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Laboratory Evaluation of Open Channel Area-Velocity Flow Meters

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Irrigation project managers are often seeking low-cost methods for accurately measuring irrigation deliveries. Area-velocity flow meters are frequently an attractive option because they create minimal head loss, are easily installed, provide SCADA-compatible outputs, and can be applied to a wide variety of flow situations. Typically, these types of flow meters are available commercially from around $2,000 to $18,000, depending on the degree of sophistication and technology used to obtain depth and velocity measurements. Often when irrigation project managers select a meter, both equipment and calibration costs can become limiting factors. This paper discusses the results from a series of controlled laboratory tests in which nine area-velocity flow meters were evaluated against a known discharge to determine accuracy and to document ease of use for the hardware and software. Each of the nine meters was individually tested in three open channels including; a 1.5-ft-wide trapezoidal, a 4-ft-wide rectangular and an 18-in-diameter circular channel. Comparisons between laboratory and instrument measured depths, calculated velocities and discharges vary widely between the tested meters.

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Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Introduction and Purpose

Area-velocity flow meters are frequently used by irrigation project managers to measure flow in irrigation systems. In general, these meters are attractive because they create minimal head loss, are easily installed, provide SCADA-compatible outputs, and can be applied to a wide variety of flow situations. Many manufacturers offer meters priced from around $2,000 to $18,000 that are targeted towards irrigation projects. Often, when irrigation project managers select a meter, both equipment and calibration costs can become limiting factors. To better understand many of the different area-velocity meters the Bureau of Reclamation (Reclamation) tested nine meters from seven manufacturers. Each meter was evaluated based on its ease of use and accuracy.

Most area-velocity flow meters measure water velocity, depth and temperature then compute a flow rate by multiplying the calculated average velocity by the cross sectional area of the flow. Each meter calculates the average channel velocity from sensed velocity measured by the meter in one of three ways; incoherent (continuous) Doppler, coherent (profiling) Doppler, or electromagnetics, as described below.

Incoherent or continuous Doppler: emit a constant acoustic signal and detects returns from scatterers (particles, air, bubbles, etc.) in the passing fluid. The Doppler shift from acoustic reflections off the scatterers is used to determine an average channel velocity (Vermeyen 2000).

Coherent Doppler: Emit encoded pulses along multiple beams which target specific scatterers at varying depths or times.

Non-Profiling: The Doppler shift from acoustic reflections off the scatterers is used to determine a velocity from targets over a fixed distance. Velocity histograms from the returns are created and then used to determine the average channel velocity.

Profiling: The Doppler shift from acoustic reflections off the scatterers is used to determine a velocity in cells of specified depth and size. Velocity profiles are created and used to determine the average channel velocity.

Electromagnetic: water moving through a magnetic field produces a voltage (Faraday’s law) which is directly proportional to the velocity of the water. The higher the velocity, the greater voltage created. The measured voltage is used to determine the velocity at the sensor, which is used to estimate the average channel velocity based on theoretical velocity profiles.

Depth measurements are obtained by either a separate ultrasonic sensor or an integrated pressure transducer. Some of the meters utilize both of these technologies. Flow is calculated using a stage-area relationship that is pre-programmed into each of the meters using manufacturer specific software.

Table 1 provides a list of each of the tested meters and their respective velocity method and accuracy specifications. Table 2 lists each of the tested meters and its respective depth method and accuracy specifications. Table 3 summarizes each meter's approximate equipment and software costs along with the types of channels that are supported by the meter. Please note that costs change regularly, refer to individual manufacturers for current pricing information.

Table 1 - List of each meter's manufacturer velocity specifications

Velocity				
Manufacturer	Model	Method	Range (ft/sec)	Accuracy
Greyline	AVFM 5.0 w/Logger	Incoherent Doppler	-5 to +20	±2% of reading
Hach	Sigma 910	Incoherent Doppler	-5 to +20	±2% of reading
Hach	Flo-Tote 3 w/FL900	Electromagnetic	-5 to +20	±2% of reading
ISCO	2150	Incoherent Doppler	-5 to +20	(-5-5 ft/s ±0.1 ft/s) (5-20 ft/s ±2% of reading)
MACE	Agriflo3	Incoherent Doppler	±0.08 to 26	±1% up to 10 ft/sec
Mainstream	Mainstream Portable	Coherent Doppler (NP)	±0.03 to 16	±2% of reading or ±0.2% full scale
Nivus	PCM Pro	Coherent Doppler (P)	-3.28 to +19.7	1%
SonTek	Argonaut-SW	Coherent Doppler (P)	± 16	1% value
SonTek	IQ	Coherent Doppler (P)	± 16	1% value (0.2in/s)

NP = non-profiling P = profiling

Table 2 - List of each meter's manufacturer depth specifications

Depth				
Manufacturer	Model	Method	Range (ft)	Accuracy
Greyline	AVFM 5.0 w/Logger	Pressure Transducer	15	±0.25% full scale
Hach	Sigma 910	Pressure Transducer	10 or 30	±0.25% full scale or ±2.1% reading
Hach	Flo-Tote 3 w/FL900	Pressure Transducer	11.5	±1.0% of reading
ISCO	2150	Pressure Transducer	34	±0.01 ft
MACE	Agriflo3	Pressure Transducer	13	1% Full Scale
Mainstream	Mainstream Portable	Pressure Transducer	7	±0.25% full scale
Nivus	PCM Pro	Pressure Transducer	11.5	0.5% value
SonTek	Argonaut-SW	Ultrasonic	16	0.1% value
SonTek	IQ	Ultrasonic & Pressure Trans.	5 or 16	0.1% or 0.01 ft

Table 3 - List of each meter's manufacturer depth specifications

Manufacturer	Model	Approx. Cost	Required Software	Channel Shapes
Greyline	AVFM 5.0 w/Logger	$3,470.00	Included	Round, Rectangular, Trapezoid, Egg or Custom
Hach	Sigma 910	$4,000.00	Costs Extra	Any
Hach	Flo-Tote 3 w/FL900	$4,110.00	Costs Extra	Any
ISCO	2150	$3,895.00	Costs Extra	Round, U, Rectangluar, Traezoidal, Elliptical, with Silt Correction
MACE	Agriflo3	$4,000.00	Included	Any
Mainstream	Mainstream Portable	$5,000.00	Included	Round, U, Rectangular, Trapezoial, Oval, Rec w/Semi Circular, Mixed
Nivus	PCM Pro	$12,000.00	Costs Extra	Any
SonTek	Argonaut-SW	$6,980	Included	Any
SonTek	IQ	$6000-8500	Included	Trapezoid, Irregular Open Channel, Trapezoidal Conduit

Test Facility & Setup

Testing was conducted in Reclamation's Hydraulics Laboratory located in Denver, CO USA. Each meter was tested in three channel configurations, a 4-ft-wide and 8-ft-deep rectangular channel (Figure 1), a 18-in circular conduit (Figure 2) and a 1.5-ft-bottom width 1.5-ft-deep trapezoidal channel (Figure 3) with side slopes of 1.5:1 (H:V). All tests were conducted under open channel (free surface) conditions with discharge ranging from 0-30 ft^3/sec. Flow was pumped using varying configurations of two 100-hp and one 150-hp centrifugal pumps.

Reference flow rates were measured using calibrated venturi meters accurate to ±0.25 percent (USBR 1989). Reference depth measurements were obtained using either a stilling well accurate to 0.005 feet, a calibrated ultrasonic depth sensor accurate to 0.005 ft, or a point gauge accurate to 0.001 ft, depending on the test channel. Average reference velocities were determined by dividing the reference discharge by the channels as-built cross sectional area. Areas were calculated using the reference depth measurements.

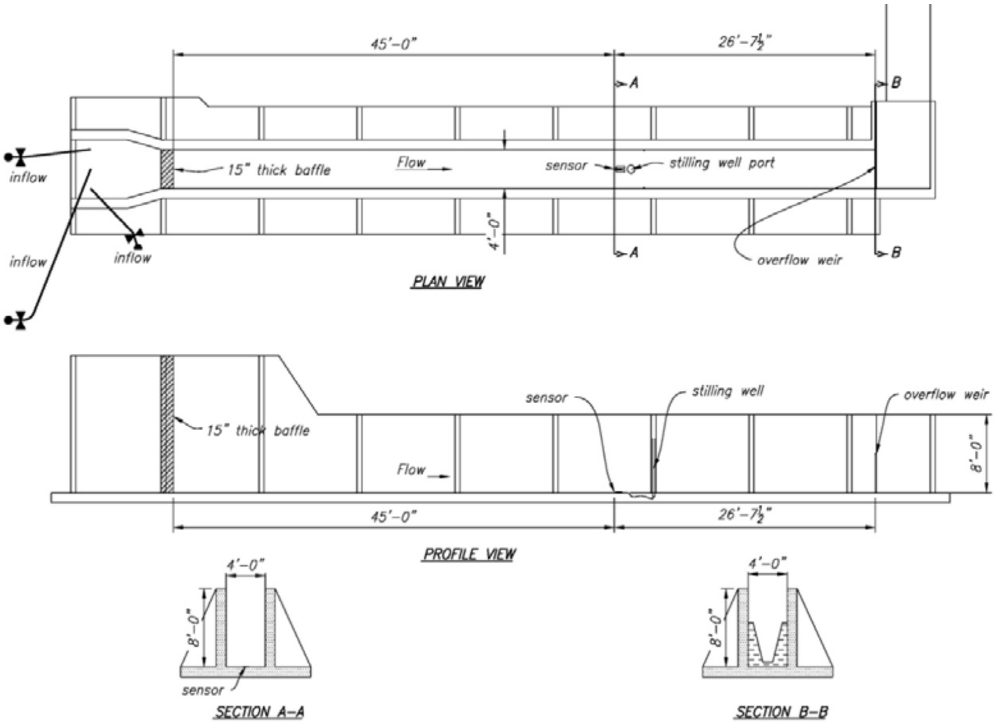

Figure 1 - 4-ft-rectangular channel setup

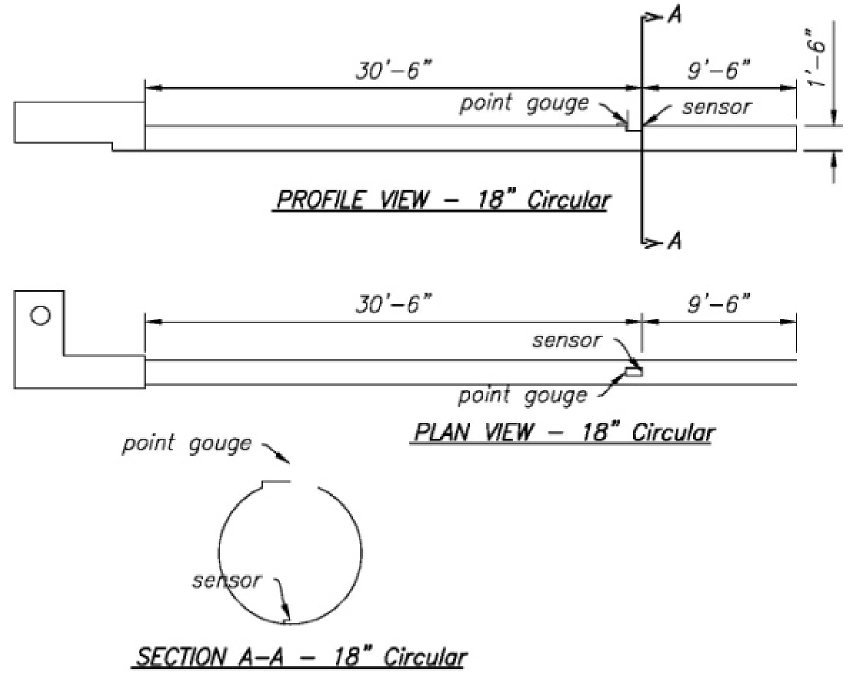

Figure 2 - 18-in-circular channel setup

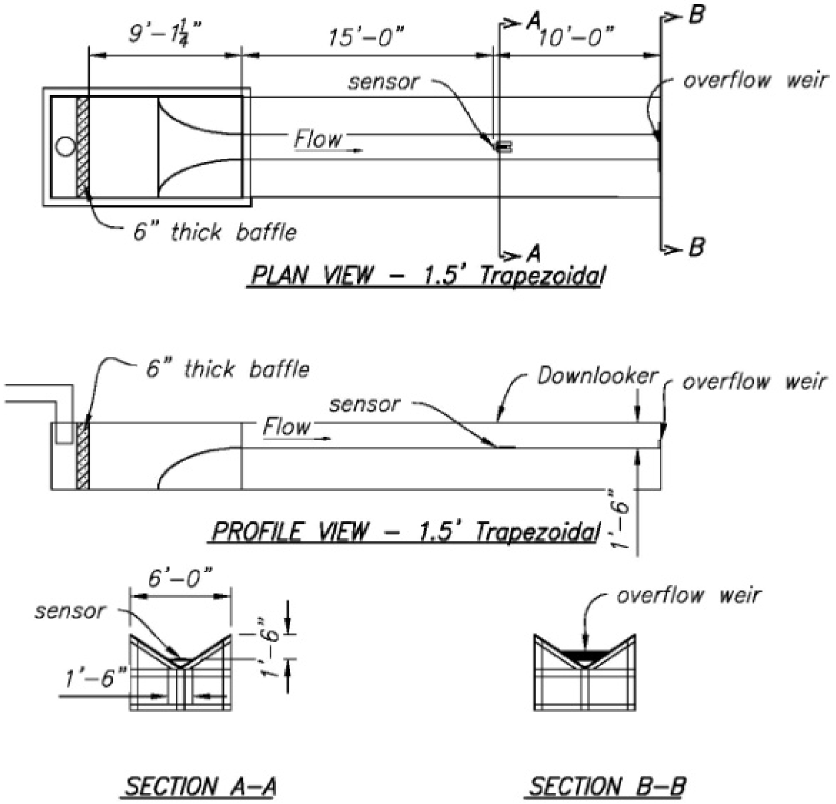

Figure 3 - 1.5-ft-trapezoidal channel setup

Test Procedure

Testing procedures were the same for each configuration. After a specific flow rate was set, the flow was allowed to stabilize for 10 minutes to ensure that equilibrium conditions had been reached. Once stabilized, flow, velocity and stage were logged using the test meter over a 15 minute interval at 1 minute increments. Laboratory (reference) flow rates were determined by continuously averaging the differential pressure from the venturi meters over the same 15 minute period. Reference depths were monitored and recorded manually for each stable flow rate. Once flows and depths were recorded the flow rate was changed and the process was repeated.

Results

4-ft rectangular channel: Graphical results comparing the discharge from the 4-ft rectangular channel tests are included in Figure 4. Results are presented plotting the laboratory flow rate (reference) against each meter's calculated flow rate (measured). Included in the Figure are 3 lines which represent no error and ±10 percent banding lines.

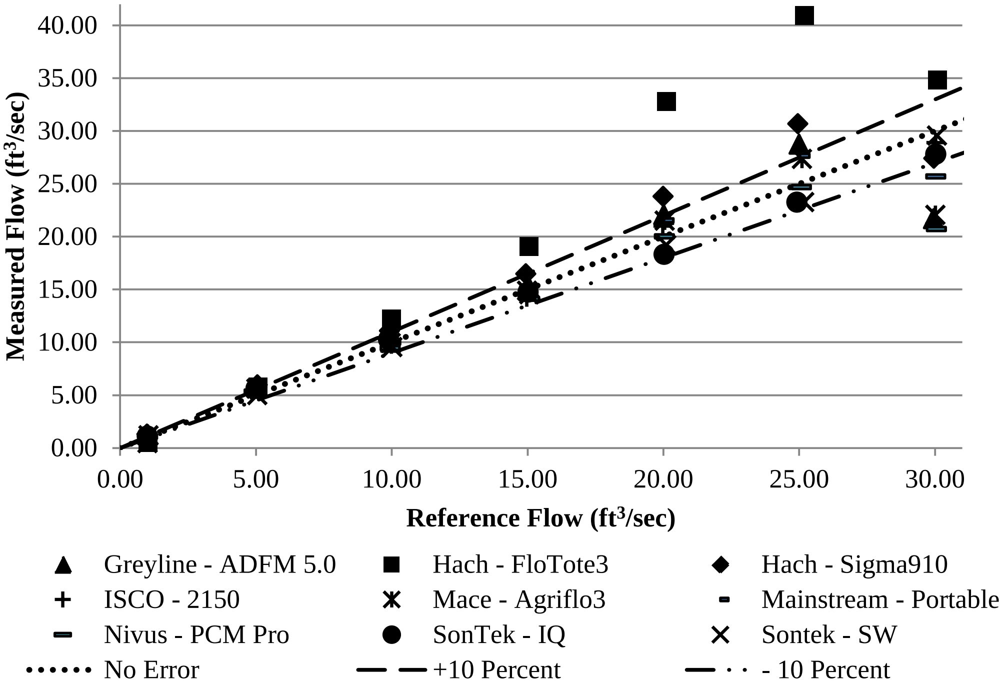

Figure 4 - Discharge comparison for all meters in the 4-ft rectangular channel

Tables 4-12 provide the tabulated data collected in the 4-ft rectangular flume for each meter. The data presents the laboratory measurements (reference), the meter’s output (measured), the standard deviation of the meter’s output (SD) and the percent deviation of the meter’s output to the reference (% Deviation) for the stage, velocity and discharge measurements averaged over the 15 minute measurement period.

Table 4 - Greyline - AVFM5.0 - 4-ft Rectangular Channel Data

Greyline - AVFM5.0 - 4ft Rectangular Channel								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
1.27	1.24 ± 0	-1.7%	0.20	0.25 ± 0.004	22.9%	1.02	1.24 ± 0.02	20.8%
2.22	2.2 ± 0.001	-1.0%	0.57	0.66 ± 0.004	16.3%	5.03	5.79 ± 0.038	15.2%
2.95	2.93 ± 0	-0.7%	0.85	0.85 ± 0.007	1.0%	9.97	10.01 ± 0.082	0.4%
3.48	3.46 ± 0.001	-0.6%	1.08	1.08 ± 0.012	0.0%	15.09	15 ± 0.169	-0.6%
3.89	3.86 ± 0.001	-0.8%	1.29	1.43 ± 0.019	11.1%	20.02	22.08 ± 0.294	10.2%
4.24	4.22 ± 0.002	-0.5%	1.47	1.7 ± 0.02	15.6%	25.00	28.76 ± 0.331	15.0%
4.55	4.53 ± 0.001	-0.4%	1.64	1.2 ± 0.037	-27.3%	29.95	21.69 ± 0.679	-27.6%

Table 5 - Hach - Sigma 910 - 4-ft Rectangular Channel Data

Hach - Sigma 910 - 4ft Rectangular Channel								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
1.27	1.29 ± 0	1.9%	0.19	0.25 ± 0.007	29.9%	0.99	1.32 ± 0.036	33.3%
2.24	2.26 ± 0	0.7%	0.56	0.66 ± 0.018	17.5%	5.05	5.96 ± 0.163	18.0%
2.94	2.96 ± 0.005	0.5%	0.84	0.94 ± 0.018	11.3%	9.93	11.08 ± 0.212	11.7%
3.47	3.46 ± 0.005	-0.2%	1.08	1.19 ± 0.027	10.5%	14.94	16.47 ± 0.383	10.2%
3.89	3.88 ± 0.008	-0.2%	1.29	1.54 ± 0.037	19.4%	20.00	23.81 ± 0.572	19.1%
4.24	4.23 ± 0.004	-0.3%	1.47	1.81 ± 0.045	23.3%	24.96	30.7 ± 0.746	23.0%
4.55	4.54 ± 0.006	-0.1%	1.65	1.51 ± 0.043	-8.5%	29.96	27.41 ± 0.804	-8.5%

Table 6 - Hach - FloTote3 - 4-ft Rectangular Channel Data

Hach - FloTote3 - 4ft Rectangular Channel								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
1.28	1.27 ± 0.005	-0.2%	0.20	0.1 ± 0.082	-51.4%	1.04	0.51 ± 0.419	-51.0%
2.23	2.24 ± 0	0.5%	0.57	0.64 ± 0.057	12.9%	5.08	5.77 ± 0.502	13.6%
2.95	2.97 ± 0	0.7%	0.85	1.03 ± 0.076	21.6%	10.00	12.22 ± 0.908	22.2%
3.48	3.49 ± 0	0.3%	1.08	1.37 ± 0.07	26.3%	15.06	19.09 ± 0.969	26.8%
3.89	3.9 ± 0.004	0.3%	1.29	2.1 ± 0.091	62.4%	20.12	32.77 ± 1.422	62.9%
4.26	4.27 ± 0	0.3%	1.48	2.4 ± 0.078	61.9%	25.20	40.92 ± 1.384	62.4%
4.55	4.55 ± 0	0.0%	1.65	1.91 ± 0.077	15.8%	30.09	34.81 ± 1.356	15.7%

Table 7 - ISCO - 2150 - 4-ft Rectangular Channel Data

ISCO - 2150 - 4ft Rectangular Channel								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
1.26	1.23 ± 0.001	-2.1%	0.19	0.25 ± 0.011	29.8%	0.97	1.23 ± 0.054	27.1%
2.22	2.19 ± 0.002	-1.4%	0.57	0.64 ± 0.01	12.9%	5.02	5.59 ± 0.086	11.4%
2.94	2.92 ± 0.001	-0.9%	0.85	0.84 ± 0.013	-1.2%	9.99	9.78 ± 0.151	-2.0%
3.46	3.43 ± 0.002	-0.9%	1.08	1.04 ± 0.03	-3.9%	14.97	14.25 ± 0.405	-4.8%
3.88	3.84 ± 0.003	-1.1%	1.29	1.37 ± 0.053	6.2%	19.98	21 ± 0.824	5.1%
4.24	4.21 ± 0.003	-0.9%	1.48	1.67 ± 0.1	12.9%	25.06	28.05 ± 1.678	11.9%
4.55	4.51 ± 0.003	-0.7%	1.65	1.6 ± 0.1	-3.1%	30.03	28.91 ± 1.819	-3.7%

Table 8 - Mace - AgriFlo 3 - 4-ft Rectangular Channel Data

Mace - Agriflo 3 - 4ft Rectangular Channel								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
1.27	1.27 ± 0	-0.1%	0.21	0.24 ± 0.007	14.7%	1.04	1.2 ± 0.037	14.5%
2.22	2.22 ± 0	0.1%	0.57	0.63 ± 0.011	11.5%	5.01	5.6 ± 0.101	11.6%
2.94	2.95 ± 0.002	0.3%	0.85	0.84 ± 0.023	-0.5%	9.97	9.94 ± 0.273	-0.3%
3.47	3.48 ± 0	0.3%	1.08	1.07 ± 0.013	-1.1%	14.99	14.87 ± 0.184	-0.8%
3.89	3.9 ± 0	0.4%	1.29	1.38 ± 0.038	6.9%	20.05	21.51 ± 0.598	7.3%
4.25	4.27 ± 0	0.5%	1.48	1.6 ± 0.033	8.6%	25.10	27.37 ± 0.562	9.0%
4.55	4.57 ± 0	0.4%	1.65	1.21 ± 0.075	-26.9%	30.02	22.05 ± 1.365	-26.6%

Table 9 - Mainstream - Portable - 4-ft Rectangular Channel Data

Mainstream - Portable - 4ft Rectangular Channel								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
1.27	1.25 ± 0.001	-1.3%	0.20	0.23 ± 0.005	15.8%	1.01	1.18 ± 0.022	17.5%
2.22	2.2 ± 0.002	-1.2%	0.56	0.64 ± 0.009	14.0%	5.00	5.68 ± 0.074	13.7%
2.95	2.92 ± 0.001	-1.0%	0.85	0.85 ± 0.016	0.3%	9.97	9.96 ± 0.189	0.0%
3.47	3.43 ± 0.002	-1.3%	1.08	1.08 ± 0.023	-0.1%	14.98	14.86 ± 0.318	-0.8%
3.89	3.84 ± 0.002	-1.4%	1.29	1.4 ± 0.035	8.8%	20.03	21.55 ± 0.549	7.6%
4.25	4.19 ± 0.001	-1.4%	1.47	1.65 ± 0.064	11.8%	25.04	27.66 ± 1.068	10.5%
4.55	4.49 ± 0.001	-1.3%	1.65	1.43 ± 0.026	-13.6%	30.03	25.7 ± 0.469	-14.4%

Table 10 - Nivus - PCM Pro - 4-ft Rectangular Channel Data

Nivus - PCM Pro - 4ft Rectangular Channel								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
1.28	1.29 ± 0.001	0.5%	0.20	0.21 ± 0.01	4.1%	1.01	1.06 ± 0.052	4.6%
2.23	2.24 ± 0.001	0.4%	0.55	0.6 ± 0.008	7.7%	4.94	5.34 ± 0.074	8.0%
2.94	2.96 ± 0.002	0.6%	0.84	0.8 ± 0.011	-5.6%	9.95	9.44 ± 0.131	-5.1%
3.48	3.49 ± 0.002	0.3%	1.08	1.01 ± 0.013	-6.7%	15.08	14.11 ± 0.179	-6.4%
3.89	3.9 ± 0.001	0.2%	1.29	1.28 ± 0.014	-0.3%	20.04	20.02 ± 0.219	-0.1%
4.25	4.26 ± 0.001	0.2%	1.48	1.45 ± 0.016	-1.8%	25.08	24.68 ± 0.28	-1.6%
4.55	4.57 ± 0.002	0.4%	1.65	1.13 ± 0.036	-31.3%	30.05	20.72 ± 0.657	-31.1%

Table 11 - SonTek - Argonaut SW - 4-ft Rectangular Channel Data

Sontek - Argonaut SW - 4ft Rectangular Channel								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
1.27	1.25 ± 0.001	-1.6%	0.20	0.09 ± 0.054	-53.9%	1.01	0.46 ± 0.267	-54.6%
2.23	2.21 ± 0.002	-1.0%	0.57	0.57 ± 0.035	-0.2%	5.06	5 ± 0.306	-1.2%
2.95	2.94 ± 0.002	-0.4%	0.85	0.81 ± 0.032	-4.6%	10.03	9.53 ± 0.382	-5.0%
3.48	3.45 ± 0.001	-0.7%	1.08	1.05 ± 0.028	-2.9%	15.07	14.53 ± 0.384	-3.6%
3.89	3.87 ± 0.001	-0.5%	1.29	1.24 ± 0.029	-3.9%	20.11	19.22 ± 0.445	-4.4%
4.26	4.23 ± 0.001	-0.5%	1.48	1.37 ± 0.03	-7.2%	25.20	23.27 ± 0.504	-7.6%
4.55	4.54 ± 0.001	-0.3%	1.65	1.63 ± 0.026	-1.4%	30.08	29.55 ± 0.465	-1.7%

Table 12 - SonTek - IQ - 4-ft Rectangular Channel Data

SonTek - IQ - 4ft Rectangular Channel								
Stage (ft)			Velocity (ft/sec)			Discharge (ft^3/sec)		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
1.26	1.24 ± 0.001	-1.2%	0.20	0.22 ± 0.01	12.6%	1.00	1.11 ± 0.048	11.1%
2.24	2.23 ± 0.001	-0.8%	0.56	0.63 ± 0.006	13.8%	5.00	5.65 ± 0.056	12.9%
2.84	2.83 ± 0.001	-0.4%	0.87	0.91 ± 0.007	4.3%	9.88	10.27 ± 0.079	3.9%
3.34	3.33 ± 0.002	-0.5%	1.12	1.11 ± 0.011	-1.2%	15.02	14.76 ± 0.152	-1.7%
3.76	3.73 ± 0.002	-0.5%	1.33	1.23 ± 0.022	-8.0%	20.03	18.33 ± 0.332	-8.5%
4.11	4.08 ± 0.002	-0.7%	1.52	1.42 ± 0.023	-6.1%	24.92	23.25 ± 0.368	-6.7%
4.42	4.39 ± 0.002	-0.5%	1.70	1.58 ± 0.039	-6.9%	30.04	27.82 ± 0.697	-7.4%

18-in circular channel: Graphical results comparing the discharge from the 18-in circular tests are included in Figure 5. Results are presented plotting the laboratory flow rate (reference) against each meter's calculated flow rate (measured). Included in the Figure are 3 lines which represent no error and ±10 percent banding lines.

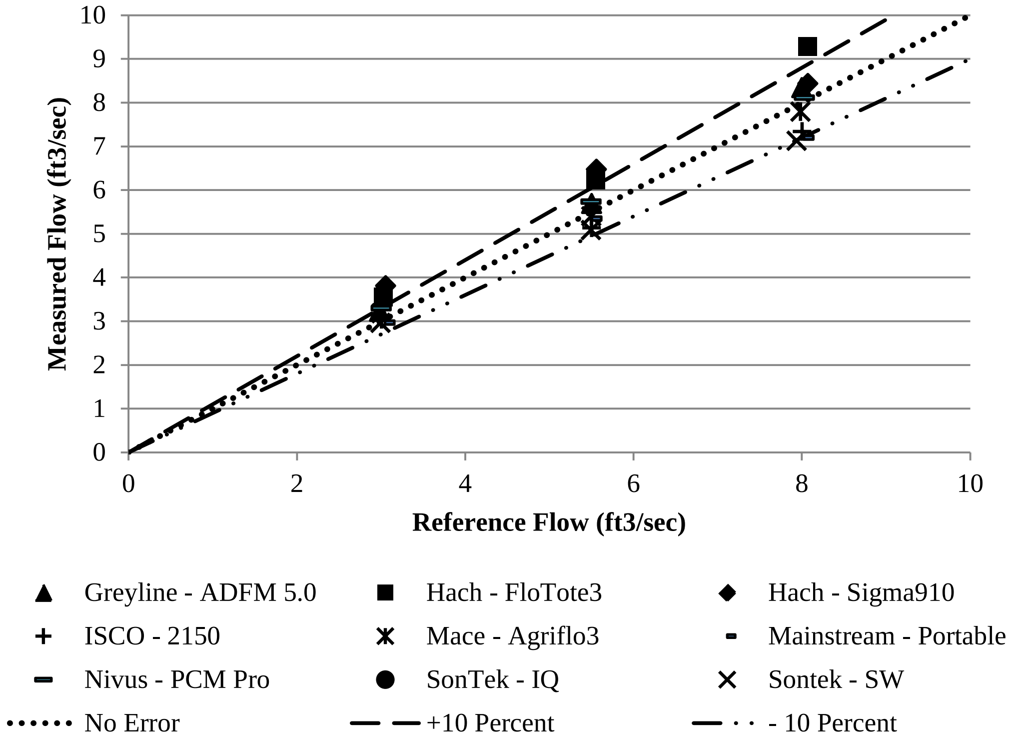

Figure 5 - Discharge comparison for all meters in the 18-in circular channel

Tables 13-20 provide the data collected in the 18-inch circular conduit for each meter except the SonTek IQ which is not intended for use in circular conduits. The data presents the laboratory measurements (reference), the meter's output (measured), the standard deviation of the meter's output (SD) and the percent deviation of the meter's output to the reference (% Deviation) for the stage, velocity and discharge measurements averaged over the 15 minute measurement period.

Table 13 - Greyline - ADFM5.0 - 18-in Circular Conduit Data

Greyline - ADFM5.0 - 18-in Circular Conduit								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.56	0.55 ± 0.005	-2.0%	4.91	5.46 ± 0.033	11.1%	2.98	3.23 ± 0.043	8.1%
0.75	0.72 ± 0.003	-4.4%	6.20	6.79 ± 0.031	9.5%	5.50	5.69 ± 0.022	3.4%
0.95	0.95 ± 0.01	0.0%	6.78	7.07 ± 0.04	4.2%	8.00	8.34 ± 0.061	4.2%

Table 14 - Hach - Sigma 910 - 18-in Circular Conduit Data

Hach - Sigma 910 - 18-in Circular Conduit								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.60	0.67 ± 0.009	11.1%	4.64	5.04 ± 0.041	8.6%	3.06	3.81 ± 0.072	24.7%
0.85	0.89 ± 0.021	4.7%	5.39	5.94 ± 0.032	10.1%	5.56	6.47 ± 0.182	16.3%
1.17	1.15 ± 0.025	-1.7%	5.46	5.81 ± 0.079	6.3%	8.07	8.43 ± 0.215	4.5%

Table 15 - Hach - Flotote3 - 18-in Circular Conduit Data

Hach - FloTote3 - 18-in Circular Conduit								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.80	0.73 ± 0.005	-8.6%	3.15	4.14 ± 0.247	31.5%	3.03	3.56 ± 0.219	17.4%
0.83	0.87 ± 0.007	4.7%	5.50	5.81 ± 0.239	5.6%	5.55	6.23 ± 0.271	12.1%
1.16	1.16 ± 0.002	-0.1%	5.50	6.33 ± 0.165	15.0%	8.07	9.27 ± 0.239	14.9%

Table 16 - ISCO - 2150 - 18-in Circular Conduit Data

ISCO - 2150 - 18-in Circular Conduit								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.58	0.57 ± 0.01	-1.3%	4.82	4.96 ± 0.142	2.8%	3.01	3.04 ± 0.102	1.0%
0.75	0.73 ± 0.012	-3.3%	6.21	6.05 ± 0.128	-2.6%	5.50	5.13 ± 0.145	-6.8%
0.97	0.94 ± 0.021	-3.2%	6.65	6.33 ± 0.095	-4.9%	8.00	7.33 ± 0.198	-8.4%

Table 17 - Mace - AgriFlo - 18-in Circular Conduit Data

Mace - AgriFlo - 18-in Circular Conduit								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.58	0.54 ± 0.009	-6.5%	4.80	5.51 ± 0.029	14.8%	3.01	3.18 ± 0.066	5.6%
0.74	0.7 ± 0.011	-5.2%	6.39	6.67 ± 0.047	4.5%	5.50	5.4 ± 0.099	-1.9%
0.95	0.92 ± 0.014	-4.0%	6.74	6.87 ± 0.063	2.0%	7.99	7.79 ± 0.166	-2.4%

Table 18 - Mainstream - Portable - 18-in Circular Conduit Data

Mainstream - Portable - 18-in Circular Conduit								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.60	0.56 ± 0.01	-5.6%	4.64	4.86 ± 0.065	4.9%	3.05	2.96 ± 0.082	-2.7%
0.84	0.78 ± 0.013	-6.3%	5.45	5.72 ± 0.074	5.1%	5.51	5.34 ± 0.145	-3.0%
0.95	0.85 ± 0.018	-10.9%	6.80	6.99 ± 0.052	2.8%	8.03	7.2 ± 0.203	-10.3%

Table 19 - Nivus - PCM Pro - 18-in Circular Conduit Data

Nivus - PCM Pro - 18-in Circular Conduit								
Stage (ft)			Velocity (ft/sec)			Discharge (ft^3/sec)		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.58	0.59 ± 0.002	1.7%	4.79	5.15 ± 0.027	7.5%	3.00	3.3 ± 0.014	9.8%
0.76	0.76 ± 0.003	0.3%	6.17	6.41 ± 0.022	4.0%	5.50	5.74 ± 0.035	4.4%
0.94	0.98 ± 0.007	4.3%	6.88	6.63 ± 0.031	-3.7%	8.03	8.12 ± 0.035	1.0%

Table 20 - SonTek - Argonaut SW - 18-in Circular Conduit Data

SonTek - Argonaut SW - 18-in Circular Conduit								
Stage (ft)			Velocity (ft/sec)			Discharge (ft^3/sec)		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.59	0.61 ± 0.005	3.6%	4.66	4.4 ± 0.095	-5.6%	3.00	2.96 ± 0.074	-1.1%
0.77	0.76 ± 0.004	-1.2%	6.04	5.68 ± 0.059	-6.1%	5.49	5.08 ± 0.058	-7.5%
0.99	0.97 ± 0.013	-1.8%	6.40	5.86 ± 0.079	-8.4%	7.94	7.12 ± 0.073	-10.3%

1.5-ft trapezoidal channel: Graphical results comparing the discharge from the 1.5-ft trapezoidal tests are included in Figure 6. Results are presented plotting the laboratory flow rate (reference) against each meter's calculated flow rate (measured). Included in the Figure are 3 lines which represent no error and ±10 percent banding lines.

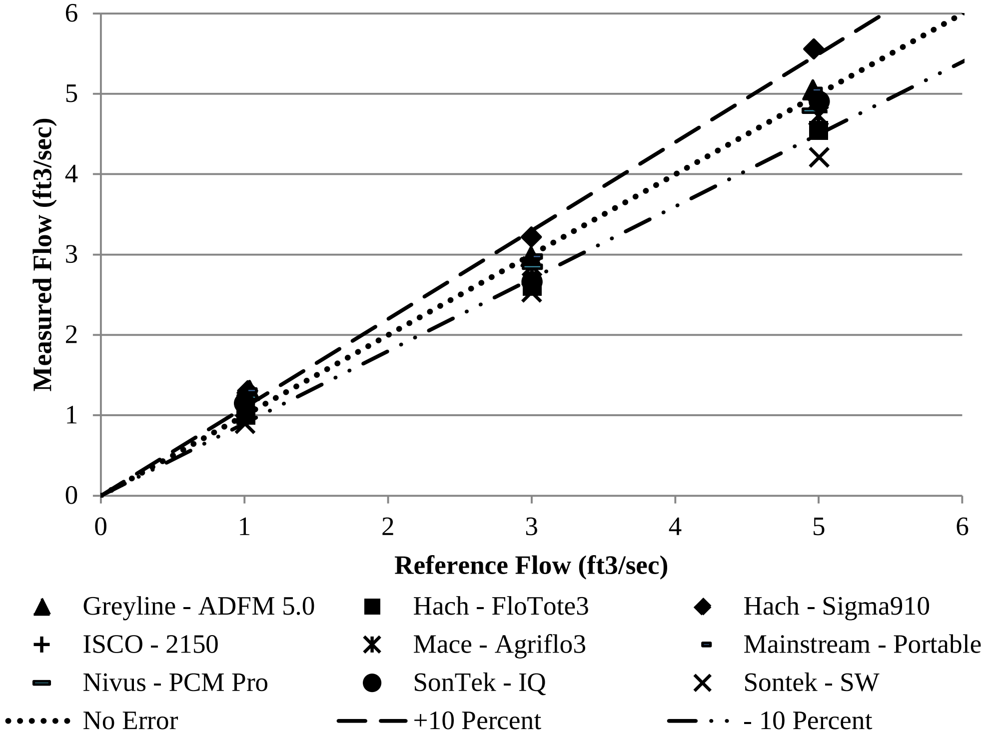

Figure 6 - Discharge comparison for all meters in the 1.5-ft trapezoidal channel

Tables 21-29 provide the data collected in the 1.5-ft trapezoidal channel for each meter. The data presents the laboratory measurements (reference), the meter's output (measured), the standard deviation of the meter’s output (SD) and the percent deviation of the meter’s output to the reference (% Deviation) for the stage, velocity and discharge measurements averaged over the 15 minute measurement period.

Table 21 - Greyline - AVFM5.0 - 1.5-ft Trapezoidal Channel Data

Greyline - AVFM5.0 - 1.5-ft Trapezoidal Channel								
Stage (ft)			Velocity (ft/sec)			Discharge (ft^3/sec)		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.69	0.68 ± 0.001	-0.9%	0.60	0.76 ± 0.009	27.3%	1.04	1.3 ± 0.014	25.7%
0.84	0.83 ± 0.001	-1.0%	1.29	1.3 ± 0.019	0.6%	3.00	2.97 ± 0.051	-0.8%
0.96	0.96 ± 0	-0.6%	1.75	1.79 ± 0.007	2.7%	4.96	5.05 ± 0.019	1.7%

Table 22 - Hach - Sigma 910 - 1.5-ft Trapezoidal Channel Data

Hach - Sigma 910 - 1.5-ft Trapezoidal Channel								
Stage (ft)			Velocity (ft/sec)			Discharge (ft^3/sec)		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.69	0.68 ± 0	-1.0%	0.59	0.76 ± 0.043	28.4%	1.02	1.3 ± 0.075	27.1%
0.84	0.84 ± 0	-0.5%	1.28	1.39 ± 0.015	8.5%	3.00	3.22 ± 0.032	7.2%
0.97	0.97 ± 0.006	0.9%	1.75	1.93 ± 0.017	10.5%	4.97	5.55 ± 0.058	11.9%

Table 23 - Hach - FloTote3 - 1.5-ft Trapezoidal Channel Data

Hach - FloTote3 - 1.5-ft Trapezoidal Channel								
Stage (ft)			Velocity (ft/sec)			Discharge (ft^3/sec)		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.69	0.72 ± 0	5.1%	0.58	0.54 ± 0.037	-7.8%	1.01	1 ± 0.066	-1.3%
0.84	0.87 ± 0	3.3%	1.29	1.07 ± 0.089	-17.2%	3.00	2.6 ± 0.215	-13.4%
0.97	1 ± 0	3.4%	1.75	1.52 ± 0.081	-13.4%	5.00	4.55 ± 0.246	-9.1%

Table 24 - ISCO - 2150 - 1.5-ft Trapezoidal Channel Data

ISCO - 2150 - 1.5-ft Trapezoidal Channel								
Stage (ft)			Velocity (ft/sec)			Discharge (ft^3/sec)		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.69	0.67 ± 0.001	-1.9%	0.58	0.71 ± 0.01	22.6%	1.01	1.2 ± 0.017	19.4%
0.84	0.83 ± 0.001	-1.8%	1.29	1.25 ± 0.026	-2.6%	3.00	2.85 ± 0.061	-5.1%
0.97	0.95 ± 0.001	-1.9%	1.75	1.72 ± 0.033	-1.6%	5.00	4.77 ± 0.095	-4.5%

Table 25 - Mace - AgriFlo3 - 1.5-ft Trapezoidal Channel Data

Mace - Agriflo 3 - 1.5-ft Trapezoidal Channel								
Stage (ft)			Velocity (ft/sec)			Discharge (ft^3/sec)		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.69	0.66 ± 0	-3.8%	0.59	0.72 ± 0.013	22.3%	1.02	1.17 ± 0.02	15.2%
0.84	0.81 ± 0.002	-3.8%	1.29	1.29 ± 0.014	-0.2%	3.00	2.85 ± 0.031	-5.2%
0.97	0.94 ± 0.003	-2.9%	1.75	1.74 ± 0.016	-0.9%	5.00	4.72 ± 0.046	-5.6%

Table 26 - Mainstream - Portable - 1.5-ft Trapezoidal Channel Data

Mainstream - Portable - 1.5-ft Trapezoidal Channel								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.68	0.68 ± 0.001	0.5%	0.60	0.76 ± 0.009	27.0%	1.02	1.3 ± 0.014	27.9%
0.84	0.83 ± 0.001	-0.9%	1.29	1.3 ± 0.019	0.1%	3.01	2.97 ± 0.051	-1.1%
0.96	0.96 ± 0	-0.5%	1.75	1.79 ± 0.007	2.7%	4.96	5.05 ± 0.019	1.8%

Table 27 - Nivus - PCM Pro - 1.5-ft Trapezoidal Channel Data

Nivus - PCM Pro - 1.5-ft Trapezoidal Channel								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.68	0.71 ± 0	5.6%	0.60	0.67 ± 0.014	11.1%	1.02	1.22 ± 0.025	20.0%
0.84	0.88 ± 0	4.4%	1.29	1.15 ± 0.011	-11.2%	3.01	2.84 ± 0.027	-5.4%
0.96	1 ± 0	3.6%	1.75	1.6 ± 0.011	-8.3%	4.96	4.79 ± 0.033	-3.4%

Table 28 - SonTek - Argonaut SW - 1.5-ft Trapezoidal Channel Data

SonTek - Argonaut SW - 1.5-ft Trapezoidal Channel								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.69	0.7 ± 0.001	2.3%	0.58	0.5 ± 0.03	-14.4%	1.01	0.89 ± 0.055	-11.6%
0.85	0.85 ± 0.001	1.0%	1.28	1.06 ± 0.037	-17.1%	3.00	2.53 ± 0.089	-15.8%
0.97	0.98 ± 0.001	0.8%	2.82	1.46 ± 0.071	-48.3%	5.00	4.21 ± 0.203	-15.9%

Table 29 - SonTek – IQ - 1.5-ft Trapezoidal Channel Data

SonTek - IQ - 1.5-ft Trapezoidal Channel								
Stage (ft)			**Velocity (ft/sec)**			**Discharge (ft^3/sec)**		
Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation	Reference	Measured ±SD	% Deviation
0.68	0.69 ± 0.001	2.4%	0.59	0.65 ± 0.011	10.7%	1.00	1.15 ± 0.02	14.5%
0.83	0.84 ± 0.001	1.2%	1.31	1.14 ± 0.021	-13.0%	3.00	2.66 ± 0.05	-11.6%
0.96	0.96 ± 0.004	0.4%	1.78	1.74 ± 0.017	-2.6%	5.00	4.9 ± 0.048	-2.0%

Analysis

Installation of each meter was performed according to manufacturer recommendations. Most manufacturers call for a certain length of upstream unobstructed flow before the sensor is mounted in the channel; in all cases these guidelines were met.

After testing was performed, researchers discovered irregular velocity profiles in the 4-ft rectangular flume that could be the result of some of the meters' poor performance at high discharges (greater than 20 ft^3/sec). At discharges less than 20 ft^3/sec irregular velocity profiles were not detected. These irregular velocity profiles were not anticipated in the laboratory tests. However, it is common to experience irregular velocity profiles when installing these meters in the field, so no attempts were made to remedy the velocity profiles. For this reason, the researchers recommend that installation locations be chosen carefully. In addition, spot checks by a separate method should be performed after the install of any of these meters to ensure accurate measurements are being obtained. In some cases, meters had internal checks to determine if possible errors could be present in the flow. Several of the meters that did have these checks found no issues with the irregular velocity profiles and thus appeared to provide accurate results. Typically, when a coherent or profiling meter is used the velocity profiles can be viewed to determine their uniformity and provide users with more confidence in their measurements.

Possible reasons the 18-in circular conduit results did not meet some manufacturer specifications was the smooth wall corrugated HDPE plastic pipe. Although the pipe is considered to have a smooth wall, slight ridges are present along the smooth interior surface of the pipe that could disrupt flow boundaries and cause the velocities in the pipe to fluctuate slightly from rib to trough (approximately 2 inches apart and less than 0.125-in difference in diameter). This slight disruption of boundary also causes a slight bounce in the water surface which presents some difficulties in obtaining an accurate reference depth. It should also be noted that the 18-in pipe used for the testing was about 0.25-0.375-in out of round (egg shaped). This occurrence is common of HDPE pipes installed in the field and no attempt was made to remedy the pipe shape. For some of the flow rates tested, the comparison between reference and measured depths varied significantly due to the slight bounce of the water surface and the bulking associated with standing waves that were caused by the sensor being installed in the pipe. For these reasons it is recommended that the reader only compare the deviations in the discharge measurements for the 18-in circular culverts and use the velocity and depth measurements for reference only.

It is recognized that some of the meters performed poorly in the 1.5-ft trapezoidal channel and the 18-in circular culvert due to the small water depths over the top of the sensor. It is recommended that users verify with individual manufacturer's that minimum depths are not violated when installing and using these instruments.

Manufacturers' Response

All participating manufacturers' were given the opportunity to respond to the results of the testing. Each was sent a similar email documenting the test conditions and providing the company's representative with a copy of the data collected using their meter. Few of the manufacturers provided feedback; those that did are summarized below:

Hach: Were generally unhappy with the results. After speaking with several representatives for both the Sigma 910 and Flo-Tote 3 no reason for the results were determined except that there may have been non-symmetrical velocity profiles and that moisture in the vent tubes may have caused an error in the depth measurements (Mulleady 2011). Without having external knowledge of the flow or depth at the site, no way to trouble shoot these issues were available. Mulleady also indicated that the data would be “considerably improved” with site calibrations. Hach funded separate tests to troubleshoot the issues that may have caused the errors in measurements. Further testing resulted in similar data. Hach indicated verbally that they could find no reason for the results and that their units have performed much better in similar tests (Alden 2003).

Mace USA LLC: After reviewing the setup files Mace was concerned that the wrong method to calculate the average velocity was selected and that aliasing of the velocity measurements was causing the meter-computed flow to stray from the reference measurements. Aliasing occurs when the velocity range of the AgriFlo3 is set lower than the maximum measured velocity in the channel, which causes the calculated average velocity to be unreliable. To verify the results of this study with the correct settings, Mace funded a set of witnessed tests of the AgriFlo3 in the same three test configurations as were originally tested. Results from the additional testing showed improved performance in the 1.5-ft trapezoidal channel (Heiner 2011) and no noticeable improvement during the 18-in circular (Heiner 2011) and 4-ft rectangular channel (Heiner 2012) tests when using the correct method to calculate the velocity magnitude and increasing the maximum velocity range.

Mathew Campbell the managing director of Mace further indicated in email correspondence that during the additional testing in the 4-ft rectangular flume the mounting brackets used to mount the sensor in the channel was not the standard mounting bracket provided by Mace and might change the results. He was further concerned that minor flaws in the trapezoidal channel could be considered a violation of the “straight run requirements.” He recommended that the meter be tested mounted on the side of the channel to see if any differences were noticed. At the time of publication no further testing was conducted with the Mace meter.

SonTek: After reviewing the Argonaut SW data, SonTek was generally pleased with the results but commented that both the 18-in circular conduit and the 1.5-ft trapezoid channel were very small for the SW. Improved performance would be possible if indexing procedures were completed for each configuration (Cook 2011).

After reviewing the IQ data, SonTek provided a detailed analysis of the results. The 1.5-ft trapezoidal results seemed high but were not entirely unexpected considering the shallow water and low velocities. The 4-ft rectangular results were acceptable when considering the low velocities for the first two tests and the irregular velocity profiles in the discharges greater the 20 ft^3/sec (noticeable in the velocity profiles provided by the IQ profiling and the horizontal velocities from the two side beams).

Conclusions

To better understand many of the different area-velocity meters the Bureau of Reclamation tested nine meters from seven manufacturers. Most area-velocity flow meters determine the average water velocity in one of three ways; incoherent or continuous Doppler, coherent or profiling Doppler, or using electromagnetics. Meters in all of these categories were tested during this study. It is understood that this study did not include all meters that are commercially available. However, two other meters not tested in this study were tested previously by Reclamation (Vermeyen 2000).

Test results from the nine meters varied based on the test configurations and meter type. Results indicate that when using area-velocity meters in controlled environments errors in excess of ±10 percent in discharge are possible. For this reason it is recommended that when using these meters careful consideration is made when selecting a site and that an independent method be used to verify discharge accuracy.

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