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Velocity Contour Weighting Method for Increased Accuracy of Upward Looking

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Project Summary

Acoustic Doppler Velocity Meters (ADVM) provide an alternative to traditional open channel flow measurement techniques such as stage-rating, flumes, and weirs. Installations of flumes and weirs require a significant capital investment and sufficient head (10-15% of total depth) (Replogle 1997). Head differences across the structure make the flow rating insensitive to downstream conditions and enable critical flow, two factors that support a high degree of accuracy (Chow 1959; Replogle 1997). Unfortunately, the necessary head is not always available, transitions to supercritical flow can create erosion problems, many designs trap sediment, and flumes can be difficult to configure for a wide range of flow rates and water levels (Replogle and Kruse 2007).

Pulsed ADVMs utilize acoustic transducers which transmit an acoustic beam as a pulse of a known frequency along a narrow path (Morlock et al. 2002; Styles et al. 2006). When the pulse hits sediment or air bubbles suspended in water, it scatters and some of the sound signal returns back to the transducer. The time it takes for this "return signal" or backscatter to return to the transducer depends on the distance along the beam path at which the sediment or air bubble is located. Factors affecting the resolution of the velocity measurements include ADVM operating frequency, pulse length, fixed pulse repetition frequency, and properties of the water that affect the speed of sound such as temperature and salinity (Hardcastle and Thorne 1997). The frequency of each backscatter signal has a Doppler shift that is proportional to the fluid velocity (Morlock et al. 2002). The set of return signals therefore provides a set of distances and velocities at that moment, measured within the limited sample area of the acoustic beam.

ADVM installations in channels may utilize either side-looking configurations that sample horizontally through the cross section, or upward-looking (bottom-mounted) configurations that sample vertically through the cross section. Because of its improved accuracy in channels with variable flow depths (Styles et al. 2006), this study focuses on a pulsed, upward-looking ADVM that is mounted at the centerline of the channel and uses two velocity measurement beams.

Device software requires that information on channel geometry be input manually for the ADVM sensor to estimate discharge. Velocities are only measured by the ADVM within a small volume of the flow cross section. Therefore, in a typical cross section, an ADVM does not provide an cross-sectional average velocity, but rather a sample of the velocity distribution in a vertical plane aligned with the channel centerline. Assumptions regarding the relationship between the ADVM sample velocity and the cross-sectional average velocity are typically provided within the manufacturer's software. One example is the approach presented by Huhta and Ward (2003) where a depth integrated power-law equation was used to relate the average ADVM sample velocity to the cross-sectional average velocity (V). However, this method has performed poorly in field applications (Styles et al. 2006).

Howes et al. (2010) describe a subcritical channel contraction design that can be used to achieve a high degree of accuracy with an upward-looking ADVM. The contraction causes rapidly varied flow that creates a relatively uniform cross-sectional velocity distribution near the contraction entrance. This makes the ADVM sample velocity a good proxy for the actual cross-sectional velocity for Froude numbers up to 0.5. Without calibration, the cross-sectional velocity can be measured within +/-4% for Froude numbers below 0.5.

While the accuracies presented in Howes et al. (2010) are considered very good for open channel flow measurement, installation of an ADVM in subcritical contraction with a Froude number below 0.5 is not always feasible and can be costly given site constraints. It should be noted that any flow measurement section including the subcritical contraction should be located in a long straight section of unobstructed flow with a consistent concrete (or equivalent) lined cross section (Styles et al. 2006).

Channel flow is typically classified as prismatic Gradually Varied Flow (GVF) in most irrigation channels because of inline control structures. Hence, flow is not strictly uniform due to backwater effects. Nevertheless, ADVMs are commonly deployed under these conditions, and a calibration procedure termed the index-velocity method (also referred to as the Flow Rate Indexing Procedure (QIP)) is the most common method of converting the sample velocity into the cross-sectional average velocity. The index-velocity method has been incorporated into the software run by many ADVM devices (Patino and Ockerman 1997; Morlock et al. 2002; Styles et al. 2006). The method takes the average of the sample velocities as a proxy for the true average velocity, and calibrates the ADVM based on site specific attributes that are impacting the measured velocity in relation to the actual cross-sectional velocity.

These attributes, the effects of which are lumped together, include channel geometry, water depth, velocities in the unmeasured "buffer" region, and boundary roughness. The primary disadvantage of the index-velocity method is that, in order to account for all attributes, at least 10 individual calibration points at differing flow and depth conditions are recommended (Styles et al. 2006). Hence, it is time consuming, logistically challenging, and costly to implement. Moreover, estimation of the cross-sectional average velocity stands to be improved by making use of the velocity distribution, not simply the sample average.

The objective of this project is to develop a new method for estimating the cross-sectional average velocity (and discharge), in straight prismatic GVF sections, that achieves comparable accuracies to the index-velocity without calibration. The Velocity Contour Weighting Method (VCWM) developed here, is predicated on a weighting of the ADVM velocity measurements to obtain the cross-sectional average velocity, thus the leveraging vertical distribution of velocities provided by the ADVM. The velocity weights adapt based on channel and flow properties and velocity distribution data acquired by the ADVM.

Information Transfer/Outreach Program

The challenge to VCWM is finding the correct weighting of ADVM velocity measurements as a function of channel geometry and roughness. This is addressed by applying a validated Computational Fluid Dynamics (CFD) model to a range of channel flow scenarios that account for typical geometry and roughness properties. In each case, a repeatable surrogate of the true average velocity is obtained and it is possible to sample the ADVM velocity distribution from simulation data based on a typical instrument configuration which is selected here to be 0.034 m bin intervals in the vertical. Moreover, CFD depicts the distribution of velocity across the entire cross section so the velocity weights can be measured with a high degree of accuracy. What remains is to understand (and predict in a reliable way) how the weights depend on channel properties. Hence, dimensional analysis and empirical modeling techniques are used for this purpose. Special attention is placed on the first weight accounting for flow near the wall because the velocity is poorly sampled here and the weight is largest and most significant relative to the cross-sectional average velocity estimate.

Analysis of CFD data as described above generated an original formula for predicting the cross-sectionally averaged velocity as a non-linearly weighted average of the ADVM data, what we call the VCWM. The project continued with validation of the formula in laboratory channels and concrete-lined irrigation canals as described in Howes and Sanders (2011a) and (2011b), respectively, which appear in the *ASCE Journal of Hydraulic Engineering* as companion papers. Pre-print versions of the papers are accessible now from the journal website, and typeset versions will appear later this year. Readers interested in methodological details and results are directed to these papers. Our major findings are described below.

Notable Achievements

VCWM offers several advantages over the commonly used index-velocity method. Leveraging the velocity distribution measured by the upward-looking ADVM, the VCWM algorithm breaks out the independent components of channel geometry, water depths, and surface roughness to circumvent the need for the intensive index-velocity calibration process under varying channel conditions. Channel geometry can be measured by surveying the site, water depth by the ADVM, and surface roughness can be estimated using tables in most hydraulics textbooks.

Laboratory testing shows that the VCWM can be used to estimate discharge with uncertainty less than +/-5% without calibration. This is an improvement on the +/-6% uncertainty using the conventional index-velocity method in a uniform cross section with a recommended 10 calibration points (Styles et al. 2006). The best strategy to minimize this error is to limit the buffer distance near the channel boundary provided that the ADVM interference on the velocity distribution can be minimized.

Field testing in concrete-lined trapezoidal channels shows that VCWM can be used to estimate the cross-sectional average velocity with errors of less than +/-6.3% without calibration. The tests were conducted on 51 cross-sectional velocity distributions under different flow rates, water depths, and channel geometries. The VCWM error is comparable to the +/-6% error using the conventional velocity-index rating method with a recommended 10 calibration points (Styles et al. 2006). For the sake of comparison, the most accurate technology for field installations is the long-throated ramp flume which can obtain discharge measurements within +/-2% if installed and designed properly (Clemmens et al. 1990). However, traditional flumes including the long-throated flume, can be cost prohibitive and require significant headloss which is not always available.

Sensitivity analysis was performed to evaluate potential uncertainties in the method arising from an uncertain roughness parameter. Changes in discharge of +/- 1% resulted from a range of reasonable roughness values selected for the channel boundary material. This demonstrates the insensitivity of the VCWM to the surface roughness assuming the roughness does not change significantly on a seasonal basis. In order to minimize seasonal and annual changes in surface roughness due to aquatic weed growth and sedimentation which can occur in lined channels, three to four channels widths upstream and two channel widths downstream of the ADVM should be cleaned regularly (depending on the amount of sedimentation this may be on a monthly basis).

The concrete-lined channels in this evaluation were relatively small with bottom widths from approximately 0.3 m to 1 m and side slopes from 0.87 to 1. Since the VCWM was developed using CFD simulations in relatively small channels (presented in the companion paper) and has been tested in similar situations, there is uncertainty related to how the method will perform under different channel conditions. VCWM testing in larger channels, channels with different boundary material, and channels with more significant side slopes is warranted.

The utility of this method is not necessarily limited to lined channel sections. However, with any flow measurement technique, the dynamic boundary conditions in earthen and natural channel conditions pose significant issues. These issues include sedimentation, erosion, and aquatic weed growth. Even if a method can compute the average cross sectional velocity accurately, there can be significant uncertainty in discharge computed using the velocity-area method, related to the area computation.