FLOW MEASUREMENT WITH LONG-THROATED FLUMES UNDER UNCERTAIN SUBMERGENCE

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ABSTRACT

The evolving circumstances under which irrigation districts operate include growing demands for more accurate knowledge and accountability of flow throughout the conveyance network, along with increased needs for timely awareness when unexpected flow conditions are present. For open channel conveyance systems, critical-flow structures (flumes or weirs) offer the simplicity of a direct correlation between upstream water level and a corresponding discharge. Unfortunately at many locations where flow measurement is desired there may be insufficient head available for operation of a critical-flow measurement structure under all flow conditions that may occur.

In recent years following development of computer-based design and calibration software, long-throated flumes have gained increasing popularity as the class of critical-flow structures which offer the greatest submergence tolerance. Numerous long-throated flumes have been installed at sites where head availability is marginal. In some cases after a flume has been installed it becomes apparent that the head is not sufficient under all operating conditions for critical-flow measurement. Reclamation’s Hydraulic Investigations and Laboratory Services Group and Yuma Area Office Water Conservation Field Services Program are field testing a system for measuring flow with long-throated flumes under submerged or unsubmerged conditions.

The initial scope this field study targeted specifically selected for continuously submerged conditions. The project scope has been expanded to include occasionally submerged sites in recognition that numerous long throated flumes have been installed at sites where submergence conditions that exceed the flume’s modular limit exist under some operating conditions.

INTRODUCTION AND BACKGROUND

Engineers at the US Bureau of Reclamation (Reclamation) Hydraulic Investigations and Laboratory Group have recently been expanding on the work of others (Replogle, 1994) in low-cost pipe venturi flow measurement by applying the venturi solution for measuring flow at submerged flumes. For the pipe venturi solution, the measured static head differential along with known cross sectional flow areas from two locations – the venturi approach section and the constricted throat section – are needed to determine

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discharge rate by simultaneously solving relationships for conservation of energy and conservation of mass.

$$Q = C_d * \frac{A_1 * A_T}{\left(A_1^2 - A_T^2\right)^{0.5}} * \left(\frac{2g}{\alpha} * \left(H_1 - H_T\right)\right)^{0.5} \qquad \text{Equation 1.}$$

Where:

Q = *Discharge* (ft^3/s)
C_d = *Discharge coefficient – determined empirically*
A_1 = *Cross section flow in the meter approach section* (ft^2)
A_T = *Cross section flow area in the constricted throat section of meter* (ft^2)
g =*Gravitational Acceleration* (= 32.2 ft/s^2)
α = *Velocity distribution coefficient (a value of 1.02 is commonly used)*
H_1 = *Approach section static head (ft)*
H_T = *Throat section static head (ft)*

Center line of meter must be horizontal
H_1 *and* H_T *measured from a common datum*

For application of this solution to an open channel structure, both the approach section and a constricted throat section must be prismatic in shape for a sufficient distance to ensure parallel flow lines past the static head measurement point of each section. This requirement is consistent with geometric requirements for a critical-flow long-throated flume. The critical flow long-throated flume calibration procedure also functions by simultaneous solution for conservation of energy and conservation of mass. Long-throated flume calibration utilizes an iterative process, whereby an appropriate approach section level is converged upon that corresponds with the unique critical depth at the throat for a given discharge.

Notable factors in comparing application of the venturi solution to a pipe meter with using the venturi solution on a long-throated flume are the magnitude of head differential observed as flow moves from the approach section, then is accelerated through the constricted throat sections. Pipe meters may be designed to provide a significant head differential (ranging from a few tenths of a foot to multiple feet) over the desired measurement range that enables a comparatively high degree of resolution in determining flow rates, yet impose comparatively small head loss on the system

In contrast, the magnitude of head differential seen for long throated flumes would typically be considerably smaller than the head differential seen using a pipe meter. For example, in a field data set discussed below measured differential at a submerged flume over a 6 hour period ranged from 0.021 ft. to 0.11 ft while corresponding submergence rates varied from 98.8% to 93.0% respectively. With the smaller ranges of head differential available, precision in measuring water levels is an important factor in obtaining flow measurements of desired accuracy with a flume using the venturi solution.

LABORATORY TESTS

Limited-scope laboratory tests were performed at Reclamation's hydraulics laboratory in 2003 and 2004. Both test series utilized a laboratory model in which a laterally contracted flume was installed at mid reach of a trapezoidal channel. A ramp-type long-throated flume was installed at the downstream end of the channel. The ramp flume served both to force submergence on the laterally-contracted flume and also functioned for obtaining control flow measurements against which to compare flow calculations from the submerged flume. Figure 1 is a photo of the laboratory test channel looking downstream.

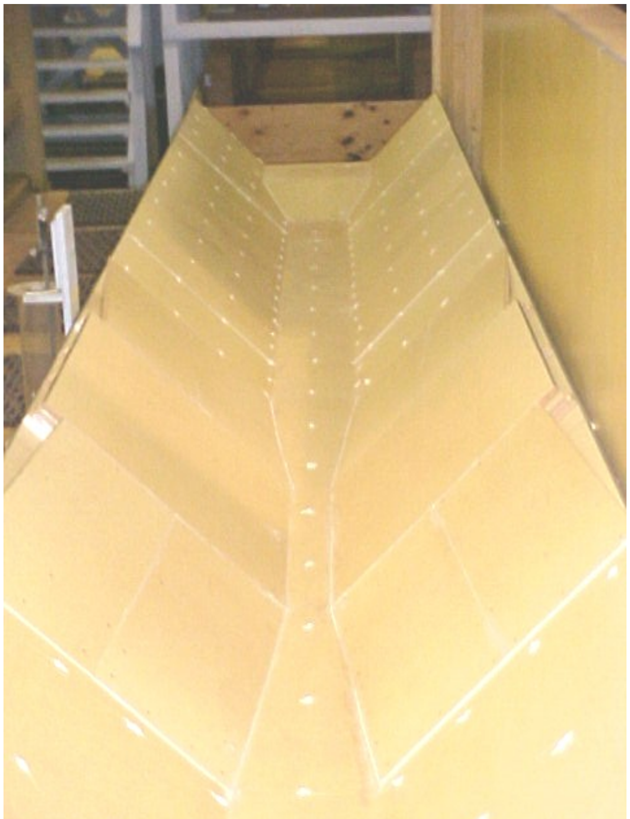

Figure 1. Laboratory Test Facility

During the 2003 testing, all water level measurements were made using a single stilling well equipped with a hook-type point gage capable of least readings of 0.001 ft. This well was connected by a valved manifold to each tap location on the test channel where water level measurements were needed. In the testing procedure, each time the stilling well was connected to a different tap, level readings were repeated at 5 minute intervals until consecutive readings were unchanged, indicating the stilling well had reached equilibrium level with static pressure at the tap.

Results from the 2003 tests showed a promising level of agreement between flow rates determined by the ramp flume and the submerged flume. The single stilling well water level measuring system that had been employed did not appear to be practical for field applications. During the laboratory tests, it had required as long as 30 minutes to confirm the stilling well was in equilibrium with static pressure at a tap. Given that water levels representing static head at two taps must be determined to apply the venturi discharge equation, a means of more rapidly determining water levels with a suitable degree of accuracy would be imperative in moving this measurement technology into field tests.

Laboratory testing in 2004 focused on identifying a means of obtaining water level measurements in a timely manner that could translate into practical field application of the technology. For the 2004 tests, stilling wells were installed at each channel tap. A bubbler sensor was utilized to electronically sense water levels. In order to minimize variability that use of multiple sensors would introduce, a single bubbler unit was used to read all taps by physically connecting and disconnecting an air line from the bubbler apparatus to taps in the various stilling wells. Using a bubbler sensor in this manner, the time required to obtain water level measurements needed for application of the venturi discharge equation was reduced to no more than a couple of minutes. The potential for further simplifying reading multiple water levels with a bubbler sensor by adding a solenoid valve controlled manifold to the bubbler output line was readily evident.

An additional feature of the 2004 test set up was the piping configuration of the stilling wells. Valves were installed in the line between each stilling well and channel tap. A line with a valve was also installed between each stilling well. This plumbing arrangement enabled all stilling wells to be isolated from the laboratory channel and to be observed with a common level at all wells. This configuration greatly simplified initial calibrations and subsequent calibration checks in assuring that sensor offset values for the respective taps reflect a common datum to the accuracy limits of the bubbler sensor. Results from the 2004 testing again showed a promising level of agreement between discharge computed for the submerged flume and discharge determined at the ramp-type long-throated flume. Figure 2 is a plot of the 2004 tests.

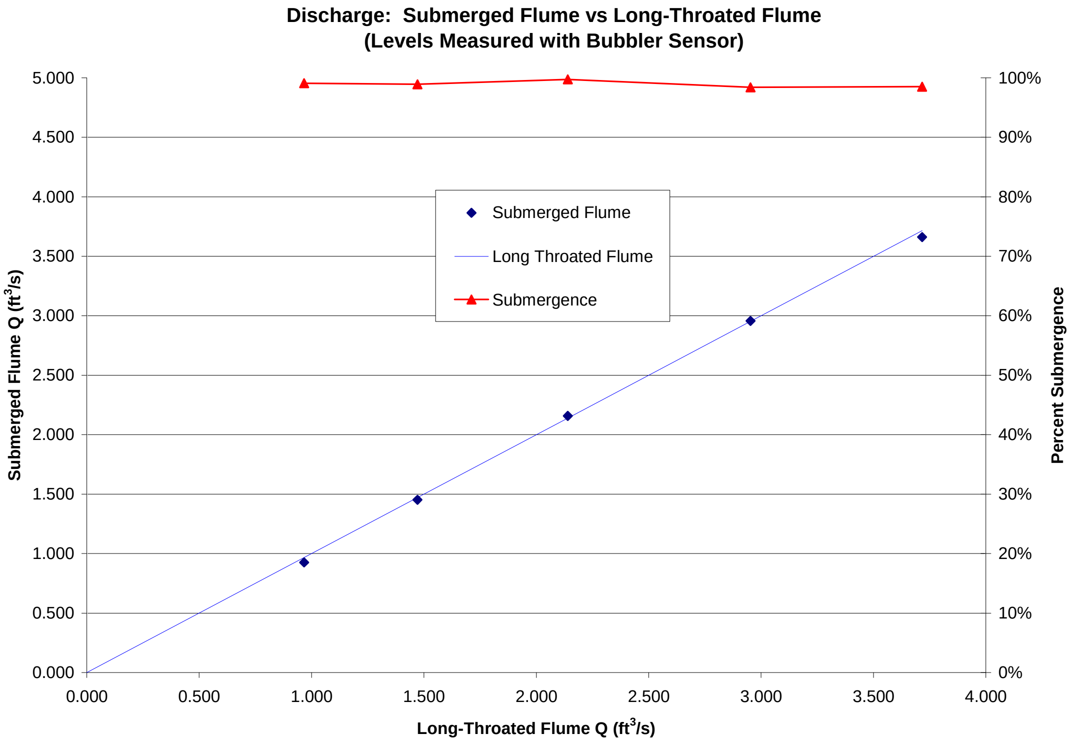

Figure 2. Comparative discharge calculations from 2004 laboratory tests

FIELD TESTS

University of Arizona Valley Farm Site An initial submerged flume field site was installed in early 2007 at the University of Arizona Valley Farm in cooperative effort including the University of Arizona Extension Service, Reclamation’s Yuma Area Office

Water Conservation and Field Services Program, and Reclamation's Hydraulic Investigations and Laboratory services group. This site is located approximately 30 feet downstream from a location where flow exits a pipeline into a concrete lined channel. No measurement structure was previously in place at this site. Figure 3 shows freshly placed concrete that forms a laterally contracted flume at the University of Arizona Valley Farm site.

As a result of a leaking valve at the head of the upstream pipe section, this site is constantly subjected to standing water at times of no discharge. Earthen berms shown in Figure 3 were necessary to isolate the flume during construction from this standing water. The standing water coupled with nearly flat canal slope create excessive submergence conditions for operation of a critical-flow flume at this location.

Figure 3. University of Arizona Valley Farm submerged flume site

Two large vertical pipes seen at the right of the freshly placed concrete flume are stilling wells. Three smaller vertical pipes are access-ways to valves in each line between the canal and respective stilling well and a line between the two stilling wells. Two float & pulley level sensors were installed for water level measurement at this site. At the time of installation, a bubbler sensor configuration capable of automatically reading multiple taps was under development at Reclamation's hydraulics laboratory but was not yet available for use at this site.. A programmable logic controller (PLC) calculates water levels from sensor inputs and calculates discharge rate on three-minute cycles. Calculated values are shown on an LED Display.

Discharges of approximately 5 ft^3/s and 10 ft^3/s as measured using the venturi solution at this site were compared with stream gated values using a Price AA meter and found to be within 10% agreement. Based on initial observations at the University of Arizona Valley Farm site, YAO inquired about application of the venturi discharge solution at existing long-throated flumes that had been designed assuming critical-flow operation, but which at times are subjected to submergence that exceeds modular limits. Following these conversations, contacts were made with both the Unit B Irrigation District and the Yuma County Water Users Association (YCWUA). Plans for three additional field sites, one at Unit B, and two at YCWUA emerged from these contacts.

Unit B Irrigation District Site: At the Unit B district a site was selected where no measurement structure had previously existed. The site is the head of a concrete-lined lateral with limited head availability. When water is conveyed in the lateral, a discharge rate of 10 ft^3/s is the consistently targeted delivery rate. Submergence conditions at this flume, seen in Figure 4, are expected to exceed modular limits during water deliveries.

Figure 4. Unit B District Flume

A laterally-contracted “insert” flume pre-constructed of plastic lumber by Reclamation’s YAO shops was installed at the Unit B site in November of 2007. A PLC with integral data communications radio was installed along with a bubbler sensor. At the time of this installation, a prototype bubbler sensor with a solenoid valve bank capable of reading multiple water levels had been configured and tested at Reclamation’s laboratory. Ae bubbler sensor unit with solenoid valve bank are seen in Figure 5 linked to a radio/control unit.

A concept employed for the Unit B and YCWUA field sites was to include measurement of actual submergence rate. To measure submergence the bubbler sensor was equipped with three solenoid valves to measure water levels in the upstream, throat and downstream sections of each flume. Upstream and downstream levels are needed to determine submergence, while upstream and throat levels are needed for the venturi solution.

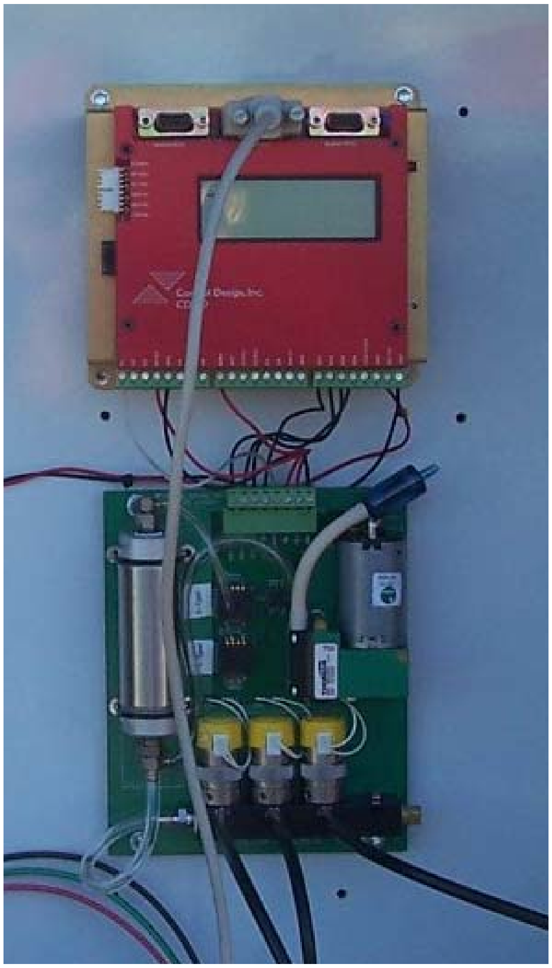

Figure 5. Radio/Control unit &
Bubbler w/ Solenoid Valve Bank

Figure 6. YCWUA Potter Flume

Figure 7. YCWUA Cumming Flume

<u>YCWUA Sites:</u> Two YCWUA sites were selected where existing long-throated flumes operate at times at submergence rates that exceed modular limits for critical-flow

operation. At the head of YCWUA's Potter lateral, the district has recently installed a ramp-type long-throated flume. At the head of YCWUA's Cumming lateral, the district had recently installed a long-troated flume featuring both lateral contraction and a ramp in the flume invert. Submerged flow instrumentation was installed at the flumes on each of these laterals in November of 2007. Figure 6 and Figure 7 are photos of the Potter and Cumming sites respectively (both views looking downstream).

In an effort geared examining a reduced cost installation alternative, the Unit B site and both YCWUA sites were initially set up without stilling wells. Bubbler lines were attached to the flume walls underneath PVC arc sections made by splitting a six-inch PVC pipe longitudinally into approximately four-inch wide strips. The bubbler tap itself was created by gluing a 90 degree, 1/8" tubing hose barb fitting into a hold in the PVC arc shield, then cutting the fitting flush with the outer surface of the shield. The green PVC arc shields may be seen installed on the leftt side of the channel at the Potter Flume in Figure 6 and the right side of the Potter lateral in Figure 7.

While installing bubbler lines on the flume walls made for a simple installation, establishing a common datum among bubbler taps with any degree of precision was a considerably greater challenge than was the case for the University of Arizona Valley Farm site with stilling wells linked by valved lines. Four months after the installations at the Unit B flume and the YCWUA Cumming and Potter sites, linked stilling wells were installed at each of the three flumes with upstream, throat and downstream taps, and the surface mounted bubbler lines were abandoned

With the linked stilling wells installed, sensor calibrations were performed at the Unit B and both YCWUA sites with accurate identification of a common datum. YAO staff suggested an effective means of creating a comprehensive data record for verifying performance of the venturi solution would be to install an acoustic-doppler flow meter adjacent to the field test flumes to enable time series logging of flow measurements. YAO had two MGD Technologies Acoustic Doppler Flow Meter (ADFM) units available for installation. In an evaluation of the MGD ADMF technology that had been previously conducted at the Reclamation Laboratory, (Vermeyen, 2000), a similar unit was tested with discharge varying from approximately 12 ft^3/s to 30 ft^3/s. In these tests, the ADFM produced discharge measurements that showed a maximum variance of 11.8% compared with the laboratory control measurements.

The two YCWUA sites were determined to be the preferred locations for installing the available ADFM units given the varied range of submergence that is experienced at each of these sites, and in consideration of the fact that flow is rarely shut off in the Cumming and Potter laterals. In contrast, flow is present only occasionally at the Unit B and University of Arizona Valley Farm sites. An output signal from the ADFM unit output would be fed into the on-site PLC unit. Information logged on the PLC included measured submergence rate, discharge measured using the venturi solution, discharge measured using the flume rating and upstream level, discharge calculated by the ADFM, and a time stamp.

For the ADFM installation at the YCWUA Potter site, a wide flange steel beam was placed approximately 30 feet upstream from the flume. An electrical enclosure with a solar panel attached to the enclosure lid was installed on the beam to house the ADFM control unit and batteries. The ADFM transducer was mounted on a steel plate to which a steel tube was welded such that the tube could be clamped to the wide flange beam to anchor the ADFM transducer to the canal invert. Figure 8 is a photo of the ADFM placement at the YCWUA Potter site.

Figure 8. ADFM unit at Potter Flume

Figure 9 ADFM unit at Cumming Flume

For the Cumming site, a bridge of plastic lumber was constructed over the flume approach section. Similar to the Potter installation, the ADFM transducer is attached to a steel plate attached at an orientation normal to a pipe. The pipe is clamped to the bridge to secure the ADFM transducer to the structure invert. The instrument enclosure and solar panel are positioned along side the flume as may be seen in Figure 9.

FIELD RESULTS

Effectiveness of using the venturi flow calculation method with long-throated flumes under submerged or unsubmerged conditions is shown in the following 24 hour time series plots including periods of differing submergence conditions. Figure 10 is a plot of flow at the YCWUA Cumming flume for the 24 hour period of February 15, 2009. Data collected included flume submergence and flow as calculated by 1) critical flow flume rating based on upstream level, 2) venturi flow calculated using upstream and throat levels, and 3) flow calculated by the upstream acoustic doppler ADFM device.

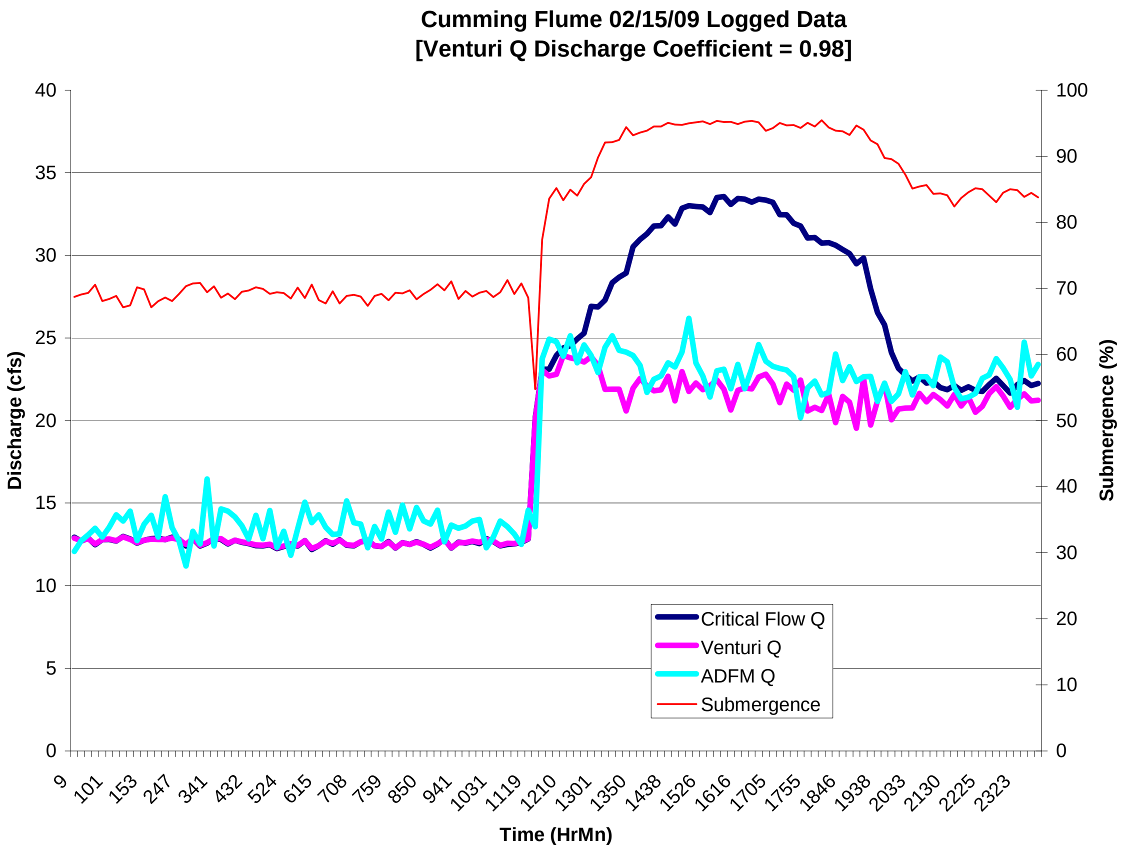

Figure 10. Plot of Discharge Under Varied Submergence at Cumming Flume

Figure 10 represents operation on a day where discharge was adjusted at mid day from about 13 ft^3/s to around 55 ft^3/s. At the lower flow, measured submergence was in the range of 70%, well below the modular limit for the flume. Hence flow calculated using the flume rating and upstream level would be valid. The plot suggests that at a submergence rate between 80% and 85%, modular limit for the flume was exceeded, and flow calculated using upstream level and the flume rating began to yield excessively high values.

Interestingly, at submergence rates below the modular limit, flows calculated using the upstream level and the flume rating are virtually identical to flow calculated using the venturi solution based on both upstream and throat levels. At submergence rates in excess of the modular limit, the relation between discharge measured using the venturi solution maintains a similar relationship to the ADFM calculated discharge that is seen at lower submergence.

Figure 11 is a plot of data from the YCWUA Potter flume for the 24 hour period of April 4, 2009. During the field testing, the Potter was observed to rarely operate under excessive submergence. For the data plotted below, the nearest downstream check was operated to deliberately create a high submergence rate which was incrementally reduced in approximately 30 minute time steps over approximately a 6 hour period.

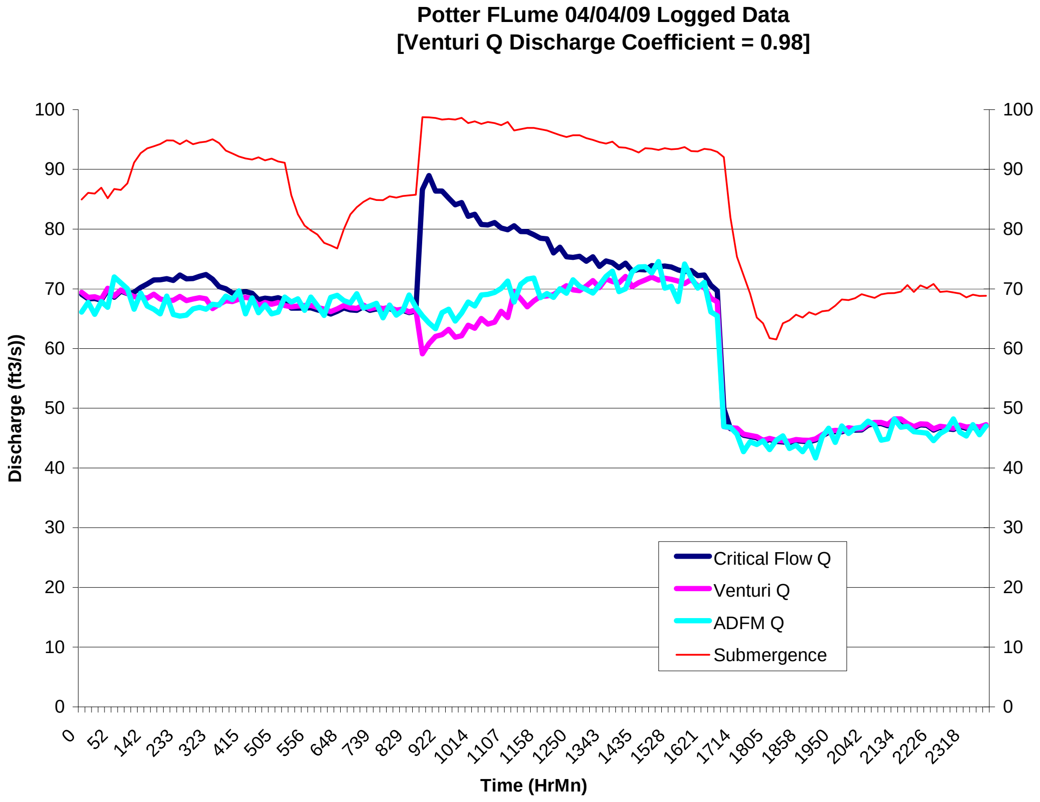

Figure 11. Plot of Discharge Under Varied Submergence at Potter Flume

The plot of data from 04/04/09 at the Potter flume suggests that the modular limit of the ramp-type flume at Potter is around 90% submergence compared with the 80% to 85% submergence modular limit suggested by data from the Cumming flume which is laterally contracted along with having a modest height raised crest. Much like the Cumming flume data of Figure 10, at submergence levels below the modular limit, flow calculated using upstream level with the flume rating and flow calculated using the venturi solution are virtually identical. At submergence rates in excess of the modular limit, discharge measured using upstream level with the flume ration is excessively high while the venturi solution discharge tracks much closer to the upstream ADFM unit.

SUMMARY

What was initiated in laboratory studies as a means of measuring flow under submergence rates that constantly exceed modular limits of a long-throated flume has been adapted in field trials to examine viability of using the venturi flow measurement solution under either submerged or unsubmerged conditions. In laboratory tests the venturi measurement system has been shown to be a viable means of obtaining measurements of reliable accuracy under submergence rates in excess of flume modular limit, given a means of accurately measuring water levels in the approach and throat sections of a long-throated flume.

In the field testing, the concept was expanded to look at developing a system for measuring flow at long-throated flumes that may or may not be submerged. The initial concept applied in the field tests was to first measure submergence, then utilize the flume rating and approach section water level for submergence conditions less than the modular limit, or for submergence rates that exceed the modular limit, use the venturi solution with approach section and throat section water levels to determine discharge.

From the field test data presented, it is apparent that the venturi solution may be used with long-throated flumes for submergence rates less than the modular as well as for submergence rates in excess of the modular limit. Thus it is not necessary to determine the degree of submergence. The practical impact is that only two water levels – the approach level and the throat level – are needed to measure flow at a long-throated flume under any submergence condition.

Efforts associated with the field testing have been unsuccessful in identifying an alternative to construction of stilling wells that can be isolated from the canal and linked together to simplify accurate level sensor set-up calibration and calibration checks. At present the linked, multiple stilling well configuration appears to be a key feature for practical use of the venturi solution with a long throated flume. Accurate determination of a common datum for multiple stilling wells is essential for obtaining differential head measurements with the resolution needed for discharge measurement precision using the venturi solution.

Use of long-throated flumes equipped to accurately measure both approach and throat water levels to enable use of the venturi solution may represent a discharge measurement alternative to emerging technologies including acoustic doppler, radar, and others for conditions of excessive or of uncertain submergence. Long-throated flumes equipped for venturi solution measurements may in many cases represent enhanced cost effectiveness, enhanced accuracy, and enhanced reliability for measuring discharge under limited head availability conditions compared with these alternatives.

DISCLAIMER

No warranty is expressed or implied regarding the usefulness or completeness of the information contained in this paper. References to commercial products do not imply endorsement by the Bureau of Reclamation and may not be used for advertising or promotional purposes.

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