Laboratory Evaluation of a SonTek Argonaut-SW Flowmeter

by

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Acknowledgments

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Purpose

The purpose of this laboratory evaluation was to determine if a newly developed acoustic Doppler flowmeter could accurately measure seepage losses from a section of unlined canal. A set of tests were designed to determine the minimum amount of seepage losses the flowmeter could accurately measure. The scope of this evaluation did not include a verification of the vertical velocity profile measurements or the algorithms used by the Argonaut-SW for the discharge computations for open channels or closed-conduits.

Introduction

The Argonaut-SW (shallow water) is a pulsed Doppler current profiling system designed for measuring water velocity profiles and level that are used to compute volumetric flow rate in natural channels, canals, culverts, or pipes. The goal of this laboratory evaluation was to determine the Argonaut-SW's flow measurement accuracy in a flume and pipe in a controlled setting.

Doppler-based Velocity Measurement Technique

The Argonaut-SW is a pulsed Doppler current meter. It uses a monostatic transceiver configuration, where the acoustic transducers transmit and receive the acoustic signals. The Argonaut-SW has three acoustic beams (figure 1). When correctly placed on the channel bottom, one of these beams is facing straight up, and the other two point upstream and downstream at a 45-degree angle. The upward-looking beam measures water depth. For a bottom mount application, the two diverging beams measure the flow velocities in two dimensions (streamwise and vertical). The manufacturer reports the velocity range, resolution, and accuracy to be ±16 ft/sec, 0.003 ft/sec, and the larger of ±1% of the measured velocity or ±0.016 ft/sec, respectively (Sontek 2003).

A key technical feature of the Argonaut-SW, which separates it from other Doppler sensors, is that velocity measurements are made to the water surface (in open channels) without any of the contamination normally associated with side-lobe interference. This enables the SW to take full advantage of the vertically-integrated velocity in its internal flow calculations.

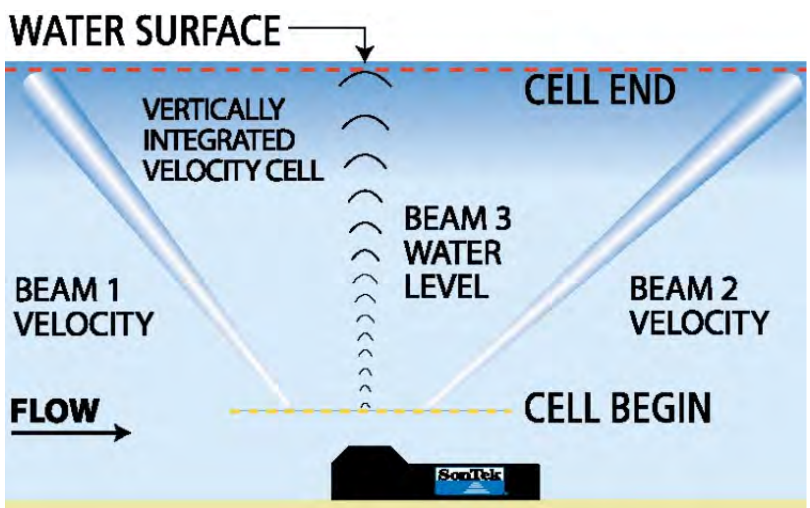

Figure 1. Argonaut–SW beam pattern and profiling extents (Sontek, System Manual, 2003).

Acoustic Water Level Measurement

A vertical beam is used to measure water level. The vertical beam sends an acoustic pulse and listens for the reflected pulse from the surface. To find the surface range from the reflection travel-time the SW uses an internal temperature sensor and user-defined salinity to calculate the speed of sound in water for the site. The SW uses the water level data for dynamic boundary adjustment which changes the velocity profile range to account for changes in depth. The manufacturer reports the water level range to be 0.6 to 16 ft, and the accuracy to be the larger of ± 0.01 ft or ±0.1% of measured depth. The minimum distance to the first velocity measurement ("cell begin" in figure 1) is about 0.3 ft above the top of the transducer.

Discharge Computations

The cross-sectional dimensions for an open channel or closed conduit are user-programmed into the flowmeter before it is deployed. The SW uses the water depth measurement and a depth-area relationship to compute the area of the flow section for each sampling period. The flow rate is computed by multiplying the area by the computed mean channel velocity for each sample. The mean channel velocity is computed from the vertically integrated velocity using an algorithm based on the 1/6th power velocity distribution model (Chen 1991). In addition, the SW has the option to use an index-velocity relationship for discharge computations. Where the index velocity is calculated from an empirical relationship between an independent measurement of the mean channel velocities and the SW-measured velocities and depths.

Laboratory Evaluation

The Facilities – Two Argonaut-SW flowmeters were tested in a large laboratory flume that is located at the Bureau of Reclamation's Water Resources Research Laboratory, located in Denver, Colorado. The glass-walled flume is 4 feet wide, 8 feet tall and 80 feet long (figure 2). The flume has a 10-ft-long headbox which contains a baffle structure to condition the flow entering the flume. The pumped flow capacity to the flume is about 20 ft^3/sec. The depth in the flume is controlled by a tailgate located at the end of flume.

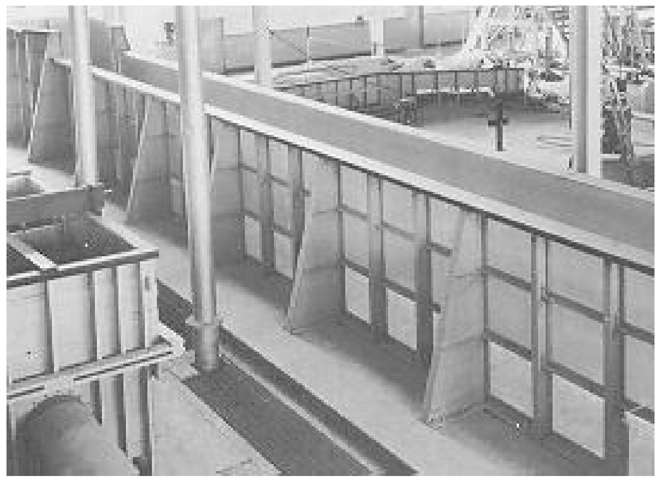

Figure 2. Photograph of the glassed-wall flume. Flow is from left to right.

The first Argonaut-SW instrument was installed 25 ft downstream from the headbox baffle and was positioned 5 ft upstream from a 1.67-ft-high labyrinth weir. The weir was being studied in the flume and was left in place with the intention of generating non-uniform vertical velocity profiles, especially at higher discharges. The non-uniform profiles would allow evaluation of the SW's theoretical discharge computation algorithm for distorted flow profiles. A staff gage mounted to the flume wall across from the SW transducer was used to measure water depth to the nearest 0.02 ft. Figure 3 is a photograph of the Argonaut-SW flowmeter installed in the flume. A 4-ft-high and 4-ft-wide channel geometry was programmed into the SW. The system elevation for this installation (offset from the flume bottom) was 0.243 ft.

A second Argonaut-SW was placed in a 9-ft-long plastic pipe located 20 ft downstream from the open channel SW. The 18-inch diameter pipe was placed in the last third of the flume and its entrance was isolated by a 4-ft-high marine grade plywood bulkhead. The bulkhead was sealed to the pipe and flume to force all the flow through the pipe. The tailgate was used to keep the water depth below the top of the pipe inlet bulkhead. The tailgate was about 15 ft downstream from the 18-in-diameter pipe outlet. Figure 4 is a photograph of the SW flowmeter installed in the pipe. Notice that the SW within the pipe was situated about 5 pipe diameters from the pipe entrance. A 1.5 ft diameter pipe description was programmed into the SW. The system elevation for this installation (offset from the pipe invert) was 0.312 ft.

Figure 3. Looking downstream at the SW and the 1.67-ft-high laybyrinth weir in the open channel section. The bulkhead entrance to the 18-inch pipe can be seen beyond the labyrinth weir. A staff gage is visible on the steel wall across from the SW transducer.

Figure 4. Looking upstream at the SW in plastic pipe section. The SW was positioned 7.5 ft downstream from the pipe entrance.

Test Procedures - Steady flows pumped from the laboratory reservoir were discharged in to the flume headbox. Inside the headbox is an 8-inch diameter drain pipe which was used to allow a portion of the inflow to bypass the flume. A series of 1 hour tests were conducted for bypass flows ranging from 0 to 10 percent of the flow supplied to the flume. Both Argonaut-SW flowmeters were programmed to store a data set every 2 minutes. During the 2 minute averaging interval, the SW collected 120 velocity profiles and depth measurements that were internally averaged prior to logging the data.

Flow supplied to the flume was measured independently using a 12-inch Venturi meter. The Venturi meter was calibrated in the laboratory calibration facility and has an uncertainty of ±0.3% of the volumetric flowrate. A laboratory control system was used to maintain a constant discharge into the flume. A strap-on acoustic flowmeter was installed on the bypass pipe to make an independent measurement of bypass flow. This flowmeter has a manufacturer reported uncertainty of about ±1 to 2 percent. A calibration test for the bypass flowmeter was not performed for this evaluation. As a result, an uncertainty of ±2 percent was used in the uncertainty analyses for the strap-on flowmeter. For most tests, the bypass flowmeter stored an average flowrate every one minute for the duration of the tests. However, for some tests the data logger memory was filled and some data were lost. For these tests, the bypass flows were observed every 15 minutes to ensure they remained constant. Typically, the mean bypass flows were very stable and the standard error was less than ±0.01 ft^3/sec for a 30-minute test.

A staff gage was used to make an independent measurement of water depth at the flowmeter location in the flume. The staff gage was read to the nearest 0.02 ft with an uncertainty of ±0.01 ft. A tailgate located at the end of the flume was adjusted to keep the pipe completely submerged during each test and to maintain a stable depth at the open channel SW location.

Tests - Two SW units were tested for 1 hour intervals at various flowrates. At each interval, the bypass flow was adjusted to represent leakage. Tests were conducted with flume flows of 1, 5, and 7 ft^3/sec with the bypass flow adjusted once every hour. For the 1 ft^3/sec test, data were collected for target bypass flows of 0, 0.05 and 0.10 ft^3/sec. For the 5 ft^3/sec test, data were collected at target bypass flows of 0, 0.20, 0.25, 0.30, 0.40 and 0.50 ft^3/sec. For the 7 ft^3/sec test, data were taken at target bypass flows of 0.25, 0.30, 0.35, 0.50, 0.60 and 0.70 ft^3/sec.

Table 1. Depth Measurement Results for the Four-Foot Channel

Test Setup	SW Measured Depth (±δy, ft)	Staff Gage (δy=± 0.01 ft)	Discrepancy (y_{flume}-y_{sw}) (ft)	Within Specs (±0.01 ft)
1 ft^3/sec - 0.00bypass	2.297±0.063	2.30	0.00	Meets
1 ft^3/sec - 0.05 bypass	3.038±0.071	3.06	0.02	Exceeds
1 ft^3/sec - 0.10 bypass	3.130±0.000	3.10	-0.03	Exceeds
5 ft^3/sec - 0.00 bypass	2.141±0.006	2.14	0.00	Meets
5 ft^3/sec - 0.20 bypass	2.013±0.000	2.00	-0.01	Meets
5 ft^3/sec - 0.25 bypass	2.619±0.000	2.58	-0.04	Exceeds
5 ft^3/sec - 0.30 bypass	2.583±0.000	2.58	0.00	Meets
5 ft^3/sec - 0.40 bypass	2.482±0.000	2.48	0.00	Meets
5 ft^3/sec - 0.50 bypass	2.417±0.000	2.40	-0.02	Exceeds
7 ft^3/sec - 0.25 bypass	3.022±0.014	2.98	-0.04	Exceeds
7 ft^3/sec - 0.30 bypass	2.916±0.000	2.90	-0.02	Exceeds
7 ft^3/sec - 0.35 bypass	3.169±0.000	3.14	-0.03	Exceeds
7 ft^3/sec - 0.50 bypass	3.069±0.001	3.08	0.01	Meets
7 ft^3/sec - 0.60 bypass	2.971±0.000	2.96	-0.01	Meets
7 ft^3/sec - 0.70 bypass	2.809±0.001	2.78	-0.03	Exceeds

Test Results - Table 1 contains a summary of the depth measurements collected by the SW in the 4-ft flume. The SW depth values are the mean and standard error (±δy) of 30 or more samples. Depth observed using a staff gage was used to evaluate the accuracy of the SW depth measurements. Table 1 also includes the discrepancy (difference) between the two depth values and whether this discrepancy meets or exceeds the water level measurement accuracy specifications, ± 0.01 ft. The width to flow depth ratios for these tests ranged from 1.3 to 2.0.

Tables 2 and 3 contain a comparison of SW mean channel velocity to the computed mean flow velocity using the continuity equation (**V=Q/A**). Where **Q** is the volumetric flowrate and **A** is the test section cross-sectional area. To compute the mean channel velocities, the actual flow was divided by the cross sectional area of the flume or pipe:

$$A_{flume} = 4d;\ where\ d \equiv\ staff\ \ gage\ depth\ reading,\ ft^2$$

$$A_{pipe} = \frac{\pi D^2}{4};\ where\ D \equiv\ pipe\ diameter,\ ft^2$$

These tables also include the discrepancy between the two mean velocity values and whether this discrepancy was with the manufacturers water velocity measurement accuracy specifications, ±0.016 ft/sec. For pipe tests with flows of 5 and 7 ft^3/sec, the water velocity measurement accuracy specifications is ±1 percent of the measured velocity. Using the manufacturers velocity specification in this evaluation was especially strict because it includes uncertainty contributions from mean channel velocity computations, as well as the cross sectional area. The uncertainties (δV) in the mean channel velocity computations were computed using the general formula for error propagation as described by Taylor (1997). The uncertainties (δV) in SW mean channel velocities were computed as the standard error of the vertical velocities measured for the duration of the test which was the combined uncertainty attributed to velocity fluctuations (turbulence) and instrument noise.

Table 2. Comparison of Mean Channel Velocity to SW Mean Velocity for Flume Tests

Test Setup	Calculated Flume Velocity (±δV, ft/sec)	SW Mean Velocity (±δV, ft/sec)	Discrepancy (ft/sec) (V_{flume}-V_{sw})	Within Specs (±0.016 ft/sec)
1 ft^3/sec - 0.00 bypass	0.109±0.002	0.103±0.012	0.006	Meets
1 ft^3/sec - 0.05 bypass	0.078±0.002	0.085±0.007	-0.007	Meets
1 ft^3/sec - 0.10 bypass	0.073±0.001	0.073±0.008	0.000	Meets
5 ft^3/sec - 0.00 bypass	0.584±0.012	0.573±0.012	0.011	Meets
5 ft^3/sec - 0.20 bypass	0.598±0.012	0.576±0.010	0.022	Exceeds
5 ft^3/sec - 0.25 bypass	0.459±0.009	0.456±0.009	0.003	Meets
5 ft^3/sec - 0.30 bypass	0.456±0.009	0.460±0.009	-0.004	Meets
5 ft^3/sec - 0.40 bypass	0.477±0.010	0.470±0.010	0.007	Meets
5 ft^3/sec - 0.50 bypass	0.476±0.010	0.453±0.007	0.023	Exceeds
7 ft^3/sec - 0.25 bypass	0.566±0.012	0.567±0.009	-0.001	Meets
7 ft^3/sec - 0.30 bypass	0.578±0.012	0.584±0.008	-0.006	Meets
7 ft^3/sec - 0.35 bypass	0.529±0.011	0.527±0.004	0.002	Meets
7 ft^3/sec - 0.50 bypass	0.528±0.011	0.542±0.006	-0.014	Meets
7 ft^3/sec - 0.60 bypass	0.541±0.011	0.549±0.006	-0.008	Meets
7 ft^3/sec - 0.70 bypass	0.567±0.012	0.547±0.016	0.020	Exceeds

Table 3. Comparison of Mean Pipe Velocity to SW Mean Velocity for 18-inch Pipe Tests

Test Setup	Calculated Pipe Velocity (±δV, ft/sec)	SW Mean Velocity (±δV, ft/sec)	Discrepancy (ft/sec) (V_{pipe} - V_{sw})	Within Specs (±0.016 ft/sec or ±1% of V_{sw})
1 ft^3/sec - 0.00 bypass	0.566±0.004	0.582±0.022	-0.016	Meets
1 ft^3/sec - 0.05 bypass	0.538±0.004	0.539±0.033	-0.001	Meets
1 ft^3/sec - 0.10 bypass	0.509±0.004	0.521±0.018	-0.012	Meets
5 ft^3/sec - 0.00 bypass	2.829±0.021	2.936±0.016	-0.106	Exceeds
5 ft^3/sec - 0.20 bypass	2.705±0.021	2.820±0.014	-0.115	Exceeds
5 ft^3/sec - 0.25 bypass	2.683±0.022	2.821±0.015	-0.138	Exceeds
5 ft^3/sec - 0.30 bypass	2.666±0.022	2.800±0.019	-0.134	Exceeds
5 ft^3/sec - 0.40 bypass	2.677±0.022	2.728±0.015	-0.051	Exceeds
5 ft^3/sec - 0.50 bypass	2.586±0.022	2.682±0.016	-0.096	Exceeds
7 ft^3/sec - 0.25 bypass	3.820±0.030	3.837±0.014	-0.017	Meets
7 ft^3/sec - 0.30 bypass	3.892±0.030	3.852±0.017	-0.060	Exceeds
7 ft^3/sec - 0.35 bypass	3.763±0.030	3.708±0.014	0.055	Exceeds
7 ft^3/sec - 0.50 bypass	3.684±0.030	3.672±0.016	0.012	Meets
7 ft^3/sec - 0.60 bypass	3.622±0.031	3.661±0.013	-0.039	Exceeds
7 ft^3/sec - 0.70 bypass	3.577±0.031	3.535±0.023	0.042	Exceeds

Tables 4 and 5 summarize the temporal mean and uncertainty (δQ) in the flow computations for the 4-ft flume and 18-inch diameter pipe tests. The uncertainty in the flow computations was computed using the general formula for error propagation as described by Taylor (1997). The actual flume flow was computed as the difference between the laboratory flow and the mean bypass flow as measured with the strap-on acoustic flowmeter.

Discussion of Results

Depth Measurements – Measurement of flow depth using the staff gage was often difficult because of small waves in the flume. The staff gage readings shown in table 1 are averages of the observations at the beginning and end of the test. The uncertainty in the staff gage readings was ±0.01 ft which was selected to be half of the staff gage resolution, ±0.02 ft. Tests were conducted under a near-constant depth, but for some tests it was difficult to achieve this condition, especially for the 1 ft^3/s test. Periodic tailgate adjustments had to be made to keep the pipe submerged during those tests. For 1 ft^3/s tests, the staff gage readings at the end of the test were compared to measurements logged by the SW at the same time.

Table 4. Flow Measurement Results for the 4-ft Flume Tests

Test Setup	Target Flume Flow (±δQ, ft^3/sec)	Actual Flume Flow (±δQ, ft^3/sec)	SW Computed Flume Flow (± δQ, ft^3/sec)	Percent Difference
1 ft^3/sec - 0.00 bypass	1.000±0.003	n/a	0.994±0.147	0.6
1 ft^3/sec - 0.05 bypass	0.950±0.003	n/a	0.941±0.194	0.9
1 ft^3/sec - 0.10 bypass	0.900±0.003	n/a	0.920±0.200	-2.2
5 ft^3/sec - 0.00 bypass	5.000±0.015	5.00±0.015	4.912±0.139	1.8
5 ft^3/sec - 0.20 bypass	4.800±0.014	4.78±0.016	4.641±0.131	2.9
5 ft^3/sec - 0.25 bypass	4.750±0.014	4.74±0.016	4.774±0.169	-0.7
5 ft^3/sec - 0.30 bypass	4.700±0.014	4.71±0.016	4.754±0.166	-0.9
5 ft^3/sec - 0.40 bypass	4.600±0.014	4.73±0.016	4.664±0.160	1.4
5 ft^3/sec - 0.50 bypass	4.500±0.014	4.57±0.017	4.379±0.156	4.2
7 ft^3/sec - 0.25 bypass	6.750±0.020	n/a	6.851±0.195	-1.5
7 ft^3/sec - 0.30 bypass	6.700±0.020	n/a	6.809±0.188	-1.6
7 ft^3/sec - 0.35 bypass	6.650±0.020	6.65±0.022	6.683±0.204	-0.5
7 ft^3/sec - 0.50 bypass	6.500±0.020	6.51±0.023	6.655±0.198	-2.2
7 ft^3/sec - 0.60 bypass	6.400±0.019	n/a	6.517±0.192	-1.8
7 ft^3/sec - 0.70 bypass	6.300±0.019	6.31±0.025	6.145±0.181	2.6

n/a – time series of bypass flowmeter data not available for this test

Table 5. Flow Measurement Results for the 18-inch Pipe Tests

Test Setup	Target Pipe Flow (±δQ, ft^3/sec)	Actual Pipe Flow (±δQ, ft^3/sec)	SW Computed Pipe Flow (±δQ, ft^3/sec)	Percent Difference
1 ft^3/sec - 0.00 bypass	1.000±0.003	n/a	1.041±0.029	-4.1
1 ft^3/sec - 0.05 bypass	0.950±0.003	n/a	0.964±0.029	-1.5
1 ft^3/sec - 0.10 bypass	0.900±0.003	n/a	0.931±0.029	-3.4
5 ft^3/sec - 0.00 bypass	5.000±0.015	5.00±0.015	5.248±0.063	-5.0
5 ft^3/sec - 0.20 bypass	4.800±0.014	4.78±0.016	5.045±0.060	-5.5
5 ft^3/sec - 0.25 bypass	4.750±0.014	4.74±0.016	5.044±0.060	-6.4
5 ft^3/sec - 0.30 bypass	4.700±0.014	4.71±0.016	5.002±0.060	-6.2
5 ft^3/sec - 0.40 bypass	4.600±0.014	4.73±0.016	4.878±0.058	-3.1
5 ft^3/sec - 0.50 bypass	4.500±0.014	4.57±0.017	4.795±0.057	-4.9
7 ft^3/sec - 0.25 bypass	6.750±0.020	n/a	6.860±0.082	-1.6
7 ft^3/sec - 0.30 bypass	6.700±0.020	n/a	6.886±0.082	-2.8
7 ft^3/sec - 0.35 bypass	6.650±0.020	6.65±0.022	6.630±0.079	0.3
7 ft^3/sec - 0.50 bypass	6.500±0.020	6.51±0.023	6.565±0.078	-0.8
7 ft^3/sec - 0.60 bypass	6.400±0.019	n/a	6.544±0.078	-2.2
7 ft^3/sec - 0.70 bypass	6.300±0.019	6.31±0.025	6.320±0.076	0.2

n/a – time series of bypass flowmeter data not available for this test

The discrepancies between the depths measured by the SW and the staff gage ranged from -0.04 to 0.02 ft for this evaluation (Table 1). The manufacturer specifies the accuracy of the of the instrument's water level measurements as the larger of ±0.1% of the measured value, or ±0.01 ft. Since all of the tests were conducted for depths less than 10 ft the ±0.01 ft criterion applies. Of the 15 tests, 7 depth measurements were within the manufacturers specifications (figure 5). The mean of all 15 discrepancies in depth were within the manufacturers specification of ±0.01 ft. This result was good considering the staff gage was read to the nearest 0.02 ft and the difficulties in maintaining a constant depth for the duration of each test.

In the case of the pipe section, the mean of the SW depth measurements was 1.496 ft. Although the resolution of depth measurements was not reported in the specifications it appears to be 0.003 ft. All other depth readings were within ±0.33% of that value. As mentioned previously, the 18-inch pipe was kept submerged for the duration of all tests with the exception of the 1 ft^3/s test with a bypass flow of 0.05 ft^3/s. During this test the depth was observed to have dropped so that the pipe was no longer completely submerged. The tailgate at the end of the flume was adjusted to correct this. The time was noted and data collected during the period in which the pipe was not fully submerged were excluded from the data analysis.

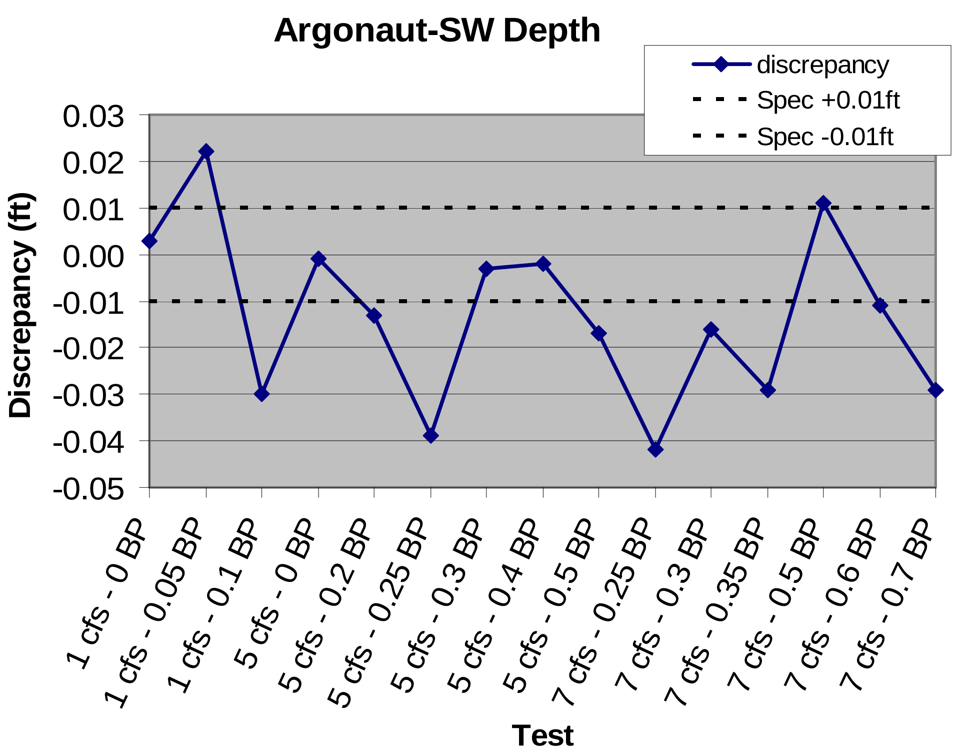

Figure 5. Discrepancies between SW and staff gage depth measurements for 15 flume tests.

Velocity Measurements - For the flume tests, computed mean channel velocities were compared to the SW computed mean velocities (Table 2). The discrepancies between these velocities ranged from -0.014 to 0.023 ft/sec for this evaluation. For the velocities measured in all 15 flume tests the ±0.016 ft/sec specification applies. In general, the performance of the SW for the flume tests was within the "strict" specifications used for this evaluation. Figure 6 shows the discrepancies for each test and the agreement with the accuracy specification. Only three tests exceeded the accuracy specification and by less than +0.008 ft/sec. A review of the individual (120 second average) SW velocity readings for each test did not reveal any unusual readings. In fact, for all flume tests the standard errors (δV) in SW mean velocity were less than or equal to the 0.016 ft/sec specification (Table 2). This result indicates that for a 60 minute long test in a nearly constant flow field the SW collected enough velocity readings to describe the mean channel velocities within the manufacturer's accuracy specifications. The discrepancies between computed mean channel velocities probably result from errors associated with the mean velocity calculation performed by the SW and/or that the cross sectional velocity distribution in the flume is not fully developed. An error in the depth measurement could also affect the mean channel velocity uncertainty.

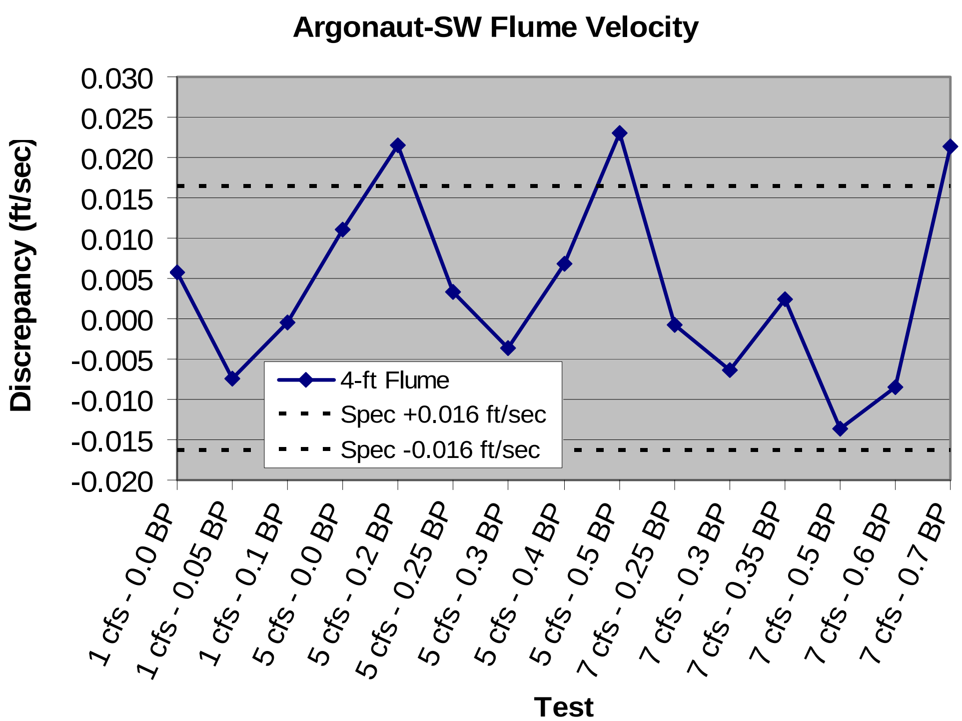

Figure 6. Discrepancy between mean channel velocities for 15 flume tests.

The SW has the capability to apply an index-velocity equation to compute the mean channel velocity using the SW-computed mean velocity and stage. For the flume tests, SW stage and velocity data were processed using multiple linear regression analysis to determine the coefficients for the index-velocity equation:

$$V_{flume} = V_{const} + V_{SW}\left(V_{coeff} + \left(Stage_{coeff} \times Stage\right)\right) \quad \text{.........Index-velocity equation}$$

Where,

V_{flume} = computed mean channel velocity, (ft/sec)
V_{const} = regression constant, (ft/sec)

V_{SW} = SW mean velocity for period of V_{flume} measurement, (ft/sec)
V_{coeff} = velocity regression coefficient, (dimensionless)
$Stage_{coeff}$= stage regression coefficient, (1/ft)
$Stage$ = SW measured stage, (ft)

For the flume tests, the multiple linear regression was performed with V_{flume} the dependent variable and the independent variables were V_{SW} and the product of V_{SW} and stage. Multiple linear regression resulted in this best-fit equation:

$$V_{flume} = -0.00089 + V_{SW}\left(1.124 - 0.0405(Stage)\right) \text{ with an } R^2 = 0.998$$

Where R^2 is the coefficient of determination. R^2 is a parameter which means that 99.8 percent of the variation in the mean flume velocity was described by the variables V_{SW} and stage, with a 95 percent confidence level. This is a small improvement over a simple linear regression with V_{flume} the dependent variable and V_{SW} the independent variable. Linear regression resulted in the following best-fit equation:

$$V_{flume} = -0.0008 + 1.014(V_{SW}) \text{ with an } R^2 = 0.996$$

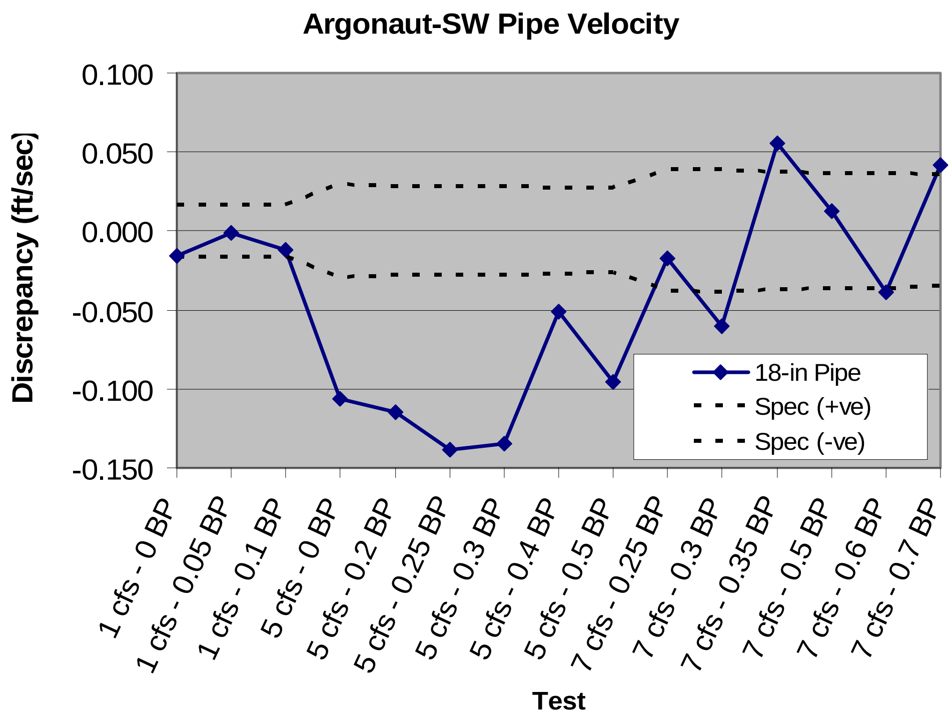

Figure 7. Discrepancy between mean velocities for 15 pipe tests.

For the pipe tests, mean pipe velocities were compared with the SW computed mean velocities. For the 1 ft^3/sec tests, the ±0.016 ft/sec specification applies. For the 5 and 7 ft^3/sec tests the ±1 percent of the measured velocity specification applies. The discrepancies between velocities ranged from -0.138 to 0.055 ft/sec for this evaluation (see Table 3). In general, the velocity discrepancies for 18-inch pipe tests exceeded the velocity specifications. Figure 7 shows the discrepancies for each test and their relationship to the accuracy specification. Ten of 15 tests exceeded the velocity accuracy specification. It is interesting that all the 1 ft^3/sec tests were within specs, all the 5 ft^3/sec tests were outside specs, and the 7 ft^3/sec tests were close to the specs. A review of the individual SW velocity readings for each test did not reveal any unusual readings as illustrated by the small standard errors in the SW mean velocities shown in Table 3. In fact, for the 5 and 7 ft^3/sec pipe tests the standard error in SW mean velocities were less than the ±1 percent velocity specification. The discrepancies between computed mean channel velocities probably result from errors associated with the mean velocity calculation performed by the SW and/or that the cross sectional velocity distribution in the pipe is not fully developed. In contrast to the flume tests, stage measurements do not enter in to the uncertainty because the pipe was kept full.

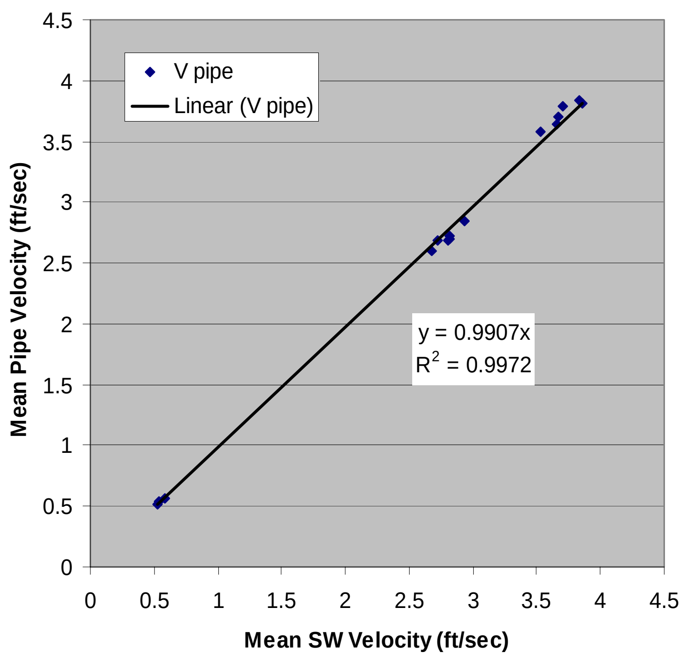

Figure 8. Linear regression relationship between SW mean velocities and the mean pipe velocity.

In an effort to describe the apparent systematic error in pipe velocities a linear regression was performed on the mean pipe velocity data. Figure 8 shows the linear regression results of all tests comparing the SW computed mean pipe velocity (V_{mean}) and the computed mean pipe velocity (V_{pipe}). For this application, the coefficient of determination (R^2) of 0.997 indicates that SW mean velocities can be adjusted to reduce the discrepancies and improve the discharge computation accuracy. This systematic error is most likely attributed to the algorithm used to convert V_x to V_{mean}. Another important factor that likely affects the velocity accuracy is the small diameter pipe used in this evaluation. In an 18-in diameter pipe the velocity measurement is determined from velocities profiled from about one half the pipe diameter because of the blanking distance above the SW transducer and the exclusion of velocity data collected near the top of the pipe because of side-lobe interference. Sontek reports that the last 20 percent of the velocity profile in a pipe may include side-lobe interference and that their algorithm automatically excludes this data (Sontek 2003).

Flow Measurement - Tables 4 and 5 present the target, actual, and SW computed flows for the flume and pipe tests. Actual flows were computed by subtracting the average flow measured in the bypass pipe from the flow supplied to the headbox. The uncertainties in the flowrate (±δQ) are included in the tables and were computed using error propagation techniques (Taylor 1997). The percent differences in Tables 4 and 5 were calculated using the SW computed flow and the actual flow when possible; otherwise the target flow was used in place of the actual flow. The equation used to compute the percent difference is: $(Q_{flume}-Q_{SW}) / Q_{flume} \times 100\%$.

Figure 9 shows the percent differences in flow measurements for the 15 tests conducted in the flume and pipe sections. For flume tests, all the average SW computed flowrates were within ±5 percent of the laboratory flowrate. The mean percent difference for the 15 flume tests was - 0.2 percent. The SW computes flowrate using velocity and area (computed from a programmed depth-area relationship) measurements. As a result, discrepancies in velocity and depth will factor into the uncertainty in the computed flowrate. However, since the flow depth was held nearly constant throughout each test, the majority of the variation in flowrate should be attributed to velocity.

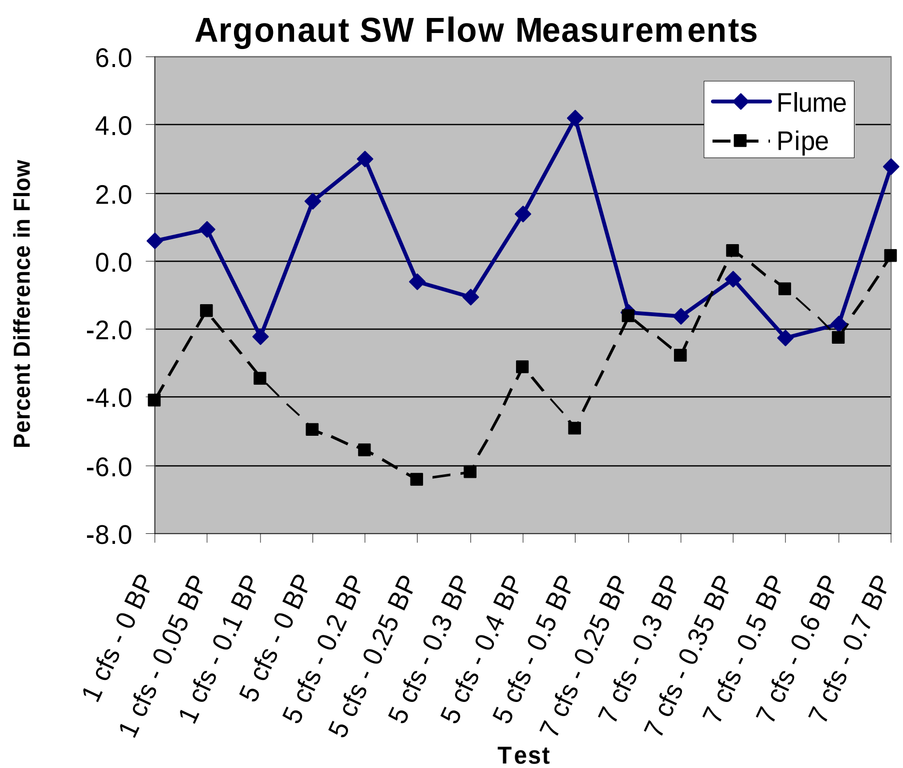

Figure 9. Percent difference of SW computed flowrates from known flowrates for flume and pipe tests.

For pipe tests, 12 of 15 tests were within ±5 percent of the laboratory flowrate. The mean percent difference for the 15 pipe tests was 3.1 percent greater than the known pipe flow. In 13 of the 15 pipe tests, the Argonaut-SW measured a flowrate greater than the flume flowrate. This systematic error in discharge seems to be related to the computation of mean pipe velocity, as described earlier.

An analysis was performed to determine the minimum averaging interval required to reduce instrument uncertainty in discharge computation to below ±5 percent. Figure 10 shows the relationship between the standard error in a series of discharge computations for a 5 ft^3/sec test and a range of averaging intervals. For the flume test, a 12 minute averaging interval was required to reduce the standard error in the SW discharge to below ±5 percent. It is important to note that this result was for steady flow conditions which may not be duplicated in a field application. Selecting an appropriate averaging interval for a field application should balance the need to capture varying flow conditions with the data storage or power requirements for the deployment. A similar analysis was done for full pipe flow and a 4 minute averaging interval was adequate to reduce the standard error in the SW discharge computation to below ±5 percent. This improved performance is likely attributed to removing the uncertainty in depth measurement (full pipe) from the discharge computations and pipe velocities that were 5 times larger than the flume velocities. Note that this analysis does not take into account uncertainties associated with the mean velocity computation (converting V_x to V_{mean}) or the discharge calculations.

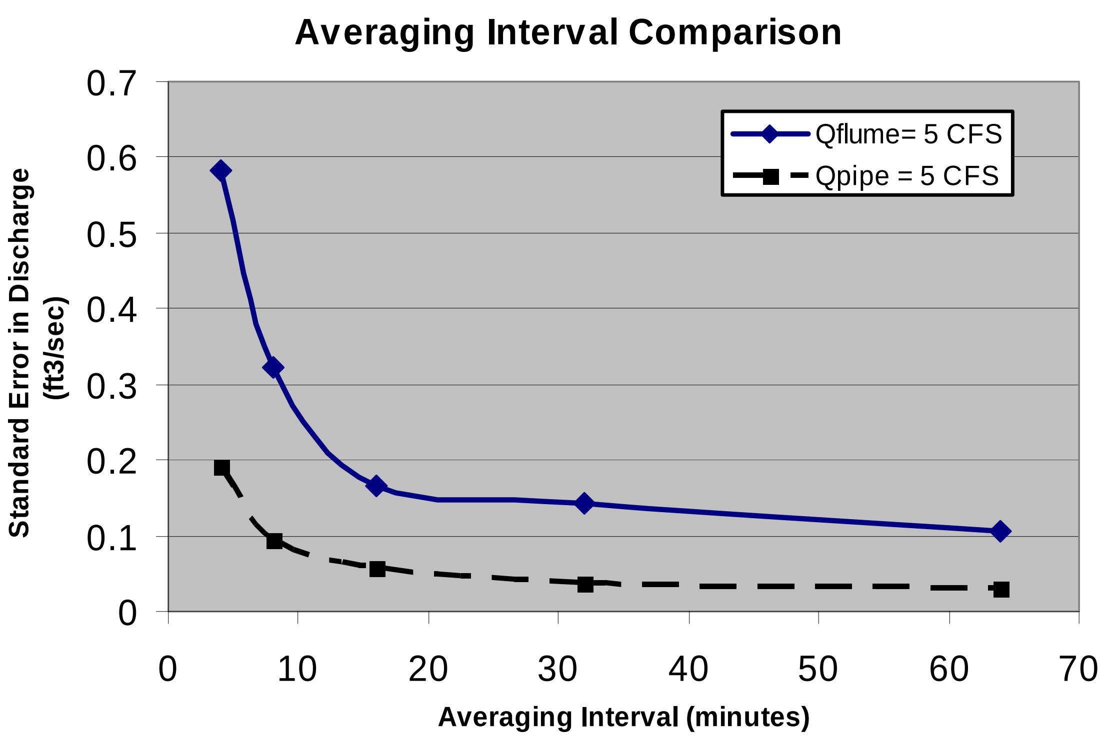

Figure 10. Standard error in SW discharges versus averaging interval for a comparable set of flume and pipe discharge measurements.

Conclusions

- Two Argonaut-SW flowmeters performed well in this laboratory evaluation for a wide range of flows. The SW-computed discharges were, on average, within +0.2 percent of the known flume discharges. For pipe tests, the SW-computed discharges were, on average, within +3.1 percent of the known pipe discharges.

- SW discharge measurement accuracy should be sufficient to quantify seepage in a canal reach provided the seepage is greater than 5 percent of the total flow and the flow conditions are steady for 30 minute intervals.

- For the majority of flume tests, the SW performed within the accuracy specifications for mean channel velocity and depth measurements. These results were notable considering the potential for a non-standard velocity profile generated from the weir located downstream. Likewise, the withdrawal of the bypass flows may have skewed the cross sectional velocity distribution.

- For the majority of pipe tests, discrepancies between computed mean pipe velocities did not meet the accuracy specifications for velocity measurements. This can most likely be attributed to the small pipe size and the algorithm (mean velocity calculation method) used by the SW to convert V_x to V_{mean}. The SW depth measurements in the pipe were within the accuracy specifications for all tests.

- For flume flow an averaging interval of 12 minutes was sufficient to reduce the instruments standard error in discharge to below ±5 percent. It is important to note that this result was for steady flow conditions which may not be duplicated in a field application. As a result, the averaging interval selected for a field application should be short enough to capture varying flow conditions.

- For full pipe flow an averaging interval of 4 minutes was sufficient to reduce the instruments standard error in discharge to below ±5 percent. The reduction in uncertainty is most likely a result of the higher velocities in the pipe as compared to the flume velocities. However, this analysis doesn't account for systematic errors attributed to the mean velocity calculation method used in the discharge computation.

References

Chen, C.L. "Unified theory on power laws for flow resistance," Journal of Hydraulic Engineering, ASCE, Vol. 117, No. 3, March 1991, pp. 371-389.

Sontek/YSI, Inc., 2003, Argonaut-SW System Manual, firmware version 9.3.

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Appendix – Uncertainty Analysis

Uncertainty analyses were performed on the measured and computed values published in this report. Uncertainties were computed using general error propagation techniques for a function with several variables (Taylor, 1997). A summary of the uncertainty equations used are included below.

Uncertainty Analysis – Laboratory and Flume Discharge

$\delta Q_{lab} = Q_{lab} * 0.003$ and $\delta Q_{BP} = Q_{BP} * 0.02$

$$\delta Q_{flume} = \sqrt{\delta Q_{lab}^{\ 2} + \delta Q_{BP}^{\ 2}} \equiv \sqrt{(Q_{lab} * 0.003)^2 + (Q_{BP} * 0.02)^2}$$

Uncertainty Analysis - Mean Flume Velocity

$V_{flume} = \dfrac{Q_{lab} - Q_{bp}}{A_{flume}}$ **continuity equation for calculating mean flume velocity**

$$\delta_{V_{flume}} = \delta_Q \frac{\partial V}{\partial Q} + \partial_A \frac{\partial V}{\partial A}$$

$$\delta V = \sqrt{\left(\frac{\delta Q_{lab}}{y_{staff} w_{flume}} + \frac{\delta Q_{bp}}{y_{staff} w_{flume}}\right)^2 + \left(-\frac{Q_{lab} - Q_{bp}}{y_{staff}^{\ 2} w_{flume}} \delta y_{staff}\right)^2 + \left(-\frac{Q_{lab} - Q_{bp}}{y_{staff} w_{flume}^{\ 2}} \delta w_{flume}\right)^2}$$

Where:

$\delta Q_{lab} = 0.003 \times Q_{lab} (ft \cdot \sec^{-3}),$
$\delta Q_{bp} = 0.02 \times Q_{bp} (ft \cdot \sec^{-3}),$
$\delta y_{staff} = 0.01\, ft,$
$\delta w_{flume} = 0.005\, ft$

Uncertainty Analysis - Mean Pipe Velocity

$$V_{pipe} = \frac{Q_{lab} - Q_{bp}}{A_{pipe}}$$

$$\delta V_{pipe} = \sqrt{\left(\frac{\delta Q_{lab} + \delta Q_{bp}}{A_{pipe}}\right)^2 + \left(-\frac{(Q_{lab} - Q_{bp})}{A_{pipe}^{\ 2}} \delta A_{pipe}\right)^2}$$

Where:

$\delta Q_{lab} = 0.003 \times Q_{lab} (\ ft \cdot \sec^{-3}),$

$\delta Q_{bp} = 0.02 \times Q_{bp} (\ ft \cdot \sec^{-3}),$

$\delta A_{pipe} = 0.012\ ft^2$

Uncertainty Analysis - SW Flume Discharge Computation

$Q_{flume} = V_{sw} \times SF \times y_{sw} \times w_{flume}$ **Continuity Equation**

Note: The velocity profile scale factor (SF) was excluded from the uncertainty analysis because determination of the uncertainty was beyond the scope of this evaluation.

$$\delta Q_{flume} = \sqrt{\left(y_{sw} w_{flume} \delta V_{sw}\right)^2 + \left(V_{sw} w_{flume} \delta y_{sw}\right)^2 + \left(V_{sw} y_{sw} \delta w_{flume}\right)^2}$$

Where:

$\delta V_{sw} = 0.016\ \ ft \cdot \sec^{-1},$

$\delta y_{sw} = 0.01\ \ ft,$

$\delta w_{flume} = 0.005\ \ ft$

Uncertainty Analysis – SW Pipe Discharge (for full pipe only)

$Q_{pipe} = V_{sw} A_{pipe}$ **Continuity Equation**

$\delta Q_{pipe} = \sqrt{\left(A_{pipe} \delta V_{sw}\right)^2 + \left(V_{sw} \delta A_{pipe}\right)^2}$ **Total Uncertainty Equation**

Where:

$\delta V_{sw} = 0.016,\ or\ 0.01 \times V_{sw},\ \ ft \cdot \sec^{-1},$

$\delta A_{pipe} = 0.012\ ft^2$