Flow Report No. F 19-001

Laboratory Flow Meter Testing Report

Low Flow Testing

Prepared by
Dan Howes, Ph.D., P.E.
Project Manager, Cal Poly ITRC
djhowes@calpoly.edu
Mobile: 858-354-0504

Gianna Cianfichi
Student Support Engineer

Prepared for
Aleksandra Wydzga, P.H.,
Central Coast Salmon Enhancement/Creek Lands Conservation
aleks@centralcoastsalmon.com
805-451-7544

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IRRIGATION TRAINING & RESEARCH CENTER
California Polytechnic State University
San Luis Obispo, CA 93407-0730
Office Phone: (805) 756-2434 FAX: (805) 756-2433
www.itrc.org

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Introduction

In arid environments, streamflow enhancement in low flow channels is common. It is challenging to assess enhancement project effectiveness in these channels because of uncertainties in metering (regarding both meters and procedures). The basic equation for flow is:

$$Q = VA \qquad \text{(Eq. 1)}$$

Where,

Q = channel flow rate (e.g., cubic feet per second, CFS)
V = cross sectional average velocity (e.g., feet per second, fps)
A = cross sectional area (e.g., square feet, ft^2)

There are three main factors that impact flow measurement uncertainty in natural channels:

1. Flow meter velocity measurements (V)
2. Depth and area measurements (A)
3. Lack of continuous measurements over time

Items 1 and 2 above are directly shown in Eq. 1. However, the third point is important to also understand because point flow measurements are difficult to utilize, since flow changes over time. The work outlined in this report only focuses on the first two factors (V and D). The last factor is typically overcome by somehow continuously measuring the flow or relating point flow measurements to water depth (stage discharge relationship).

The objectives of this study were to evaluate several meters under laboratory and semi-laboratory conditions in order to:

1. Determine the most effective meter to use under low flow conditions
2. Identify constraints in the metering process or with meters themselves
3. Utilize the results to identify improved methods or recommendations for improving low flow measurement accuracy

Velocity Terminology

The uncertainty in flow measurement or estimation is the overall question that must be addressed. However, for this study the uncertainty in the two measured components used to compute flow will be evaluated: velocity and depth. Sensors with low uncertainty in velocity and high uncertainty with depth measurements can still provide low uncertainty in flow measurement if an improved depth measurement is obtained.

No meter is capable of measuring all of the velocities in a channel, so each meter will sample velocities at specific locations in the cross section. The cross-sectional average velocity will be used to evaluate the uncertainty. A procedure is then used to convert the sampled velocities to the average cross-sectional velocity. This will be discussed in the following sections. In this report, the terms *measured* *velocity* and *actual velocity* both refer to cross-sectional velocities. The term *sample velocity* will indicate a point velocity measurement or only a sample of the velocities in the cross-section.

The uncertainty will be evaluated by examining the percent error between the measured and actual velocity. The actual velocity is the actual average cross-sectional velocity determined by using a control flow measurement divided by the control area. The terms *control* and *actual* are interchangeable. The measured actual flow was determined using a calibrated flow meter, as will be discussed. It is important to point out that the actual flow and the “true” flow are not the same. There is no method to directly measure the true flow (with no uncertainty). The calibrated flow meters used to determine the actual flow have uncertainties within ±2% or better for this study.

Meter Descriptions

AgriFlo

The In-Situ AgriFlo XCi (AgriFlo) device uses a Doppler ultrasonic area/velocity sensor (Figure 1). This device was originally developed by MACE, which was acquired by In-Situ. These sensors use continuous wave Doppler ultrasound to measure the speed of the particles (including dirt and bubbles) in the stream[1]. This means that when using the device only one measurement is required (directly in the center of the channel). The device then uses an algorithm to estimate the cross-sectional average velocity. The circular sensor on the top of the device is a pressure transducer, which measures the depth. User inputs on channel dimensions are used to relate the depth measurement to the area of the flow. Manual calibration of the depth, prior to initial use, was necessary for proper operation.

Figure 1. AgriFlo sensor

The AgriFlo was designed for a permanent installation but was modified to test it in a portable mode. To make it portable, the sensor was mounted on a plastic tube, similar to PVC, that could connect to a pool rod (Figure 2). The sensor and chords were carried in a bag. The rod and data logger unit were carried separately. The data logger unit was difficult to carry into the field because it didn't have handles. Overall, the AgriFlo was relatively easy to set up, but required a power source to turn on and had to be initiated with a laptop in the field. As part of this project, In-Situ will be contacted regarding the potential of creating a portable version of this meter.

Figure 2. Assembled (left) and disassembled (right) AgriFlo

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[1] Information and images of AgriFlo sensor from: *MACE XCi User Manual*, MACE P/L, Sebring, FL. 2019

FlowTracker2

The FlowTracker2 uses an acoustic Doppler velocimeter sensor. This device has two separate transducer sensors: one is used as the transmitter and the other as the receiver. The transmitter generates sound at a known frequency. The sound then reflects in all directions from particulate matter traveling in the water. The receiver detects the reflected signals[2]. The FlowTracker device then measures the change in acoustic frequency to compute the water velocity, also known as the Doppler shift. The Doppler shift is proportional to the velocity of the particles. It is important to note that the beams on these sensors project 4 inches from the tip of the probe. When using the FlowTracker2, multiple measurements must be taken across the whole profile of the flow (current metering). For example, each of the vertical lines in Figure 3 represents the locations of velocity and depth measurements required along that cross section. Standard current metering practices were employed when testing this device, as will be discussed in the *Procedures* section.

The depth for the measurement was determined using the wading rod the device is attached to. The wading rod measurement uncertainty is related to the gradations for measurement. Standard wading rod gradations are in tenths of a foot, which are very large. The operator attempted to interpolate between these, but uncertainty would be relatively high.

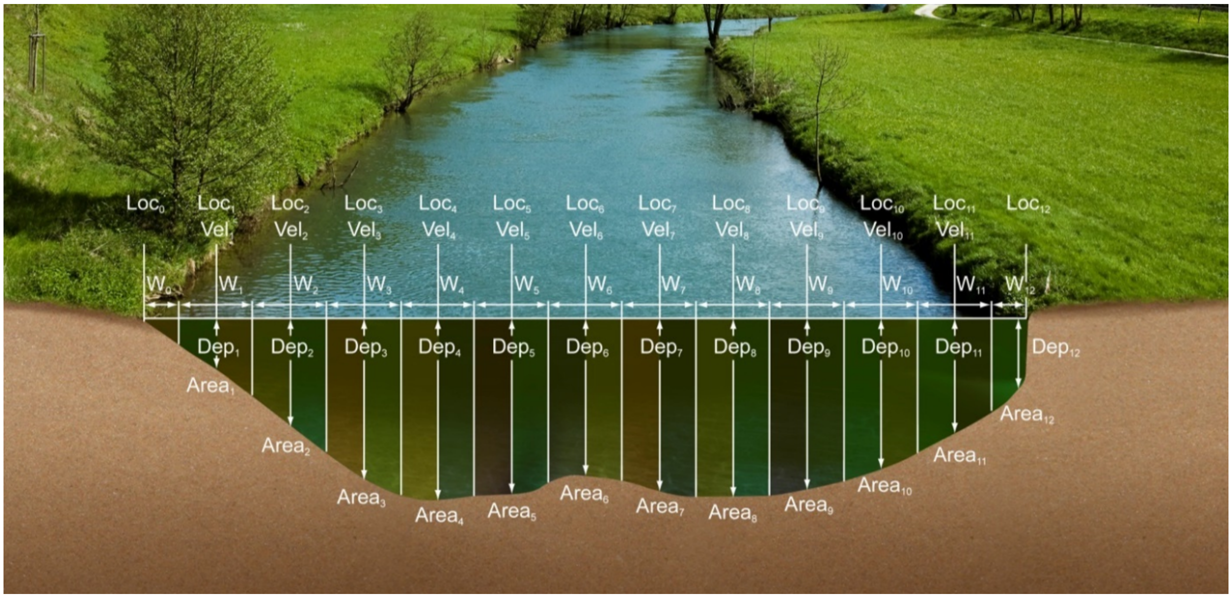

Figure 3. Cross-section of measurement locations

The FlowTracker2 comes in a portable case (Figure 4). Once in the field the rod, portable display, and sensor had to be assembled. The FlowTracker2 was relatively time-consuming to set up, but easy to use.

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[2] Images and information about the FlowTracker from: *FlowTracker2 User's Manual*, Xylem Inc., San Diego, CA. 2019.

Figure 4. FlowTracker2 disassembled in portable case (left) and assembled (right)

MantaRay

The MantaRay also uses an acoustic Doppler area/velocity meter sensor[3] similar to the AgriFlo. As stated previously, these types of sensors measure the velocity along a vertical beam. An algorithm is then used to estimate the average velocity across the profile. Since this device calculates an average velocity, only one measurement is needed (directly in the center of the channel).

The MantaRay sensor was mounted on a steel rod so it could be used portably. Once in the field, it had to be hooked up to its portable display (Figure 5). The MantaRay was the easiest to set up and use, but the steel rod was awkward to carry out to the field. Greyline makes different brackets for the MantaRay sensor that might be easier to use.

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[3] *MantaRay Portable Area-Velocity Flow Meter- User's Guide*, Greyline Instruments Inc., Largo, FL. 2019.

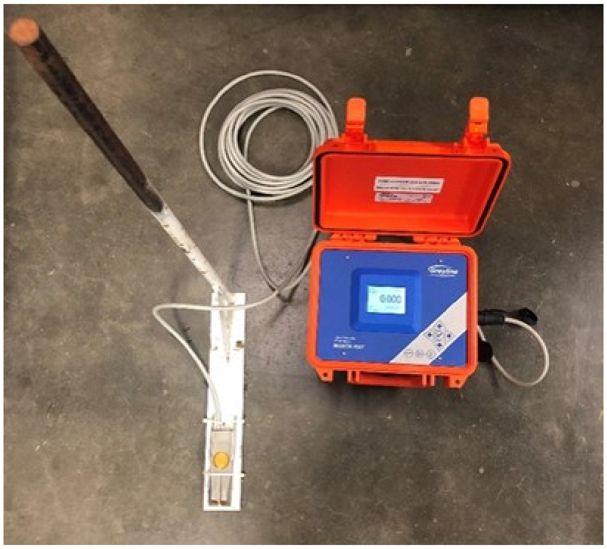

Figure 5. MantaRay

Hach

The Hach FH950 uses an electromagnetic sensor. This sensor creates a magnetic field that, when placed in flowing water, creates a voltage that can be detected by the sensor[4]). The signal is then sent to the processor, which displays the velocity measurement. When using the Hach, current metering procedures were used where multiple measurements across the profile were made (same process as the SonTek Flowtracker2). The Hach had a bag that the portable display and the sensor fit in together. In the field they were attached to the rod (Figure 6). The Hach was easy to set up and operate.

Figure 6. Hach FH950

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[4] Images and information regarding the Hach FH950 from: *FH950 Portable Velocity Meter with Electromagnetic Sensor.* < https://www.hach.com/fh950 > Hach, Loveland, CO. 2019.

Pygmy

The Pygmy meter uses a mechanical propeller with anemometer cup wheels to measure velocity[5]. This consists of little buckets attached to a wheel that spins when the water flows through it (Figure 7). Each rotation is counted by the digitizer. The number of rotations per 40 seconds determines the velocity of the water.

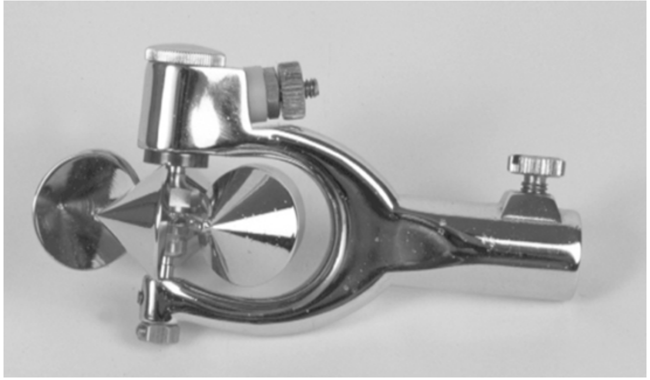

Figure 7. Pygmy meter[6]

The Pygmy propeller was carried in a protective bag. In the field the group had to attach the propeller and digitizer to the rod (Figure 7). The Pygmy required special care so that it would not be damaged, but was easy to set up and use.

Figure 8. Pygmy meter attached to wading rod

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[5] USBR, (2001). *Water Measurement Manual.* <https://www.usbr.gov/tsc/techreferences/mands/wmm/index.htm> United States Department of the Interior Bureau of Reclamation, Washington, DC.

[6] Image from: *USGS Pygmy Current Meter*, Rickly Hydrological Co., Inc., Columbus, OH. 2019.

Description of Channels and Testing Procedures

Rectangular Channel

Each of the meters was first tested in the rectangular channel (Figure 9). The rectangular channel was the most controlled environment for testing, so the measurement error due to channel shape and hydraulic irregularities was minimized in this channel. The channel was consistently three feet in width.

Figure 9. Rectangular channel

The testing location was 11 feet in front of the flashboard canal structure (Figure 10). The water was the most uniform there and the water depth was adjustable using the flashboards.

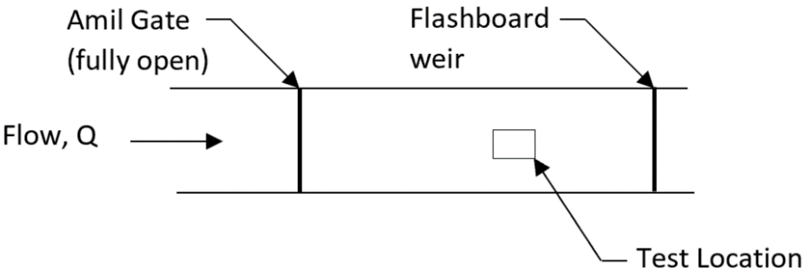

Figure 10. Rectangular channel (top view)

The control flow was measured using an Ultra Mag electromagnetic meter (Figure 11). It was located upstream of the testing location at the inlet of the channel. The control flow was recorded every ten seconds for one minute at the beginning and end of each test. It was also periodically checked throughout the test to make sure it was not fluctuating significantly.

It is also important to keep this pipe with the magnetic meter full. If the pipe was not full, then the mag meter could not read properly, and the control data would be incorrect.

Figure 11. Inlet pipe

For each meter, tests were conducted at three flow rates (0.7, 1, and 2 CFS nominal flows). The actual flow rate varied from the nominal since the control gate upstream could not set an exact flow. In general, the flows were within 10% of the nominal. All control results are based on actual flows measured in the magnetic meter at the head of the channel. At each flow rate, four water depths were tested by adjusting flashboards downstream of the testing facility. The actual depths were not exactly the same between each test because the flow rate over the downstream weir was not precise between each test. The rectangular channel testing depths were approximately 0.2’, 0.4’, 1’, and 1.5’.

Testing Procedure

1. Start at the testing location at the left bank of the channel.
2. Test one device at a time. Measure and record the velocity and the depth every half foot (Figure 12).
    a. When on the left bank the FlowTracker must be turned so that the sensor is facing away from the wall and the correction factor must be set to negative one (Figure 13).
    b. According to the *MACE XCi User Manual*, the AgriFlo and MantaRay only needed one measurement in the center of the channel (Figure 14).
        i. If the AgriFlo velocity range needs to be adjusted, follow these instructions: In order to set the velocity range correctly for the AgriFlo go to the “Configure channels” dialogue box, then click edit. An “Edit channel” dialogue box will appear. A general rule is to set the velocity range double of the average velocity of the stream.
        ii. If the AgriFlo depth sensor needs to be calibrated, follow these instructions: In order to manually set the depth sensor for the AgriFlo, go to the “Edit channel” dialogue box and click “2-point calibration”. The “Current value” is displayed at the top of the window. When the “Current value” has stabilized, click the “Set” button in the “1st point” box.

This enables the “Actual value” text box. Type the correct depth in the “Actual value” text box. This first test point should be the upper range limit. For the second point, use the lower range limit. Click on the “Set” button in the “2nd point” box. The “Current value” is copied to the “Measured value” and the “Actual value” box is enabled. Enter the actual depth into the “Actual value” box. Finally, click on the “Accept” button to calculate the new slope and offset parameter values for the associated channel. Note: the “Cancel” button erases the entire procedure.

Figure 12. Left bank, center, and right bank measurements

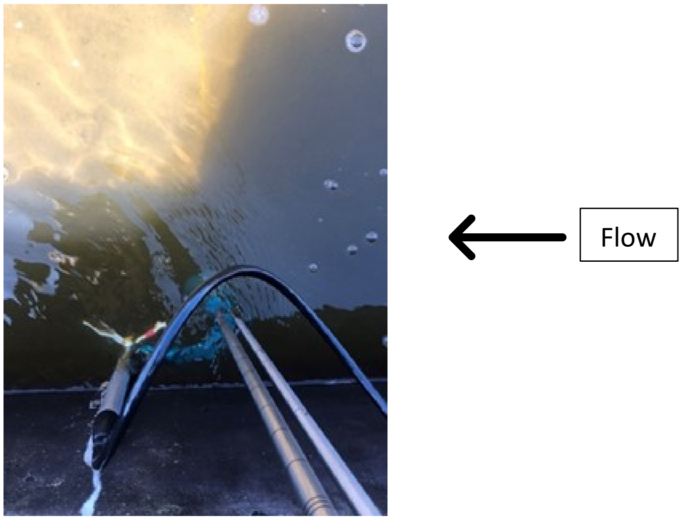

Figure 13. FlowTracker2 against left bank

Figure 14. AgriFlo (left) and MantaRay (right) measurement

3. Using the depths, velocities, and width calculate the measured flow rate using the equation Q=V*A.
4. Knowing the areas and the control flows, calculate the actual average cross-sectional velocities ("actual velocities") for each test using the same Q=V*A equation.
5. Compare the velocities of each of the instruments to the actual velocity.

Trapezoidal Channel, Concrete Channel, and Earthen Channel (IPF Channels)

In order to test low flows, closer to what may be seen in the field during the summer months, the group was tested at the Cal Poly ITRC Irrigation Practices Field (IPF) in the trapezoidal, concrete, and earthen channel. The trapezoidal channel was the most controlled, because it was the most uniform (Figure 15). The best location to test in the trapezoidal channel was about five feet in front of the rectangular weir because the channel was the most uniform there. Surveying equipment was used to get the most accurate profile of the channel (Figure 16). This was used to calculate the area.

Figure 15. Trapezoidal channel testing location

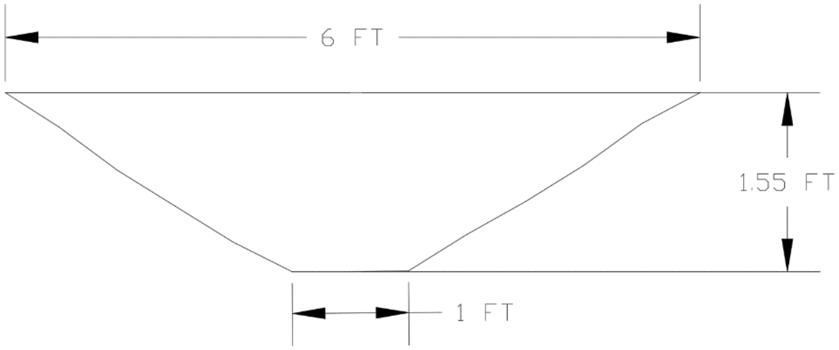

Figure 16. Trapezoidal channel cross section

The concrete channel was less uniform. It did not have a distinct shape (Figure 17). In the concrete channel the group tested the meters two feet in front of the rectangular flume. Figure 18 shows the surveyed cross-section of the channel. This cross-section was used with a meter stick to find the exact area of the flow.

Figure 17. Concrete channel testing location

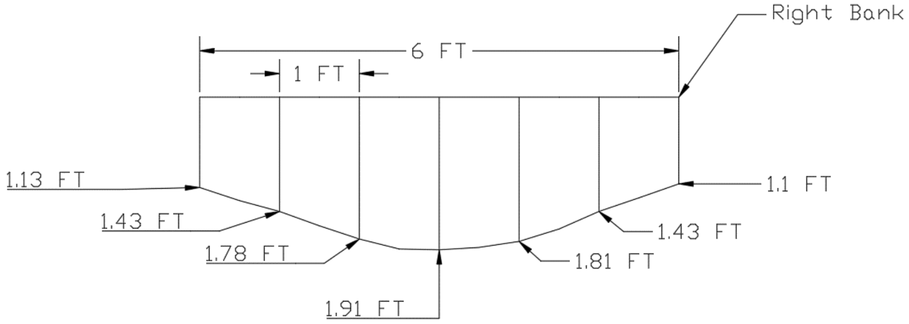

Figure 18. Rough concrete channel cross section showing relative bottom depths every 1 foot across the channel

The earthen channel was the least uniform (Figure 19). The cross-section (Figure 20) was used to find the cross-sectional area of the water flow for each flow.

Figure 19. Earthen channel testing location

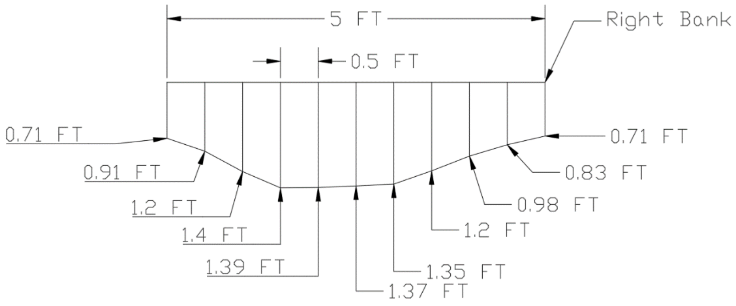

Figure 20. Earthen channel cross section showing relative depths (depth from arbitrary datum) every 0.5 ft across the channel

Each of these channels was connected, so they had the same inlet. The control flow rate was recorded from a McCrometer Ultra Mag UM006-06 during each test. The water was gravity fed into these channels. The flow was controlled by adjusting valves upstream of the channel's inlet. The Ultra Mag electromagnetic meter was located upstream of the channel on the inlet pipe. The pipe was kept full during the tests by maintaining a back pressure on the pipe of at least one bar. This was possible because there was a valve and a pressure gauge at the inlet to the channel.

The tests for the five meters in each of the three channels was similar. Four flow rates were tested at approximately 0.1, 0.2, 0.3, and 0.4 CFS. The Agriflo had several additional tests to confirm the high percent errors at the lower depths. The depths in each of the IPF channels could not be modified as they were in the rectangular channel testing. Typically, the depth was between 0.4-0.6 feet in the trapezoidal channel, 0.18-0.3 feet in the concrete channel, and 0.15-0.25 feet in the earthen channel.

Testing Procedures

1. Start at the right bank of the channel.
2. Measure the top width of the water.
3. Calculate the appropriate intervals between the velocity and depth measurements. For example, if the top width of the water was 2.85 feet, then take the velocity and depth measurement for the Pygmy, Hach, and FlowTracker2 every 0.48 feet.
    a. The measurements should be taken every 0.2-0.5 feet.
    b. AgriFlo and MantaRay would be taken directly in the center of the channel at 1.43 feet.
4. Test one device at a time. Measure and record the velocity and the depth at its appropriate location(s). Figure 21 shows the AgriFlo test in the center of the channel. Figure 22 shows the FlowTracker2 being tested in the earthen channel. This picture is of a measurement in the center of the channel, but to complete this test multiple measurements were taken across the profile.
5. Record the velocity and depths at each appropriate location according to instructions in the *MAC XCi User Manual*.
    a. If the AgriFlo velocity range needs to be adjusted, follow these instructions: In order to set the velocity range correctly for the AgriFlo go to the “Configure channels” dialogue box, then click edit. An “Edit channel” dialogue box will appear. A general rule is to set the velocity range double of the average velocity of the stream.
    b. If the AgriFlo depth sensor needs to be calibrated, follow these instructions: In order to manually set the depth sensor for the AgriFlo, go to the “Edit channel” dialogue box and click “2-point calibration”. The “Current value” is displayed at the top of the window. When the “Current value” has stabilized, click the “Set” button in the “1st point” box. This enables the “Actual value” text box. Type the correct depth in the “Actual value” text box. This first test point should be the upper range limit. For the second point, use the lower range limit. Click on the “Set” button in the “2nd point” box. The “Current value” is copied to the “Measured value” and the “Actual value” box is enabled. Enter the actual depth into the “Actual value” box. Finally, click on the “Accept” button to calculate the new slope and offset parameter values for the associated channel. Note: the “Cancel” button erases the entire procedure.

Figure 21. AgriFlo in rough concrete channel

Figure 22. FlowTracker2 testing in earthen channel

6. Using the cross section and the depths, find the cross-sectional area.
7. Find the device's measured flow by using the equation, Q=V*A.
8. Using the areas and the control flows, calculate the actual velocities for each flow.
9. Compare the velocities of each of the meters to the corresponding actual velocities.
10. Change the flow rate and repeat the test to get a larger sample.

Possible Sources of Error

Rectangular Channel

The rectangular channel was the most controlled channel, but there were still some potential sources of error. Some of the water was leaking through a small gate, as seen in Figure 23. This was occurring during all of the testing. Since the mag meter was measuring the flow upstream of the leak, it was not accounting for the minor loss of water. This means that downstream, where the testing was taking place, there was slightly less flow. The amount was very small (less than 5 GPM) so it would have had little effect on the data. Additionally, it was constant, so the percent error from this should be constant for all tests.

Figure 23. Gate leak

Another possible source of error was turbulence in the water. At 1 and 2 CFS with no boards, the hydraulics caused ripples in the water (Figure 24). The test was done in the furthest location as possible away from the drop. The ripples made it more difficult to manually measure the depth. However, under the same depth and velocity conditions, these ripples would be common in field settings. Therefore, the tests are consistent with those found in the field. The ripples would increase the uncertainty in depth measurements but would not have a significant impact on velocity.

Figure 24. Rectangular channel without flashboards (left) and with four flashboards (right)

Trapezoidal, Concrete, and Earthen Channel

The trapezoidal channel was less controlled than the rectangular channel because it was less uniform. The rectangular channel was consistently a three-ft wide rectangle (Figure 9), whereas the trapezoidal channel is not a true consistent trapezoid (Figure 15). At some parts of the channel the base was 1 ft wide and at other locations in the channel the base was 1.5 ft wide. It was also more difficult to get depth measurements with the devices, because there was a consistent slant on either side of the trapezoidal channel. This is because these rods have a round bottom that when placed on an uneven surface did not lay flat on the surface. This would contribute to uncertainty in the measured area during a current metering test. The actual/controlled area used for the actual velocity computation was measured using survey equipment that would negate most of these issues for the control.

Furthermore, the concrete channel is less uniform than the trapezoidal and rectangular channels. As seen in the left-hand photo in Figure 25, the channel causes more turbulence in the water because of its irregular shapes. This would impact the measured velocities taken from the meters.

The right-hand photo shows the earthen channel. This channel had the most possible sources of error. Since it was an earthen cross-section, area can fluctuate considerably from test to test. Soil and gravel can move around and changed the cross section of the channel. There was also vegetation that could have caused the velocities to vary during testing. The uncertainty in both the measured area and measured velocity will increase under these conditions.

Figure 25. Concrete channel (left) and earthen channel (right)

Velocity Results and Discussion

This section will show the testing results for each meter in all of the channels. More testing was conducted in the rectangular channel, so additional statistics are shown including a regression analysis of the actual cross-sectional average velocity compared to the measured. In general, there was an attempt to maintain consistent ranges on each graph axis for comparison. In several instances the percent error was very high, and the axis range had to be extended.

The first set of results will examine the measured velocity uncertainty. Percent error in the velocity measurements is computed as:

$$\text{Percent Error} = \frac{\text{Measured Velocity} - \text{Actual Velocity}}{\text{Actual Velocity}} \times 100$$

The percent error results will be compared against the actual velocity and depth (horizontal axis of different graphs for each meter). An increase or decrease in uncertainty at different depths and velocities can be assessed. The uncertainty is a quantifiable value wherein the percent error for the tests reside. Typically, it is not the ± percent error of all of the tests, but instead the tests that reside within either one or two standard deviations. In this report, the uncertainty will be discussed in relative terms utilizing all of the testing results for a meter under specific conditions. This study focused on a variety of conditions that impact the uncertainty. The results are presented so the reader can assess the meter type and conditions to best meet their needs.

A regression evaluation between measured and actual velocity is also conducted to determine relationship and potential bias. The relationship between the sampled and actual velocity is generally best represented by a power or logarithmic relationship[7,8]. At the very basic level, the velocity profile from the zero-slip boundary to the high velocity point is best represented by a power law relationship for flow resistance. For this reason, the power regression relationship was used for the evaluation in this study.

The regression equation could be used as a “correction” equation when consistent bias exists between the measured and actual velocities. This is commonly considered calibration and should generally be done in situ. However, in some cases an initial assessment or calibration may be conducted that will at least get the values to be close initially. The “corrected” percent error shown for some of the meters utilizes the correction equation (regression) to correct the measured velocity. If the regression analysis was not considered an important statistical parameter for a specific meter (no bias or adjustment needed), it is not shown.

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[7] Chen, C. L. (1991). "Unified theory on power laws for flow resistance." Journal of Hydraulic Engineering 117(3): 371-389.

[8] Cheng, N.-S. (2007). "Power-law index for velocity profiles in open channel flows." Advances in Water Resources 30(8): 1775-1784.

AgriFlo Velocity

Figure 26 shows the percent error between actual and measured velocities in the rectangular channel. The raw velocity was taken from the AgriFlo, which should lead to an overestimation in the velocity compared to the cross-sectional average if the velocity is not adjusted. However, the data shows that overall, the uncorrected velocity was consistently 10% above the cross-sectional average. This would indicate that the AgriFlo measured velocity is adjusted in the AgriFlo software to estimate the cross-sectional velocity. Figure 27 shows the regression equation for the measured and actual velocity and the corrected velocity error (using the regression equation). The corrected error shows considerably improved results with errors within ±10% for most tests (average corrected error of 3%). The results indicate that there is a limitation in the default settings of the AgriFlow software leading to an underestimation in flow and velocity within the rectangular channel.

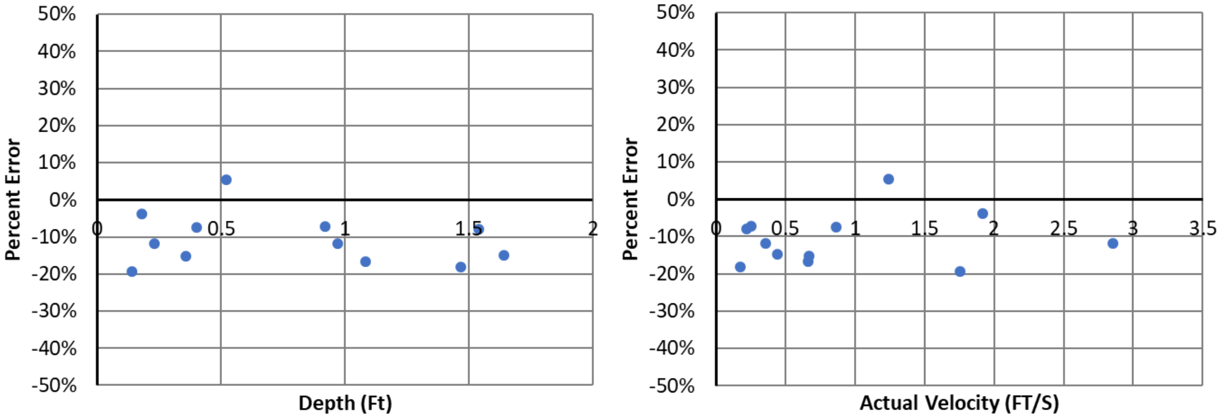

Figure 26. Percent error in measured AgriFlo velocity versus depth (left) and actual velocity (right)

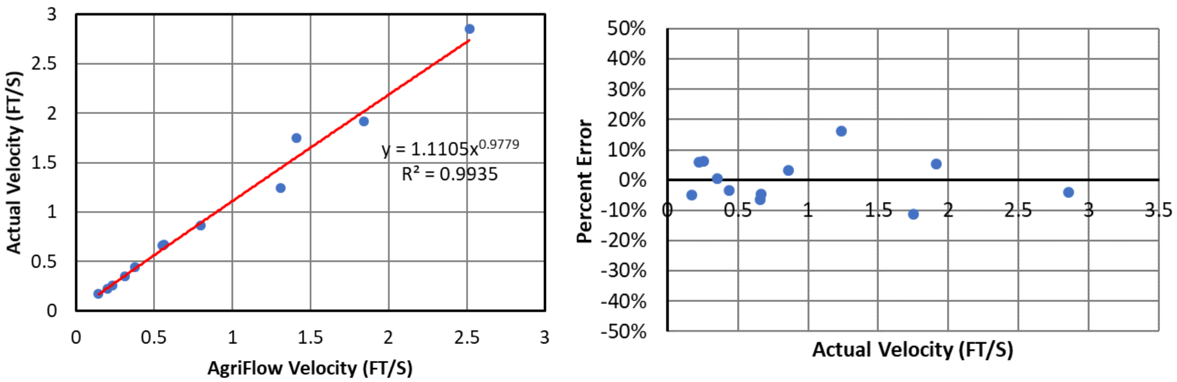

Figure 27. Actual velocity and AgriFlo velocity regression relationship (left) and percent error of measured AgriFlo velocity versus corrected actual velocity using the regression equation (right) in rectangular channel

Figure 28 shows the percent error versus velocity and the percent error versus depth in the three IPF channels (trapezoidal, concrete, and earthen). Take note that the percent error on the y-axis goes all the way to ±200% because of the larger percent errors. In the trapezoidal channel, the AgriFlo velocity measurements were relatively consistent ranging from plus or minus 0 to 20% error (Figure 28), similar to the uncorrected results in the rectangular channel. The regression equation was not used in the other channels. However, the AgriFlo velocity measurements at the concrete and earthen parts of the IPF channel had a high level of uncertainty. The percent errors in the concrete channel varied from 20% to 182%. In the earthen channel the velocity measurement percent errors were -47% to – 56%.

In these channels, the highest uncertainty occurred at the lower depths (below 0.3 feet). This is not unexpected since the sensor and mount are approximately 0.1 feet from the bottom of the channel. Therefore, there is insufficient depth to obtain an accurate reading. It is unclear why the concrete channel had such a significantly high level of uncertainty compared to the other two channels.

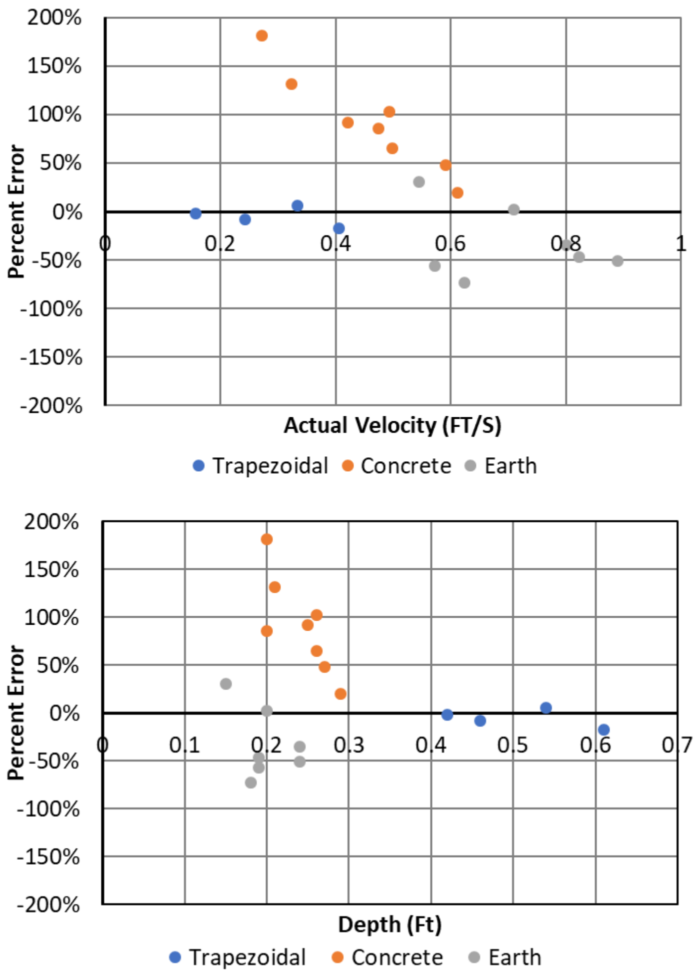

Figure 28. IPF channel results showing percent error in measured AgriFlo velocity compared to actual velocity (top) and flow depth (bottom)

FlowTracker2 Velocity

The percent error between the measured and actual cross-sectional velocities for the rectangular channel are shown in Figure 29. The data showed that at each of the tests with no boards (low depth and higher velocities) had percent errors closer to ±10%. One of the sources of this error could have been the increased turbulence in the water at those low depths. The percent error versus velocity measurement graph shows the FlowTracker's measured velocities had less uncertainty when velocities were 0.25 feet per second to 1.5 feet per second. When the velocity went below 0.25 feet per second or above 1.5 feet per second there were slight increases in uncertainty. The number of tests outside of these bounds are limited so for this particular set of tests these should be considered observations. Overall the uncertainty was relatively low for the FT2 in the rectangular channel.

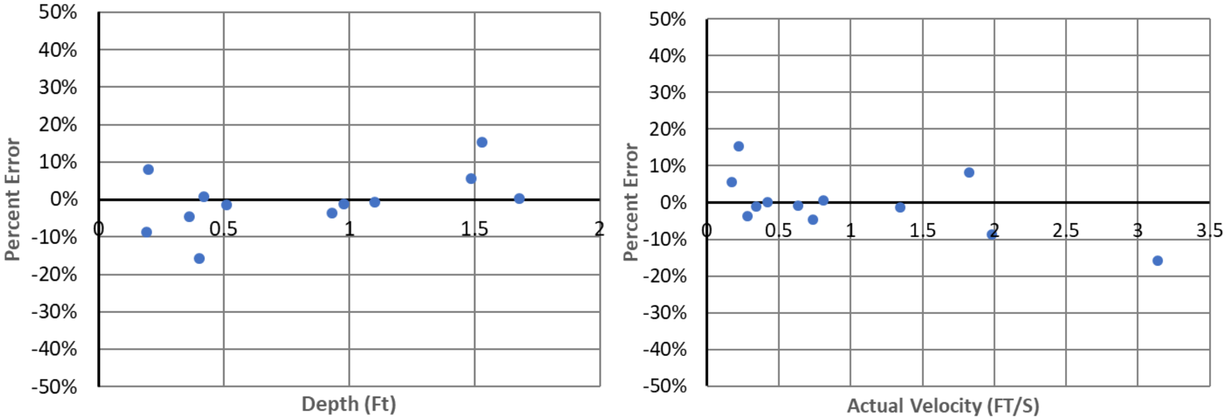

Figure 29. Percent error for measured FT2 velocity versus depth (left) and actual velocity (right)

The FlowTracker2 velocity measurements at the trapezoidal channel had percent errors ranging from 16% to -16%, higher than the level of uncertainty as the rectangular measurements. At the concrete channel the percent errors of the measured velocities ranged from 14% to 38%. At the earthen channel the percent errors of the measured velocities ranged from 29% to 81%.

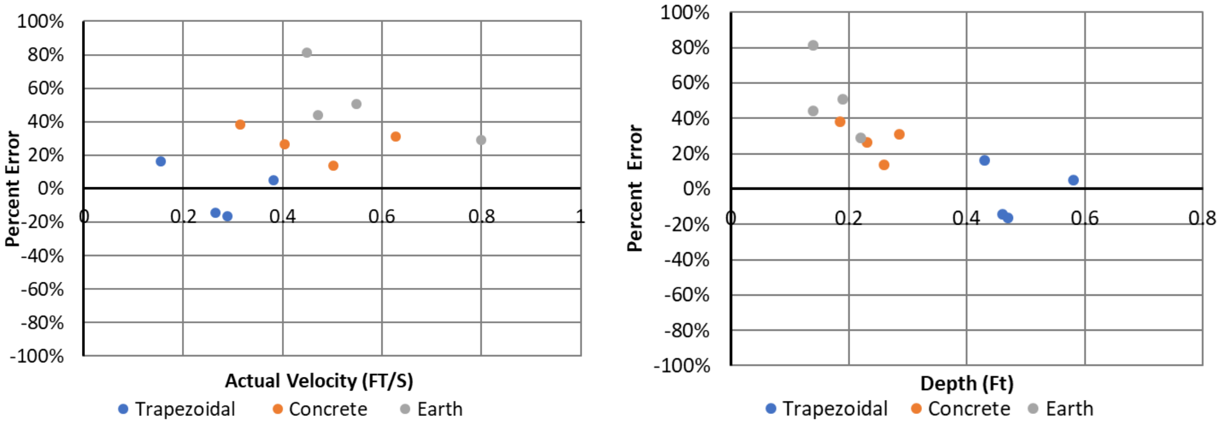

Figure 30. Percent error for measured FT2 velocity compared to actual velocity (left) and flow depth (right) for the three channels

As the depth dropped below 0.3 feet in the three channels shown in Figure 30, the uncertainty increased. It is difficult to position the FlowTracker within the shallow flow. If the operator is off on the angle of the device even slightly the beams hit the channel bottom or the water surface. The higher depths in the trapezoidal channel were still relatively shallow. Examining the deeper flows (greater than 0.6 feet) in the rectangular channel indicates less uncertainty with FlowTracker2 measurements. Keep in mind that the depth measurement is not the cause of the uncertainty, obtaining an accurate velocity reading at the low depth is the issue.

MantaRay Velocity

The MantaRay results from the rectangular channel are shown in Figure 31. The regression analysis and corrected velocity error analysis are shown in Figure 32.

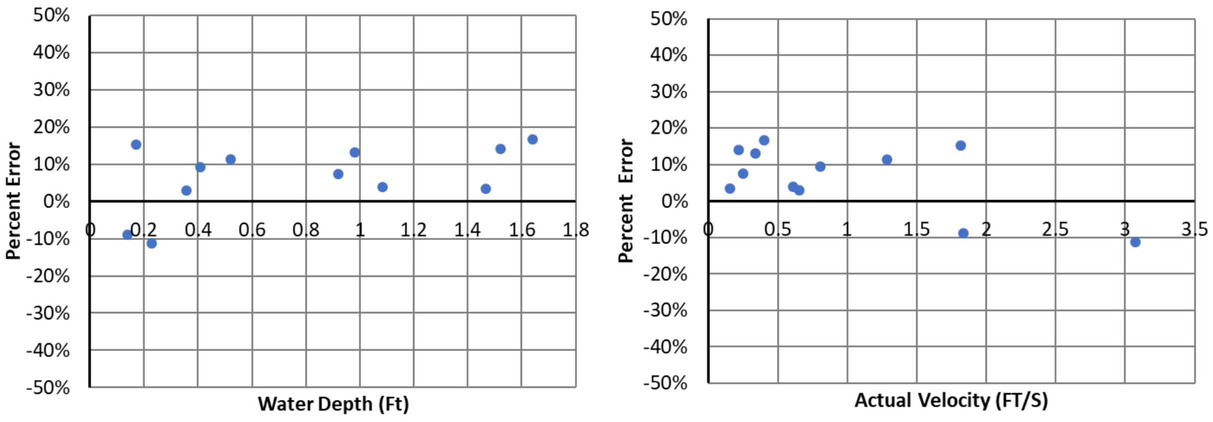

Figure 31. Rectangular channel percent error of measured MantaRay velocity compared to depth (left) and actual velocity (right)

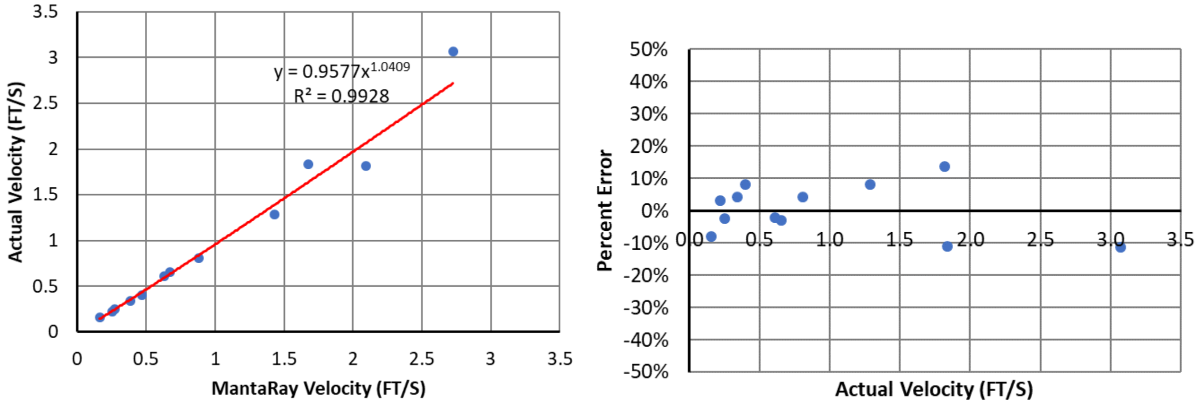

Figure 32. Regression analysis for data from the rectangular channel comparing actual velocity to MantaRay measured velocity (left) and percent error of measured MantaRay velocity versus the regression corrected actual velocity (right)

The MantaRay velocity measurements had a percent error around -11 to 17% above the actual velocity in the rectangular channel. The graphs show the percent error of the MantaRay velocity measurements from 0 to 3.5 feet per second. The percent error was negative at the higher velocities; this correlates with the tests at low depths. The average uncertainty was improved from a positive (overestimation in velocity) of 6% to 0% with the linear regression equation. The uncorrected over-estimation was expected since the MantaRay is placed in the center of the channel where the highest velocity is found. The variation is still higher than expected in the rectangular channel (-16 to 18%)

The MantaRay's velocity measurements at all three of the channels at the IPF showed substantial error and uncertainty (Figure 33). The percent errors at the trapezoidal channel ranged from -69% to 60%. The percent errors at the concrete channel ranged from -57% to 91%. Finally, the percent errors at the earthen channel ranged from -55% to 77%.

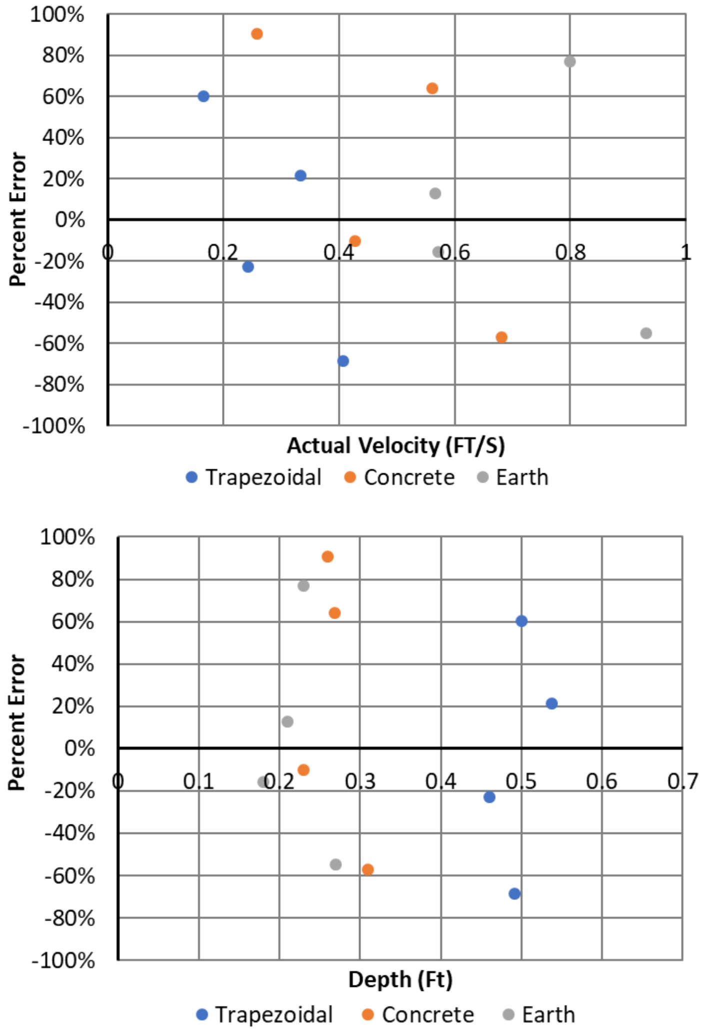

Figure 33. Percent error for the measured MantaRay velocity in the three channels at the IPF compared to actual velocity (top) and flow depth (bottom)

Hach Velocity

The Hach electromagnetic flow meter results from the rectangular channel are shown in Figure 34. The regression analysis and percent error using regression “corrected velocities” are shown in Figure 35.

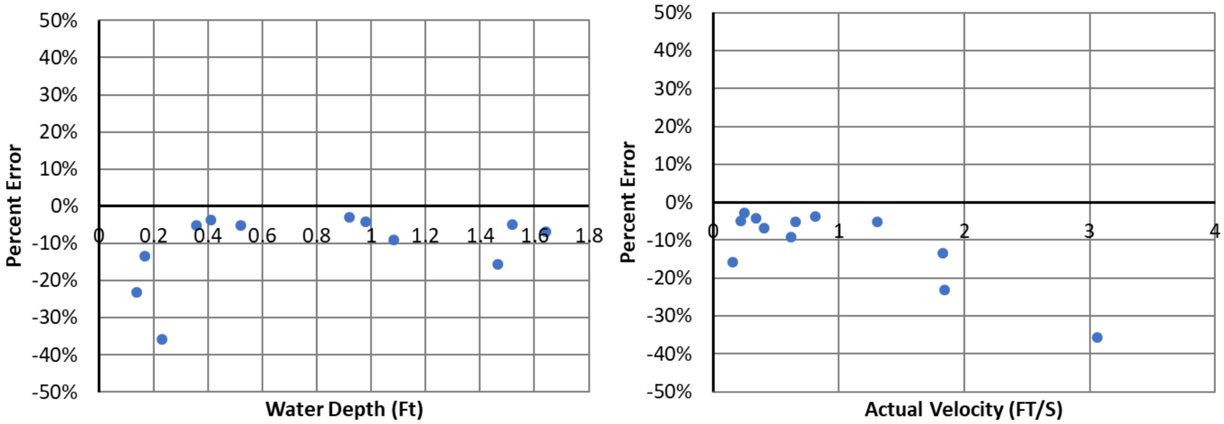

Figure 34. Percent error for the measured Hach meter in the rectangular channel tests compared to water depth (left) and actual velocity (right)

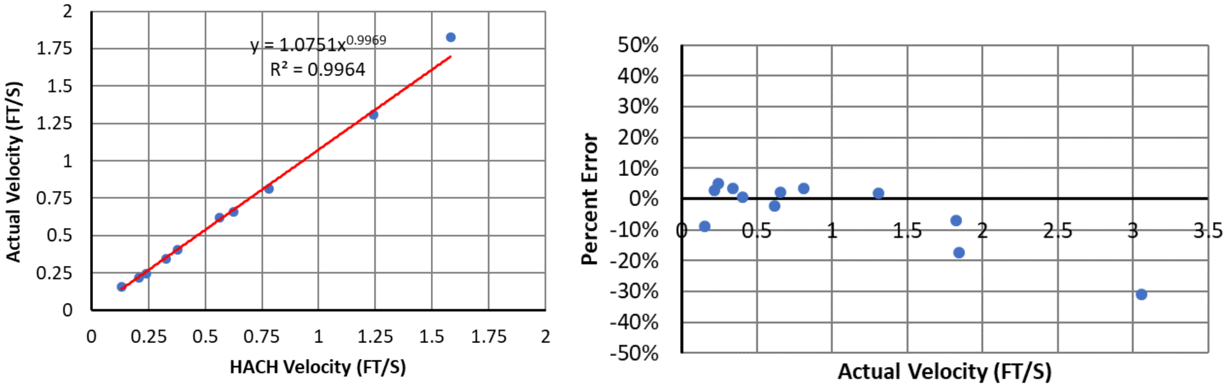

Figure 35. Regression analysis using the Hach actual velocity data versus measured velocities in the rectangular channel (left) and the percent error of the measured Hach velocity versus the actual “corrected” Hach velocities

The uncorrected Hach velocity measurements in the rectangular channel had percent errors ranging from 0 to -10% at water depths above 0.25 feet. At low water depths the Hach had larger percent errors of -23%, -36%, and -13%. This larger percent errors are likely due to turbulence in the water and insufficient flows going around the meter at the low depths.

The bias in velocities is evident in the data and the regression curve. The regression analysis excluded two of the major outliers at the low depths. The corrected errors stayed within ±10% other than for the low depth outliers in the for the rectangular channel.

The Hach meter performed better than the other meters tested in the trapezoidal, concrete, and earthen channels (Figure 36). The velocity measurements at the trapezoidal channel were within ±10% of the actual velocities. The velocity measurements were slightly more accurate at the concrete channel with percent errors of ±8%. The velocity measurements at the earthen channel were relatively accurate for a variable cross section. The Hach's velocity measurements at the earthen channel had percent errors of ±17%.

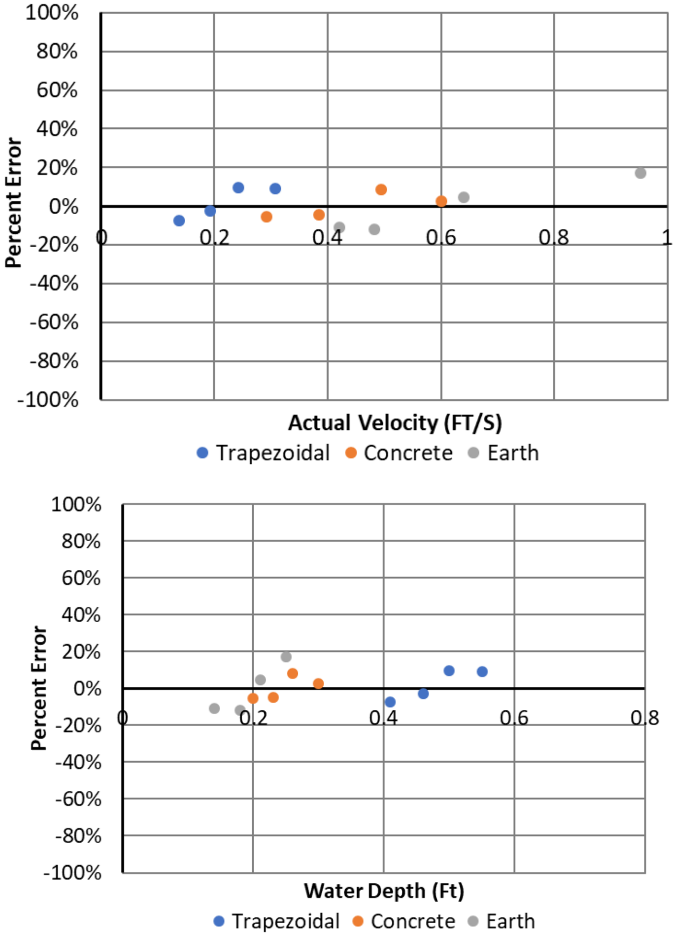

Figure 36. Velocity measurement percent error for measured Hach velocities in the three channels at the IPF compared to actual velocity (top) and water depth (bottom)

Pygmy Velocity

During the rectangular channel testing the Pygmy meter was not working or would show unreliable data. Therefore, no results are available for that channel. The meter itself was eventually replaced as well as the digitizer. Even with the new Pygmy meter, there were still some difficulties getting the correct readings.

The Pygmy meter results in the IPF channels were mixed (Figure 37). The percent error for the velocity measurements at the trapezoidal channel ranged from -41% to 11%. The percent errors at the concrete channel ranged from -12% to 41%. The percent errors at the earthen channel were between -4% and 29%. There did not seem to be a direct cause for the uncertainty.

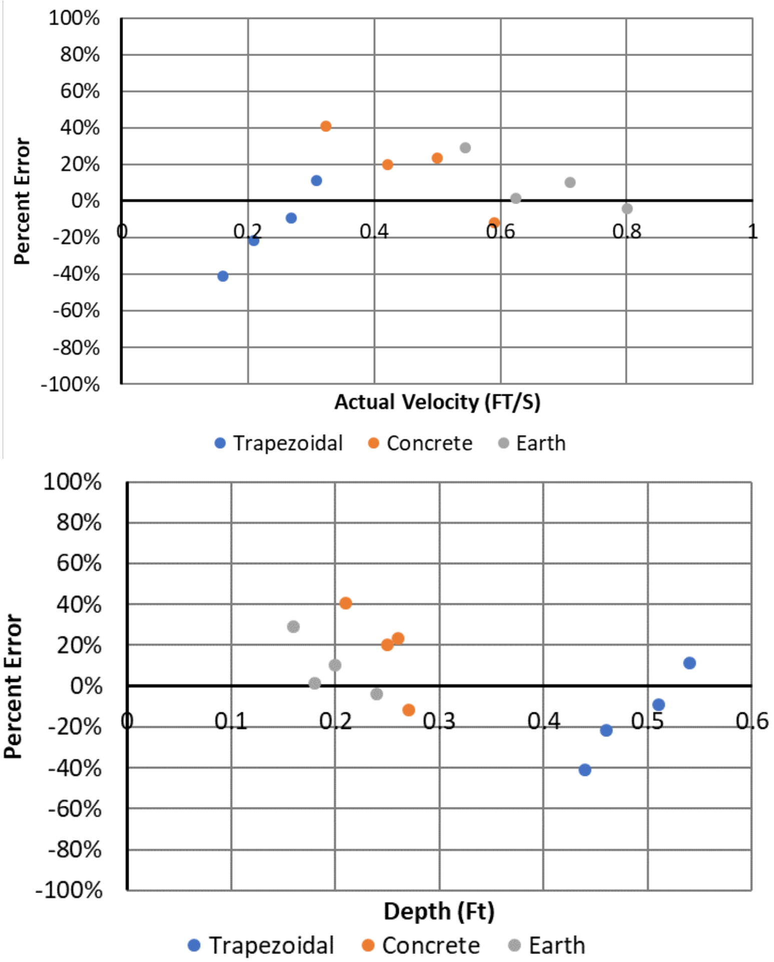

Figure 37. IPF channel results for the measured Pygmy velocities versus actual velocity (top) and versus depth (bottom)

Depth and Area Results

Having a flow meter that measures velocity with a low uncertainty is only one part of an accurate flow measurement. The meter (or user) also must have some way of calculating area. Most flow meters used for streams or canals have a measuring rod like those seen in Figure 4 and Figure 8. This requires the operator to read the depth of the water from the rod and log it in the device. Some flow meters such as the AgriFlo, MantaRay, and as an option on the FlowTracker2, have a sensor that measures the depth. Since the depth measurement affects the area and therefore the flow measurement, the uncertainty of the depth/area measurements on these devices was evaluated. Surveying equipment and meter stick depth measurements were used as the control.

The area was computed for the tests (control and measurements) in AutoCAD 2019. The channel was surveyed (laser level and rod), the bottom topography was input into AutoCAD (2D cross section), and a benchmark reference was set. The actual measured depths at each measurement location, using a meter stick (in millimeters then converted to feet), was input onto the AutoCAD bottom for the control. The wading rod depths at each measurement location for the current metering devices were input into AutoCAD to develop the area. For the AgriFlo and MantaRay, a single depth from the meter at the single measurement location was used with the survey cross section to develop the measured area. A meter stick was used at the same location to develop the control area. For all measurements (control and tests) the surveyed cross section was used in combination with the measured depths to develop the areas. In general, the uncertainty in area will be the uncertainty in measuring water depth, not necessarily the channel cross section since the cross section was surveyed. In practice, a cross section may not be surveyed in detail, which could contribute to flow measurement error. The goal in this study was to assess the accuracy in depth measurement using the tools that would be used in the field. A separate study could be conducted examining the error in overall measured area.

The FlowTracker2, Hach, and Pygmy used a wading rod to measure depths. Even though the FlowTracker2, Hach, and Pygmy all use a similar wading rod, their depth measurements had different ranges of percent error. This is because there was so much variability in these measurements. The rod only had measurement markings every tenth of a foot, so there was much room for error in interpolation, especially with turbulence in the water. Another source of error was the velocity head. When there were higher velocities the velocity head would cause the depth measurements to read high because of runup on the upstream side of the rod and the depression on the downstream side of the rod. Although the average depth between the runup and the depression was visually estimated for each depth measurement as is standard practice, this visual estimation invariably introduces some error. The base of the rod may also contribute to flow measurement error in low depth conditions. Some rods have a large base that could obstruct flow. In undulating cross sections, it may also create problems when trying to obtain an accurate depth measurement.

The percent error in depth measurements shown in this section is the difference between the average actual flow area and the average measured flow area. The measured flow area was computed using individual depth measurements at each flow measurement location. These depths were brought into AutoCAD 2019 and overlaid on the cross-section survey information to compute the area. This method ends up weighting errors in individual measurements by depth (shallower depth in the cross section is weighted less because it has a lower impact on area). As previously described, although area is utilized the results are due to depth uncertainty and all results are presented as percent error of average measured depths versus actual depths.

AgriFlo

Of the five meters tested, the AgriFlo was the most precise and accurate device for measuring depth (Figure 38). This was because the sensor eliminated the human error of reading the depth. Keep in mind that this depth sensor had to be calibrated during the initial testing (only once during the entire testing period). The average percent error in area at the trapezoidal channel was -1 %, with a range of ±10%. The average percent error at the concrete and earthen channel was only -2%. The range of percent errors at the concrete channel was ±13% with one outlier at -26%. The range of the percent errors at the earthen channel was ±11%. Uncertainty increased at shallower flows.

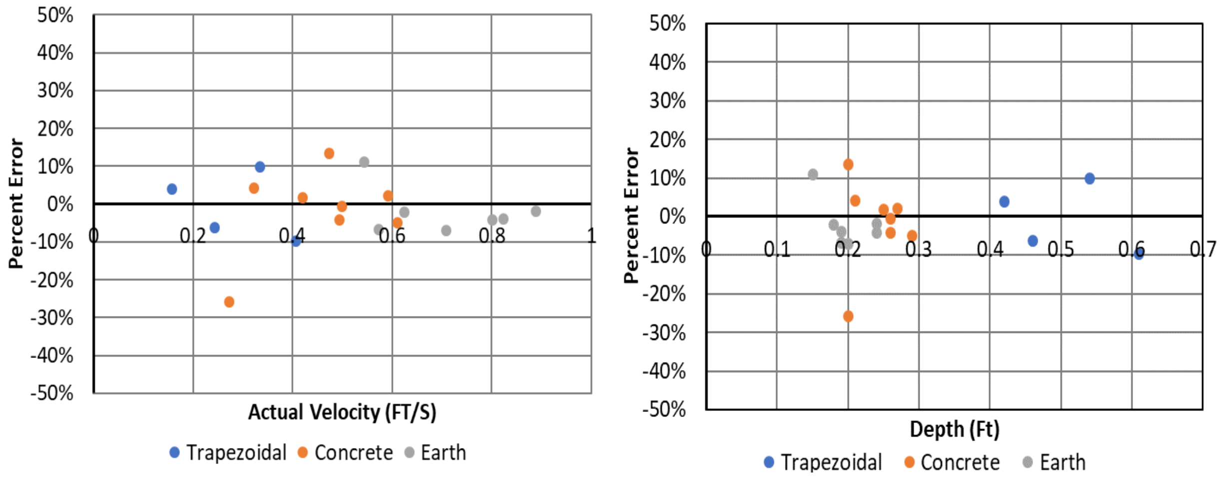

Figure 38. Percent error in average measured depth with the AgriFlo in the three IPF channels compared to actual velocity (left) and the average actual channel depth (right)

FlowTracker2

The average percent error of the area measurement for the FlowTracker2 at the trapezoidal channel was -9% with a 4% range. The average percent error at the concrete channel was -8% with a 16% range. The average percent error at the earthen channel was 0% with a 14% range.

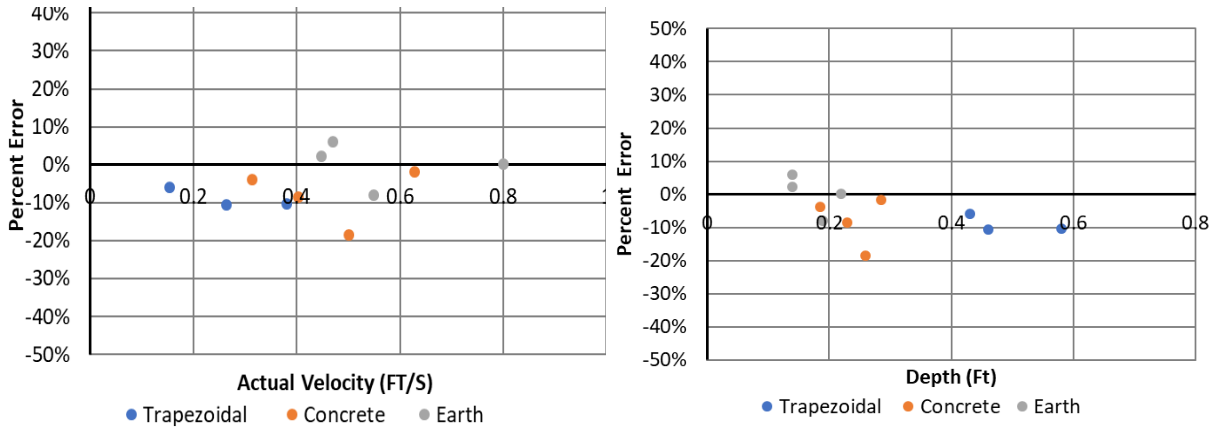

Figure 39. Percent error in average measured depth using the FlowTracker2 wading rod compared to actual velocity (left) and the average actual channel depth (right)

MantaRay

There is no data for the MantaRay depth measurements, because it was not reading correctly. The solution could not be determined during the project timeframe. Velocity measurements were directly read from the meter (no need for depth measurements for the previous portion of the study).

Hach

The Hach also had a wading rod as its depth measuring device. The measured area was more precise at the trapezoidal channel, but not the most accurate out of the three channel measurements. The average percent error at the trapezoidal channel was -10% with a range of -4 to -15%. The average percent error at the concrete channel was -12% with a range of -3 to -18%. The average percent error at the earthen channel was -2% with a range of -17 to 23%. The depth measurement at the earthen channel was the least precise although the 23% uncertainty seemed to be an outlier likely due to the shallow depth that is difficult to measure in an earthen channel.

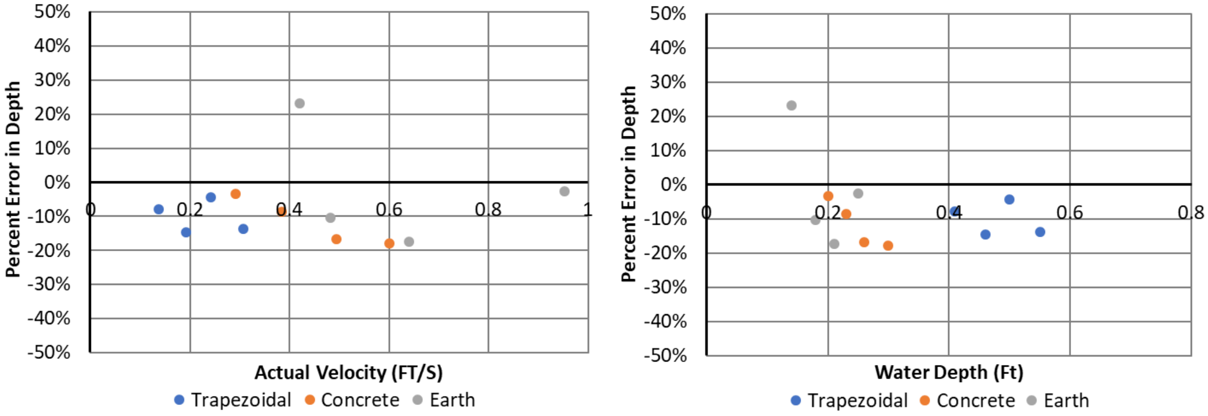

Figure 40. Percent error in average measured depth with the Hach wading rod in the three IPF channels compared to actual velocity (left) and the average actual channel depth (right)

Pygmy

The Pygmy meter also had the wading rod as the depth measuring device and got similar results as the Hach and the FlowTracker2. The average percent error was -11% at the trapezoidal channel with a -9% to -11% range. The average percent error was -7% at the concrete channel with a range of -3 to -10%. The average percent error was -4% at the earthen channel with a -1 to -8% range.

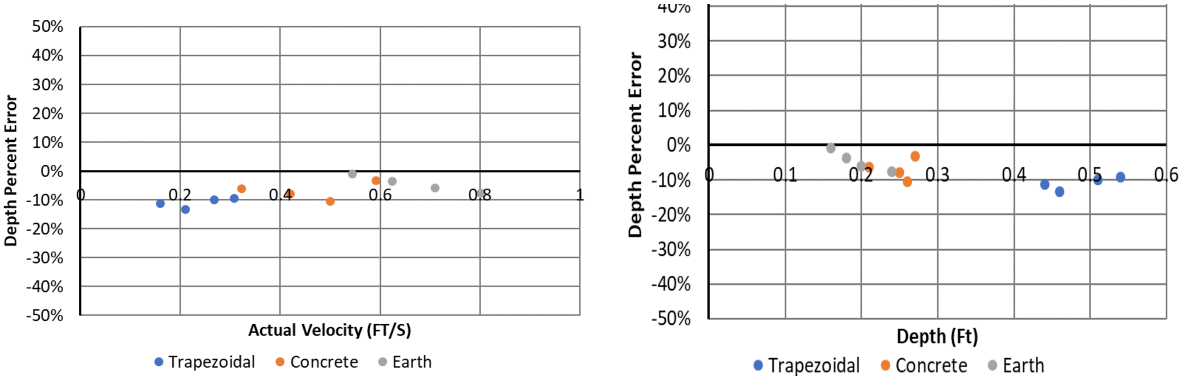

Figure 41. Percent error in average measured depth for the Pygmy meter wading rod readings compared to actual velocity (left) and the average actual channel depth (right)

Summary

Overall, all the meters preformed relatively well in the highly controlled rectangular channel. The FlowTracker2, AgriFlo (corrected), and the Hach had a high level of performance in the rectangular channel. The AgriFlo and the MantaRay, after initial calibration, performed well in the rectangular channel on average although they had a larger overall variability. The Pygmy meter was not tested in the rectangular channel. A summary of the testing results can be found in Table 1.

Table 1. Summary of percent errors (of measured velocity versus actual velocity) for each meter in each channel tested

Channel	Description	AgriFlo	FlowTracker2	Hach	MantaRay	Pygmy
Rectangular Channel (uncorrected)	**Mean Error**	**-11%**	**-1%**	**-11%**	**6%**	
	Max. Error	5%	15%	-3%	17%	
	Min. Error	-19%	-16%	-36%	-11%	
Rectangular Channel (corrected)	**Mean Error**	**0%**		**-4%**	**0%**	
	Max. Error	16%		5%	14%	
	Min. Error	-11%		-31%	-11%	
Trapezoidal Channel (uncorrected)	**Mean Error**	**-5%**	**-2%**	**2%**	**-2%**	**-15%**
	Max. Error	6%	16%	10%	60%	11%
	Min. Error	-18%	-16%	-7%	-69%	-41%
Concrete Channel (uncorrected)	**Mean Error**	**91%**	**27%**	**0%**	**22%**	**18%**
	Max. Error	182%	38%	8%	91%	41%
	Min. Error	20%	14%	-5%	-57%	-12%
Earth Channel (uncorrected)	**Mean Error**	**-33%**	**51%**	**0%**	**5%**	**9%**
	Max. Error	31%	81%	17%	77%	29%
	Min. Error	-73%	29%	-12%	-55%	-4%

Taking a closer look at the FlowTracker2 and the Hach data, both had larger percent errors at low depths (depths below 0.3 feet). The main reason for this larger percent error (above ±10%) was the turbulence in the water and the small sampling area at these low depths. Additionally, the hydraulics were causing a wave effect in the water, which made the depth difficult to read. Both devices had anomalies at deeper depths where the percent error was an outlier for one reading. It is unknown why this occurred and should not be weighted heavily when deciding which meter to utilize.

The results from the IPF testing (trapezoidal, concrete, and earthen channels) showed that the Hach outperformed the other meters overall. It was the most consistent and accurate in the trapezoidal, earthen, and concrete channels, even at depths below 0.3 feet. The FlowTracker2 performed well in the trapezoidal channel but not in the concrete or earthen channels, which tended to have shallower flows (less than 0.3 feet). This is because the FlowTracker's sensor was difficult to place and orient in the shallow flows. The AgriFlo also did not perform well at the shallow depths in the concrete and earthen channels. It consistently measured high in the concrete channel and low in the earthen channel. It did perform well in the deeper trapezoidal channel. MantaRay and the Pygmy were inconsistent in measuring the correct velocities in all three IPF channels. This can be seen in their larger spreads in Table 1.

Since flow rate is determined by the velocity multiplied by the area, it is important to consider the area measurements for each of the meters. The meters do this by measuring the depth of the water. The AgriFlo's pressure transducer depth measured was very accurate and took out some of the potential for human error. After manually calibrating the AgriFlo depth measurements, the calculated AgriFlo area was within ±10% of the actual area. None of the meters that used the wading rods were extremely consistent, because of the relatively large gradation on the rods (0.1 feet). At shallow depths, errors in interpretation of the reading between 0.1 foot marks can have a substantial effect (percent error) on the depth measurement. The wading rod measurements were within ±20% even in the earth and concrete channels.

In conclusion, the Hach was the best meter for low flow and low depth measurements. It also did well with flow rates up to 2 CFS. It measured precisely in all the channels. It was reliable and easy to use. It consisted of a wading rod, sensor, and a portable display. It was easy to carry it into the field and record measurements.

Recommendations

While the Hach meter seemed to perform well under shallow flow conditions (less than 0.3 feet), overall it is recommended that a minimum depth of 0.3 feet be used for metering. Ideally, a minimum depth of 0.5 feet should be targeted if other devices are used. If the depth is greater than 0.3 feet, the FlowTracker2 and AgriFlo performed well in this testing (rectangular and trapezoidal channels). The Pygmy meter has been used for many years in current metering. However, it is not recommended in shallow conditions (below 0.5 feet) as were tested here.

The MantaRay and AgriFlo are not currently designed to be used as portable meters, as they were used for this study. However, the AgriFlo acoustic velocity meter and pressure transducer depth sensor preformed relatively well. It is recommended that In-Situ work to create a portable readout unit that can be used with the flow sensor.

Maintaining a constant, consistent cross section is imperative if accurate flow measurement is desired. With a consistent concrete cross section (rectangular and trapezoidal), the area uncertainty becomes a smaller component of the overall uncertainty. In natural channels, especially with the shallower flows, inaccuracies in depth measurements and cross-sectional area errors have a major impact on flow uncertainty. It may be difficult or impossible to line a section of a natural channel. However, if it is possible to modify a channel section using rocks laid as flat and consistently as possible, this would be a major improvement over earthen channels. If possible, the modified cross section should be a slight contraction of the channel although not enough to create a standing wave (keep the Froude number[9] below 0.4). The contraction maintains a consistent, easy-to-measure cross section, and it helps maintain a uniform velocity profile (it will not increase the depth). It should be wide enough to take measurements with the device of choice. If the depth is not consistently higher than 0.3-0.5 feet, rocks should be placed downstream to back the water up in the cross section.

Figure 42 shows an example of a channel with a rock cross section for flow measurement. This is a very large channel but can be scaled down. Ideally in a smaller channel the rocks should either be flat in the cross section to give an accurate, easy-to-measure cross sectional area or smaller rocks can be used to create a relatively flat surface. The sides should be vertical if possible or at a consistent, easy-to-measure slope (e.g., 1:1).

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[9] Froude number (F) for a rectangular channel is $F = V/(gD)^{0.5}$ where V is the velocity, g is gravitational acceleration, and D is the water depth. One maintains a lower Froude number by decreasing the velocity or increasing the depth. The key for the contraction is to not contract the channel too much or it will increase the velocity too much.

Figure 42. An example of a cross section made of rocks in a large channel; the rocks look small but can be seen in patches out of the shallow water

There are also several portable/temporary steel and aluminum flumes that could be installed (Figure 43). If installed correctly, these would be more accurate than the portable electronic flow meters tested. The difficulty is installing these correctly and in a condition that would allow them to be used over the full range of flows in the streams and creeks.

Figure 43. Portable Replogle/ramp flumes used for very accurate flow measurement