Vermeyen, Tracy B., ADFM Measurement of Tidally-induced Flow and Stage in a Canal Headworks, ASCE/EWRI Joint Conference on Water Resources Engineering and Water Resources Planning and Management, Minneapolis, MN, July 30 - August 2, 2000.

ADFM Measurement of Tidally-induced Flow and Stage in a Canal Headworks

Tracy B. Vermeyen, P.E. (1)

(1) U.S. Bureau of Reclamation, Water Resources Research Laboratory, P.O. Box 25007, Denver, Colorado 80225. Phone (303) 445-2154, FAX (303) 445-6324, e-mail: tvermeyen@do.usbr.gov

Abstract

The Bureau of Reclamation (Reclamation) recently completed a design of a fish screen at Contra Costa Water District's (CCWD) canal at Rock Slough, near Brentwood, California. An important component of the fish screen design process was an accurate determination of the maximum flow through the fish screen. Canal flow can be generated by the pumping plant and/or tidal flows. Reclamation used an acoustic Doppler flow meter (ADFM) to measure the tidally-induced flow and corresponding stage over several tidal cycles. The acoustic Doppler velocity profiles were compared to velocity profiles measured using electromagnetic current meters.

Introduction

The Contra Costa Canal (CCC) facilities and operations serve as CCWD's main water supply and delivery system. The CCC intake is located off Rock Slough on the lower San Joaquin River near Brentwood, California. The CCC has been used to convey water from the San Joaquin/Sacramento River delta since 1940. Currently, the CCC diverts between $148x10^6$ to $166x10^6$ m^3 per year (Liston, et. al, 1997). Reclamation and CCWD cooperated in the planning and design a fish screen structure for the CCC as part of the Contra Costa Pumping Plant Mitigation Program (Reclamation 1997). This program is designed to mitigate fishery impacts resulting from operations of the CCC Pumping Plant No. 1 (located 4 miles downstream from the proposed fish screen). A fish screen is required per section 3406(b) of the Central Valley Project Improvement Act (CVPIA), and the Los Vaqueros Biological Opinion for delta smelt, issued by the U.S. Fish and Wildlife Service in September 1993 (USFWS 1993). The Biological Opinion required that entrainment losses of delta smelt be reduced by screening the Rock Slough intake.

Reclamation recently completed a hydraulic model study of the proposed fish screen design for the CCWD (Hanna and Mefford, 1999). An important component of the fish screen design process required accurate determination of the maximum flow through the fish screen. The maximum flow was needed to design the fish screen so that the approach and sweeping velocities meet criteria set forth by the National Marine Fisheries Service and the California's Department of Fish and Game. Flows in the canal can be generated by a downstream pumping plant and/or the local tides. Reclamation used an ADFM to measure the tidally-induced flow and corresponding stage over several tidal cycles.

The ADFM System

Figure 1 shows a typical ADFM installation for measuring open channel flow in a pipe. A 1.23 MHZ transducer assembly is mounted on the invert of a pipe or channel. Piezoelectric ceramic transceivers emit short pulses along narrow acoustic beams pointing in different directions. Echoes of these pulses are backscattered from particles suspended in the flow. As this material has motion relative to the transducer, the echoes are Doppler shifted in frequency (MGD Technologies 2000). Measurement of this frequency shift along the set of four beams enables the calculation of the flow speed and direction. A fifth transducer is mounted in the center of the transducer assembly and is used to measure the flow depth.

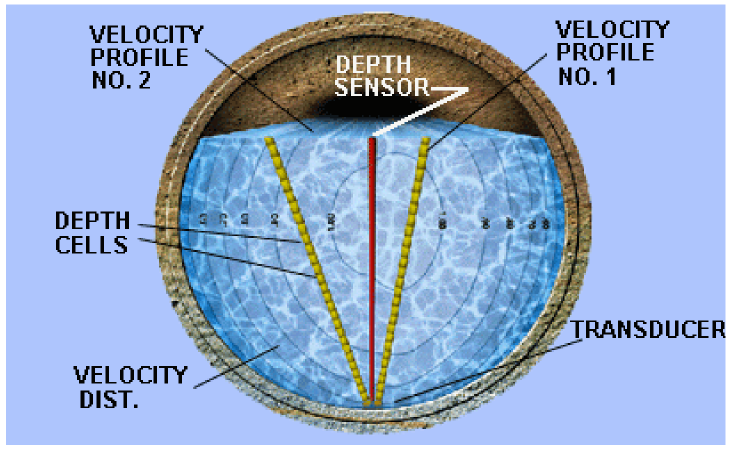

Figure 1. Cross section view of typical ADFM application. This figure shows the spatial relationship of the depth cells and the velocity profiles relative to the transducer. The middle beam represents the depth sensor.

The ADFM divides the return signal into discrete intervals which correspond to different depths in the flow. Velocity is calculated from the frequency shift measured in each interval. The result is a profile, or linear distribution of velocities, along the direction of the beam. Each of the small circles in figure 1 represent an individual velocity measurement in a small volume known as a depth cell.

The position of the velocity profiles in figure 1 are based on the geometry of the ADFM's transducer assembly. Figure 2 shows a side view of the transducer assembly. The profiles shown in figure 1 are generated from velocity data measured by an upstream and downstream beam pair. The data from one beam pair are averaged to generate profile no. 1, and a beam pair on the opposite side of the transducer assembly generates profile no. 2.

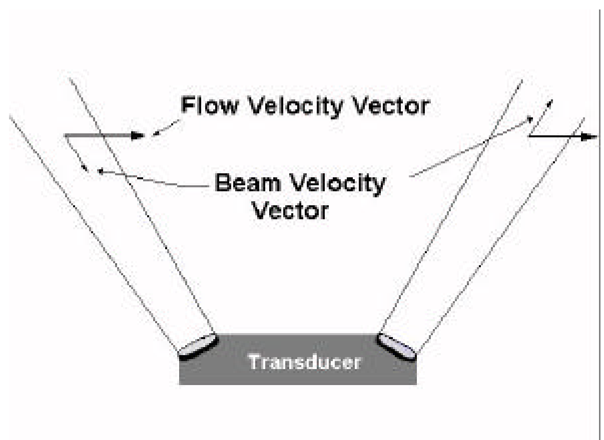

Figure 2. Side view of the ADFM transducer, beam geometry, and velocity vectors.

Since Doppler measurements are directional, only the component of velocity along the direction of the transmit and receive signal is measured, as illustrated in figure 2. Narrow acoustic beams are required to accurately determine the horizontal velocity from the measured component. The narrow acoustic beams of the ADFM insure that this velocity measurement is accurate. Also, the range-gate times are short and the depth cells occupy a small volume - cylinders approximately 5 cm (2 in.) long and 5 cm in diameter (MGD Technologies 2000). These small sample volumes insure that the velocity measurements are truly representative of that portion of the flow and potential bias in the return energy spectrum due to range dependent variables is avoided. The result is a very precise measurement of the vertical and transverse distribution of flow velocities.

The ADFM uses two methods to compute discharge. One method (Q_{VA}) uses the depth-averaged velocity, computed from the two velocity profiles, and the channel's cross sectional area. The second method (Q_{PRO}) uses the velocity data from the two profiles which are entered into an algorithm to develop a mathematical description of the flow velocities throughout the entire cross-section of the flow. The algorithm fits the velocity data to the functions of a parametric model for a certain type of channel (e.g. circular or trapezoidal). The parametric model is used to predict velocities at points throughout the flow field. The resulting velocity distribution is integrated over the cross-sectional area to compute Q_{PRO}.

The key benefit to this method is that the system will operate accurately under variable hydraulic conditions. As hydraulic conditions change, the change will manifest itself in the distribution of velocity throughout the depth of flow. Because the ADFM is measuring the vertical velocity distribution directly, it can adapt to changes in the hydraulics insuring an accurate estimate of flow rate.

Performance specifications for the ADFM system are as follows (MGD Technologies 2000):

- Flow - ±2% of reading
- Horizontal velocity range - ±9.1 m/sec
- Depth cell size - 12 to 30 cm (user selectable)
- Vertical velocity profiling range - up to 6 meters (dependent on particle concentrations)
- Velocity measurement - 1.0% ± 0.3 cm/sec of reading
- Water level measurement range - 10 to 610 cm
- Water level accuracy - 0.5% ± 0.5 cm

Contra Costa Canal Headworks near Rock Slough

The existing canal headworks structure consists of three identical rectangular bays which are 6.65 meters wide (21.8 ft). The headworks is designed for a maximum flow of 10 m^3/sec (350 ft^3/sec), but when high tides occur the flow into the canal can exceed 17 m^3/sec (600 ft^3/sec). The canal was designed for a high tide stage of El. +2.6 m (8.5 ft) and a low tide stage of El -0.5 m (1.6 ft). For the period of 1984 to 1996, the gage in Rock Slough near the CCC intake has recorded a maximum high tide at El. +1.9 m (6.3 ft) and a minimum low tide at El. -0.6 m (1.9 ft) (Liston et. al February 1997).

Typically, the pump flow rates vary from about 3.4 m^3/sec (120 ft^3/sec) in the winter to 7.1 m^3/sec (250 ft^3/sec) in the summer. However, peak daily flows up to 7.9 m^3/sec (280 ft^3/sec) have been reported. Tidal fluctuations create two unusual flow conditions for designing fish screens:

they can increase the flow through the screens above the design discharge of 10 m^3/sec

they can cause a reverse flow through the screens

Maximum flows were estimated by CCWD to be as high as 17 m^3/sec (Christensen, et. al August 1996). The larger flow into the canal increases the velocity through the fish screens and may cause more fish and debris to be impinged on the screens. Tidal flows must be considered when sizing the screen area to design a structure which meets the approach velocity criteria of 6 cm/sec. Reverse flow can be as high as 4.5 m^3/sec during non-pumping periods. Reverse flow has positive and negative impacts on the screen design. The positive impact is that reverse flow can help move fish back to the estuary. The negative impact is that it may cause debris to collect on the back of the screens where it would be difficult to remove.

Once the CCWD's Los Vaqueros Reservoir project is operational, use of the CCC is expected to be reduced. However, there may be operational conditions under which CCWD would pump the full capacity flow rate through the CCC (Reclamation 1997).

ADFM Data Collection

The purpose of the field test was to use the ADFM to measure the depth, velocity, and flow through the CCC headworks over a 48-hour period. The collection period was selected because it was projected to have a seasonal maximum high (flood) tide and a minimum low (ebb) tide. The final product was to be a record of depth, average cross sectional velocity, and flow in the canal (with no pumping) for several tidal cycles.

The ADFM was installed at the downstream end of headwork's concrete apron and was aligned parallel the centerline of the middle bay. The transducer was positioned so that positive and negative velocities indicated flow into and out of the canal, respectively. After the ADFM was positioned, the ADFM's depth reading was verified using a survey rod to confirm that the depth sensor was measuring perpendicular to the concrete apron. The ADFM was configured to collect data every 5 minutes and was powered using a 12-volt battery.

Field data collection began at about 10:00 a.m. on December 3, 1997. The field data collection was concluded at 12:45 p.m. on December 5, 1997.

Electromagnetic Current Meter Measurements

In addition to ADFM measurements, independent velocity profiles were collected to verify the ADFM velocity measurements and to measure the velocity in the other two bays of the headworks. Two Marsh-McBirney (MMB) electromagnetic current meters (Model 201D) were used to collect velocity profiles in the center of each of the three rectangular bays. The MMB velocity profiles were collected at 30-cm increments. Two sets of profiles were collected in each bay. The MMB velocity measurements revealed an uneven flow distribution between the three bays. According to a CCWD maintenance worker, the trashracks had not been cleaned in over 12 months. As a result, flows through each of the trashrack bays were not equally distributed.

Depth-averaged velocities through the right, center, and left bays for the first set of profiles were 4.6, 10.4, and 8.2 cm/sec, respectively. Similarly, the average velocities through the right, center, and left bays for the second set of profiles were 6.7, 13.1, and 9.8 cm/sec, respectively. The two profiles for each bay were averaged. These average velocities were used to determine the ratio of the flow through each bay by dividing the average velocities measured in the right and left bays by the average velocity in the center bay. The velocity ratio for the right bay was 0.48 and for the left bay was 0.78. To calculate the total flow through the headworks, the center bay discharge (from the ADFM) was multiplied by the appropriate velocity ratio to determine the flow through the right and left bays. The total flow through the headworks was the summation of flows through each of the three bays. Both sets of MMB velocity profiles were collected with the flow in the upstream direction. As a result, it was decided that further measurements were needed to accurately determine the flow distribution for both flood and ebb tides.

Another factor that must be considered in this analysis is the accuracy of the MMB velocity meters. The MMB velocity meters have an accuracy of ±2 percent of the reading ±1.5 cm/sec (zero stability) which for the low velocities that were being measured results in a large degree of uncertainty in the velocity measurement. For example, the uncertainty in a 15 cm/sec velocity measurement is 1.8 cm/sec or ±12 percent, whereas the ADFM's time-averaged velocity uncertainty is 0.66 percent of the maximum velocity. For this application, the maximum velocity was set at 91 cm/sec, so the uncertainty in each velocity profile is 0.6 cm/sec.

ADFM Measurements

Prior to using the ADFM in a field application the system was tested in Reclamation's Water Resources Research Laboratory. The ADFM was installed in flumes that were 1.2-m wide and 3.6-m wide. The results of these tests were satisfactory (Metcalf and Vermeyen, 1997).

The time period considered for this analysis was from 2:30 p.m. on December 3 to 12:45 p.m. on December 5, 1997. For this data set, the ADFM was positioned 1.7 m (5.5 ft) from the center bay's southwestern pier. For this time period, there was limited pumping from the canal (according to CCWD operators). The pumping volumes for December 3, 4, and 5 were 1110, 3200, and 45,640 m^3, respectively. The ADFM collected depth, depth-averaged velocity, and discharge measurements every 5 minutes; depth and discharge data are shown in figure 3.

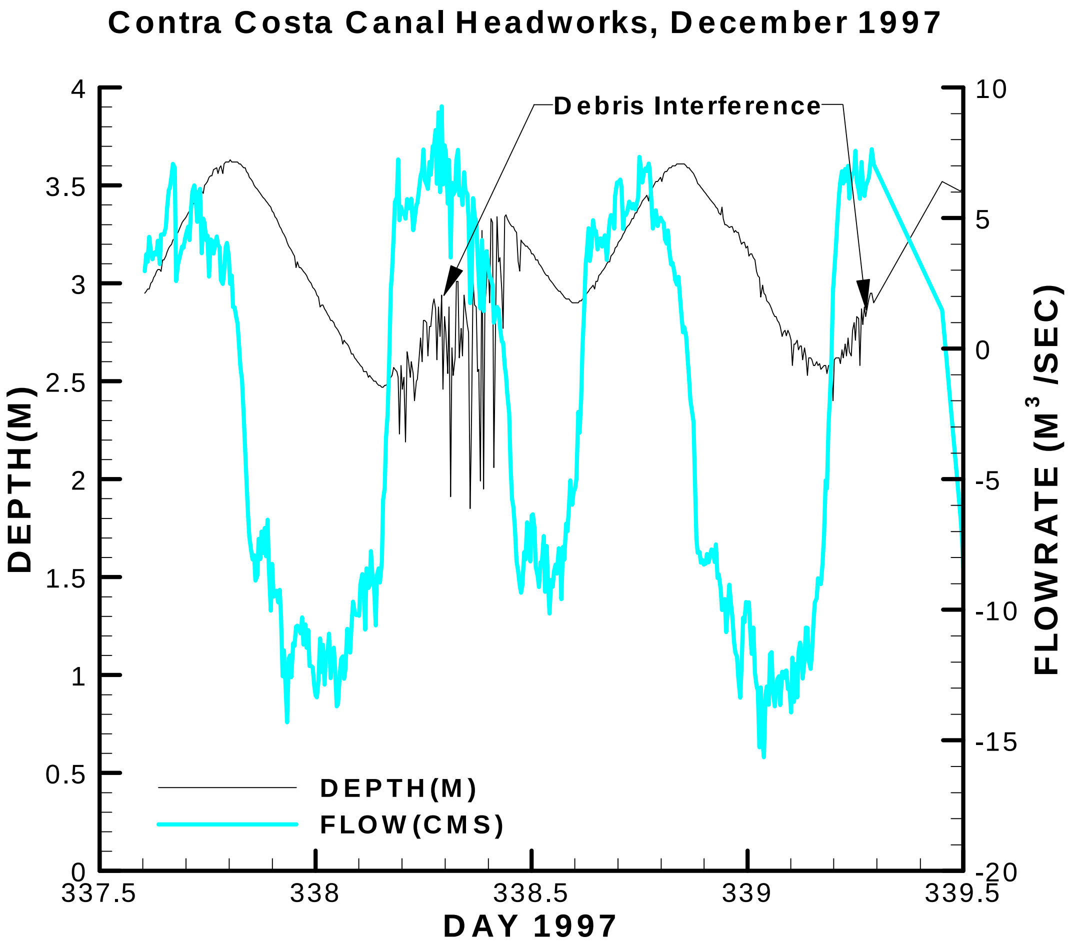

Figure 3. Plots of ADFM data collected December 3-5, 1997 (calendar days 337 to 339). The plot shows a time series of ADFM discharge and depth. The noise in the depth data during the morning hours of days 338 and 339 was likely caused by aquatic debris interfering with the ADFM's acoustic signals.

Figure 4 shows a comparison of ADFM depth measurements and depths based on stage measurements at a nearby gage in Rock Slough. The tidal stage data were converted to a depth referenced to the invert of the headworks structure. A comparison of these depths showed very good agreement except for two time periods. The first occurred on December 4 (day 338) from 4:00 to 10:30 a.m. when aquatic debris appeared to have interfered with the acoustic signal (figure 4). The second time, this problem occurred during the early morning hours on December 5 (day 339). Eventually, the acoustic signal was totally blocked and no useful data were

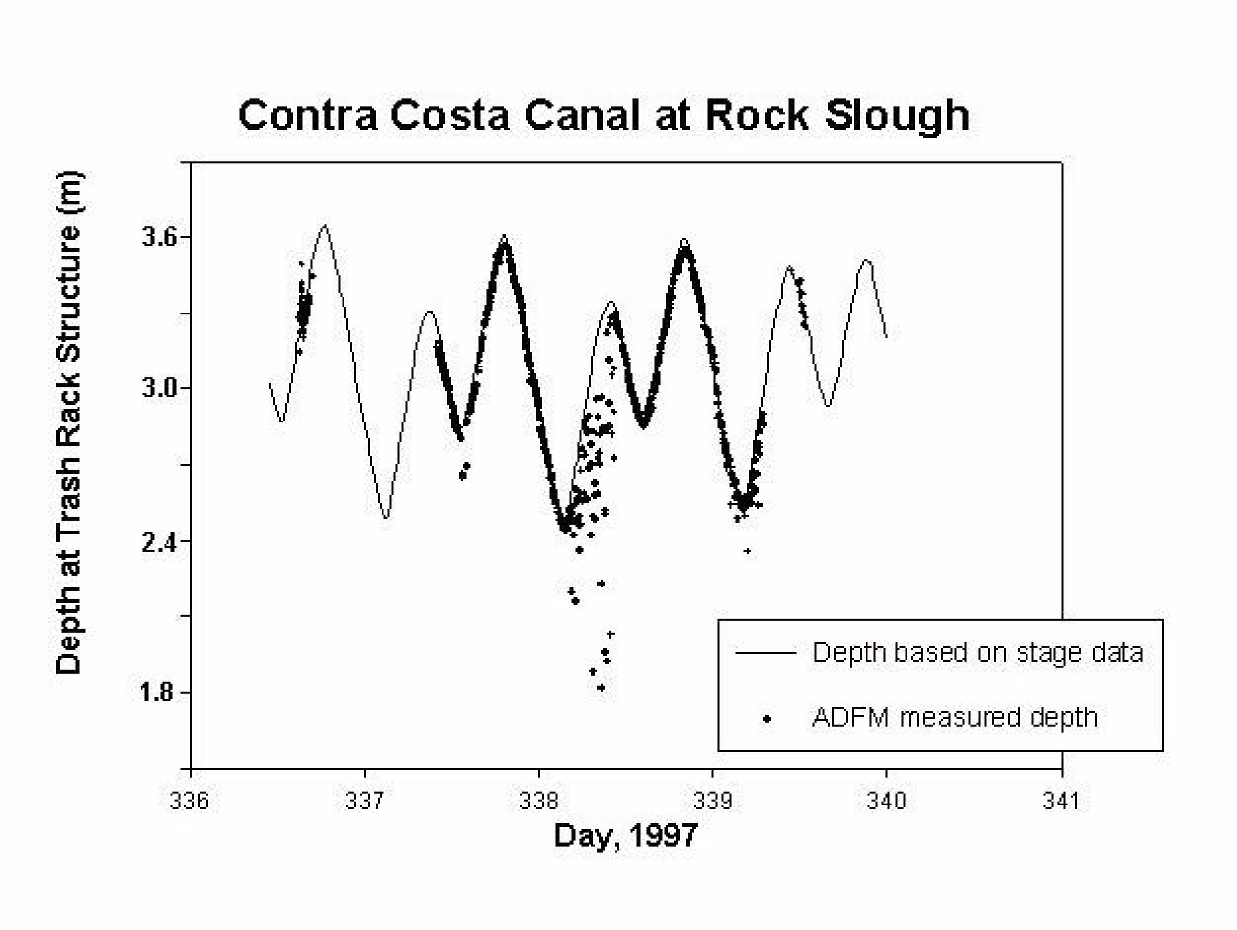

Figure 4. Plot comparing ADFM measured depths and depths computed using Rock Slough stage data. The plot shows very good agreement between the two independent data sets. Periods of poor agreement are when aquatic debris interfered with the acoustic signal.

collected from 7:00 a.m. until 12:45 p.m. Fortunately, these problems occurred during intermediate flood tides and did not affect the analysis to determine the maximum inflow and outflows.

A summary of the ADFM data and analyses is as follows:

- Of the two methods used for computing flow rate, the method using the depth-averaged velocity and the cross sectional area (Q_{VA}) was the most consistent and reliable. The method using the parametric velocity distribution model (Q_{PRO}) produced sporadic and inconsistent discharges. However, when the Q_{PRO} method did yield a discharge it agreed reasonably well with the Q_{VA} method.

- The minimum flow depth in the headworks occurred at 3:40 a.m. on December 4 and was 2.5 m. The maximum flow depth occurred at 7:15 p.m. on December 3 and was measured to be 3.6 m. For the same times, the minimum and maximum depths computed using Rock Slough stage data were 2.5 and 3.6 m, respectively.

- The maximum downstream velocity of 15.5 cm/sec was measured at 6:50 a.m. on December 3. A maximum upstream velocity of -24.7 cm/sec was measured at 3:40 a.m. on December 4. Positive velocities correspond to flood tides and negative velocities were measured during ebb tides.

- The maximum downstream discharge occurred at 6:50 a.m. on December 3 and was calculated to be 6.7 m^3/sec. The maximum upstream discharge occurred at 0:55 a.m. on December 5 and was -11.6 m^3/sec.

- It was interesting that when the discharge was integrated over one tidal cycle (about 1.04 days) a net outflow of 1.8 m^3/sec was calculated. The reason for this net outflow is unclear, but may result from a different inflow distribution through the three bays.

- Comparisons of Marsh McBirney to ADFM velocity profiles were attempted, but the ADFM does not have a straight-forward means of extracting the velocity profiles from the raw data files. An attempt was made to resolve the individual beam velocities into a vertical velocity, but the resulting profiles did not compare very well with the MMB velocity profiles. The ADFM manufacturer has since developed software which allows the user to view the velocity profiles for the two acoustic planes. However, they still need to develop a method to output the vertical velocity profile.

Conclusions

The ADFM worked very well to measure the tidally-induced flows and water levels at the Contra Costa Canal headworks near Rock Slough. The only problem encountered during the field test was when aquatic debris interfered with the acoustic signal which resulted in periods of erratic depth and velocity measurements. Comparison of ADFM depths to Rock Slough stage measurements showed very good agreement. Of the ADFM's two methods of computing flow rate, the method using the depth-averaged velocity and the cross sectional area (Q_{VA}) was the most consistent and reliable. The method using the parametric velocity distribution model (Q_{PRO}) produced sporadic and inconsistent discharges.

While the ADFM is an acoustic Doppler current profiler, the manufacturer has not developed a method to extract the three dimensional velocity data from there raw data file. The ADFM's high resolution velocity profile data would be useful in many hydraulic engineering studies where traditional velocity measurement methods are impractical.

References

Bureau of Reclamation, Contra Costa Pumping Plant Mitigation Program, Contra Costa Canal Intake (Rock Slough) Fish Screening Project, United States Department of Interior, September 5, 1997.

Christensen, R., A. Glickman, C. Liston. August 23, 1996. Report on fish screening alternatives for the Contra Costa Canal Intake (Rock Slough), California. United States Department of Interior, Bureau of Reclamation. Technical Service Center, Denver, CO.

Hanna, L. J. and B.W. Mefford, Hydraulic Model Study of Contra Costa Canal Fish Screen Structure and Trash Rake, Report R-99-05, Technical Service Center, Denver, Colorado, October 1999.

Liston, C., R. Christensen, A. Glickman, February, 20, 1997. Contra Costa Canal Fish Screens, Report 2: Preliminary Information on Designs, Costs, and Schedules, Contra Costa Canal Intake (Rock Slough), California. United States Department of Interior, Bureau of Reclamation. Technical Service Center, Denver, CO.

Metcalf, M. and T.B. Vermeyen, "The ADFM Velocity Profiler -- A Report on Laboratory and Field Demonstrations Conducted for the Bureau of Reclamation," Water Operations and Maintenance Bulletin, No. 182, U. S. Bureau of Reclamation, Denver, Colorado, December 1997.

MGD Technologies, ADFM Velocity Profiler Technical Manual, 9815 Carroll Canyon Rd., Suite 200, San Diego, California 92131, January 2000