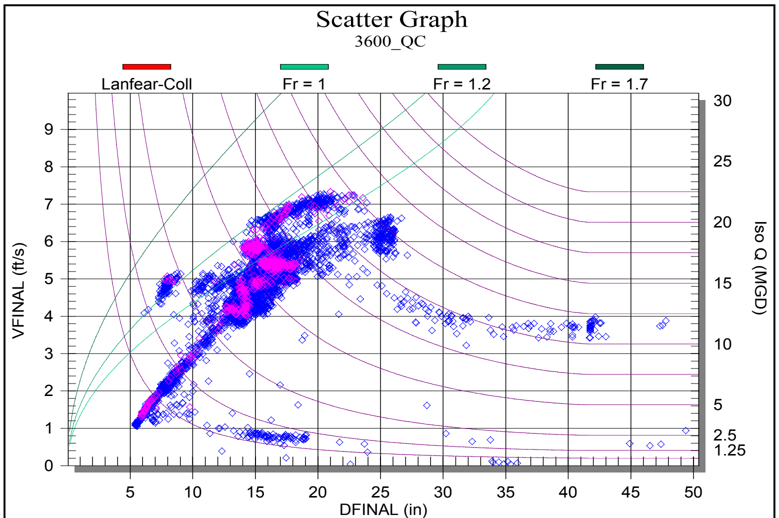


Figure 17 All test data with one test cycle highlighted in violet. Undular hydraulic jump pattern appears at or near the Iso-Willie of Fr = 1 or greater.

CONCLUSIONS

Jumps and Waves can be detected though examination of Depth-Velocity scattergraphs by the presence of a characteristic stair step pattern provided the flow is at a Froude number greater than 1.

Undular hydraulic jumps can cause significant deviation in the calculation of a flow rate. The testing performed during the ETV demonstrated that the deviation could be as high as 25%.

Potential for the appearance of undular hydraulic jumps can be predicted with Iso-Willies™ - lines of constant Froude number.

Hydraulic jumps and waves should be avoided as monitoring locations. If they cannot be avoided the user must be aware of the effect of the waves on the calculated flow rate.

REFERENCES

Chow, V.T. (1959). *Open Channel Hydraulics*, McGraw Hill Book Company, New York, NY.

Joint Committee of the American Society of Civil Engineers and the Water Pollution Control Federation (1969). *Design and Construction of Sanitary and Storm Sewers*.

Kimbrough. H. R., Stevens P. L., Davison, P. J. and Frederick, R. M. (2003), "Comparing Sewer Flow Meter Performance - The Necessity of ETV Program Participation," *Proceedings of the 76th Water Environment Federation Technical Exhibition and Conference*; Los Angeles, CA. Water Environment Federation: Alexandria, VA.

Montes, J.S. and Chanson, H. (1998). "Characteristics of Undular Hydraulic Jumps: Experiments and Analysis," *Journal of Hydraulic Engineering*, American Society of Civil Engineers, 124(2), 192-205.

"*Navies in Transition*", http://www.btinternet.com/~philipr/froude.htm, for background on William Froude.

NSF International (2000). *Generic Verification Protocol – Flowmeters for Wet Weather Flow Applications in Small- and Medium-Sized Sewers*, Ann Arbor, MI

Ohtsu, I., Yasuda, Y., and Gotoh, H. (2001). "Hydraulic Condition for Undular-Jump Formations," *Journal of Hydraulic Research*, 39(2), 203-210.

Stevens, P. L. (1997). "The Eight Types of Sewer Hydraulics", Proceedings of the Water Environment Federation *Collection Systems Rehabilitation and O&M Specialty Conference*; Kansas City, MO. Water Environment Federation: Alexandria, VA.

Stevens, P.L. (2001), "Peeling the Onion of Meter Accuracy - Two Steps to Evaluating Flow Meter Data," *Proceedings of the 74th Water Environment Federation Technical Exhibition and Conference*; Atlanta, GA. Water Environment Federation: Alexandria, VA.

U.S. Environmental Protection Agency (June 2002). *EPA's Environmental Technology Program*, EPA/600-F-02-036; Washington, D.C.