TECHNICAL MEMO

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DEPARTMENT OF WATER RESOURCES
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SUBJECT: **PERFORMANCE EVALUATION OF UN-CALIBRATED PACKAGED CONTINUOUS DOPPLER FLOW METER SYSTEMS IN A VARIETY OF WATER DIVERSION SCENARIOS.**

INTRODUCTION

There is an on-going need by Irrigation Districts, Canal Companies, Lateral Associations, farmers, and other agricultural water users in the State of Idaho for reliable, accurate, low cost methods of water measurement. As advancements in technology provide new methods of water measurement the Idaho Department of Water Resources (Department) has a responsibility in evaluating and providing recommendations and guidance is association with burgeoning technologies. Furthermore, as the Department gains practice, experience, and acceptability with new technology there is a need for applicable Department guidance documentation[1] to be updated accordingly.

One such "new" technology is termed acoustic Doppler flow measurement, whereby the physical principal of the Doppler shift is utilized to measure the velocity of a moving stream of water, which when coupled with a known relationship describing the cross section area of the stream of water yields a stream discharge rate. Although the technology itself was referenced by the Bureau of Recreation as being in the development phase as early as 1966 (BoR 1984), it is only in the last five years that it has become commercially available and affordable enough to garner the attention of agricultural water users in Idaho.

Several major advantages of Doppler flow meter[2] (DFM) systems are their ability to measure a wide range of water quality types, their ability to measure flow in extreme low energy systems,

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[1] Specific applicable guidance documentation put out by the Department that addresses and governs water measurement includes the references "Minimum Acceptable Standards for Open Channel and Closed Conduit Measuring Devices" and "State of Idaho Department of Water Resources Water Measurement Guidelines".

[2] Doppler flow meters are known and referenced by a variety of names including acoustic velocity meter, ultrasonic velocity meter, ultrasonic Doppler instrument, area velocity flow meter, & acoustic Doppler flow meter.

their ability to measure flow in both directions of a channel (upstream and downstream), their ability to measure flow when the stage-discharge relationship varies with time, and their ability to readily support programmable data collection and logging rates.

This technical memo is a summary of the performance evaluation of DFM technology undertaken by the Department during the calendar years of 2008 and 2009. The performance evaluation set out to evaluate the following specific criteria while in the course of actual water measurement:

1. Accuracy and precision of un-calibrated Doppler flow meters in low energy, typical energy, and high energy scenarios.
2. Accuracy and precision of un-calibrated Doppler flow meters in various water quality environments including pristine spring flows and typical high turbidity irrigation flows.
3. Ease in programming, installing, and maintaining continuous flow measurement and data logging capabilities with a Doppler flow meter system.

THEORETICAL PRINCIPLES OF OPERATION

Doppler[3] flow meters rely on a physical principle termed the Doppler effect or Doppler shift, which is described as the apparent change in the frequency of a harmonic wave (sound, electromagnetic, etc.) due to relative motion between the source and observer (Serway 1990).

Doppler flow meters (DFM) rely on a transducer to transmit sound waves (ultrasonic) into a stream or flow of liquid. The sound waves encounter acoustically reflective particles[4] in the stream and reflect back to the sensor where they are received. As long as there is a measureable flow to the stream the frequencies of the transmitted sound waves and the reflected sound waves received by the sensor will always be different; the magnitude of the difference between the transmitted frequency and the reflected frequency is directly proportional to the velocity of the reflective particle (Unidata 2008, MACE 2009, Metcalf 1997).

There are two distinct DFM technologies that rely on the Doppler shift principle to measure velocity: they are the coherent (profiling) method and the incoherent (continuous) method (TRC 02-004, Vermayen 2000). The profiling method relies on transmitting encoded pulses with varying transmission frequencies from multiple narrow beam transducers at specific target-volumes or bins along the acoustic signal beam; the sensor then listens for reflected sound waves from particles within each specific bin and calculates a bin specific velocity, refer to *figure 1*. A single cylindrical bin is approximately 4 cm in diameter and 5 cm long; in a flow with

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[3] Named after Christian Doppler (1803-1853) an Austrian physicist who is credited with first describing the effect.
[4] Acoustically reflective particles can consist of suspended solids, air bubbles, or surface detritus (i.e. leaves or other debris). As an aside, stream flow can transport material as individual ions or molecules in solution (dissolved load) or as solid particles (particulate load), the particulate load is further classified into a suspended load component and a bed load component (Dingman 2002). DFM's are reliant on the suspended load to measure velocity, as material in solution (comprising the dissolved load) will not reflect sound waves and material comprising the bed load is typically too large and too close to the sensor to be accurately measured.

a depth of 2 m there are as many as 40 discrete bins for every signal beam (Metcalf 1997). This process is the same for each transducer beam, which is targeting or looking at a different location in the stream flow. This allows for the discretization or profiling of velocities within the entire stream flow.

The continuous method of Doppler metering relies on a continuous transmission of sound waves from a single wide-beam transducer, and a receiver to measure reflected sound waves from particles traveling anywhere and everywhere within the pathway of the transmitted acoustic waves, refer to *figure 1*. These measurements are resolved into a mean velocity, which can be related to an average stream channel velocity at suitable measurement locations.

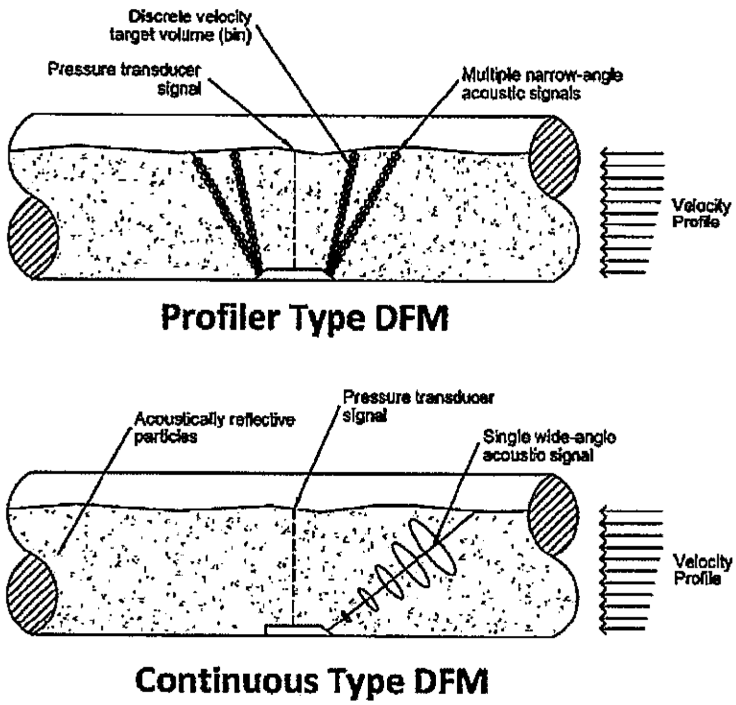

Figure 1 - Schematic of profiler type DFM measurement technique (above) and continuous type DFM measurement technique (below).

When compared to continuous DFMs, profiling DFMs allow for a more accurate and detailed measurement of velocity over a wider and more diverse range of flows. However, profiling DFMs are technically more complex, requiring multiple transducers, whereas, continuous DFMs rely on simpler technologies and only one transducer. As would be expected, the more complex profiling DFM technology is more expensive, typically an order of magnitude greater than continuous DFMs. Due to this price discrepancy, profiling DFMs are usually reserved for industrial and wastewater treatment applications and are beyond the price range of typical agricultural irrigation applications, where continuous DFMs are more likely to be implemented. The devices reviewed by the Department in this performance evaluation are all continuous type DFM systems.

Doppler based velocity measurement is a direct function of the speed of sound in water, which in turn is a direct function of the density of water. Density of water is commonly approximated based on the temperature of the water. Therefore, all of the packaged DFMs considered in this evaluation incorporate a temperature sensor in their instrumentation for the determination of water density and the subsequent correction of stream flow velocity.

In addition to measuring velocity, all of the packaged DFMs evaluated come with a pressure transducer in their instrumentation, which allows for the measurement of the depth of standing water over the sensor. This measurement, along with a relationship describing cross sectional area of the channel as a function of depth of flow, when multiplied by the mean velocity, allows for the calculation of the mean channel discharge rate.

In conclusion, continuous DFM instruments are in essence a combination of three sensors, a velocity and temperature sensor for the calculation of mean velocity and a pressure transducer for the calculation of depth of flow. A packaged DFM system refers to the combination of the DFM instrument with a computer processor, data logger, and power supply, which allows for the programmability of the DFM instrument, continuous recording of instrument output (data logging), and post-processing of instrument output into meaningful values. At the time of this study the Department is unaware of any unpackaged or piecemeal systems, whereby the DFM sensor can be purchased separately from the other packaged components.

REVIEW OF MANUFACTURERS AND PRODUCTS INVESTIGATED

Products from three separate and independent manufacturers of packaged DFM systems were evaluated by the Department. The systems reviewed included the Starflow System by Unidata[5], which is a self described complete hydrographic data collection system that combines water velocity, depth, flow and temperature instruments integrated with a fully featured 120K Starlog Micrologger; the AgriFlow Series 3 irrigation flow meter by MACE[6], which includes up to five velocity meters (insert or strap mount) and/or depth/velocity meters, built-in data logger, weather proof enclosure with digital read out, and power supply; and the AVFM-II area velocity flow meter by Greyline Instruments[7], which consists of a velocity water level sensor, optional data logger, and enclosure with digital read out. *Table 1* compares a number of relevant characteristics of the three packaged DFM systems covering required stream flow, power input, and general system parameters.

[5] Unidata is an Australian based company that specializes in the design, manufacture, supply and support of new technologies for environmental monitoring, for more information visit www.unidata.com.au.

[6] MACE is an Australian family company that specializes in the design and manufacturing of electronic monitoring instrumentation including ultrasonic flow meters, data loggers, and controllers, for more information visit www.macemeters.com.

[7] Greyline Instruments, Inc. is an American-Canadian company with a US base of operation in Massena, NY that develops and manufactures industrial flow and level monitoring instruments for measurement and control in water and wastewater treatment, industrial process automation, and for environmental monitoring, for more information visit www.greyline.com.

Table 1 – Packaged DFM System Comparison. Cost includes sensor, enclosure, display, data logger, & power supply.

		Stream Flow Parameters			Power Requirements					
Manu-facturer	Model	Vel. Range (ft/sec)	Depth Range (ft)	Water Temp. Range (deg-F)	Battery (amp hr)	Solar Panel (watts)	Data Logger	Volatile Memory	Digital Display	Cost (Fall '09)
Unidata	Starflow	0.07-14.7	0.0-16.4	1.4-140.0	12	5	Yes	Yes	Yes	$3795*
MACE	AgriFlow	0.08-26.0	0.0-13.0	-4.0-150.0	7 or 12	5	Yes	No	Yes	$4,993
Greyline	AVFM-II	0.1-20.0	0.08-15.0	5.0-150.0	100	20	Yes	No	Yes	$3,975

*Converted from Austrailian Dollar amount of $4,121, shippling and handling from Austrailia included in quote.

Description and Review of Known DFM Installations in the State of Idaho

Ovid Creek

In June of 2006, in conjunction with Rocky Mountain Power and a recently issued basin-wide water measurement order, the Department deployed a Unidata Starflow DFM system with Unidata's proprietary data logger (Starlog) on Ovid Creek to evaluate in-channel flows in the lower end of the drainage where Ovid Creek crosses Cutler Lane northeast of Ovid, ID. The Starflow was deployed in a 36" diameter CSP culvert, flowing partially full, for three weeks. During initial deployment the stream channel was current metered to verify Starflow accuracy. Flow rate data were collected after one day; the flow rate data and the current meter measurement are presented in *Figure 2*.

Following three weeks of data collection Department staff returned to the sight to retrieve the DFM. At that time staff disconnected the power supply from the data logger and unknowingly discovered a substantial flaw in the Unidata DFM package. When power is lost to the data logger stored data is also lost. Unfortunately, due to the lack of understanding of the volatile memory constraints of the Unidata all stored data for Ovid Creek were lost. This is considered a substantial flaw by the Department because often DFM systems are deployed remotely with a standalone power supply where the Department cannot afford a high frequency of visits by personnel. Standalone power supplies are notoriously fickle and power interruptions are an unavoidable occurrence that can be expected over long (seasonal) timeframes, unless extreme measures are undertaken to avoid losing power.

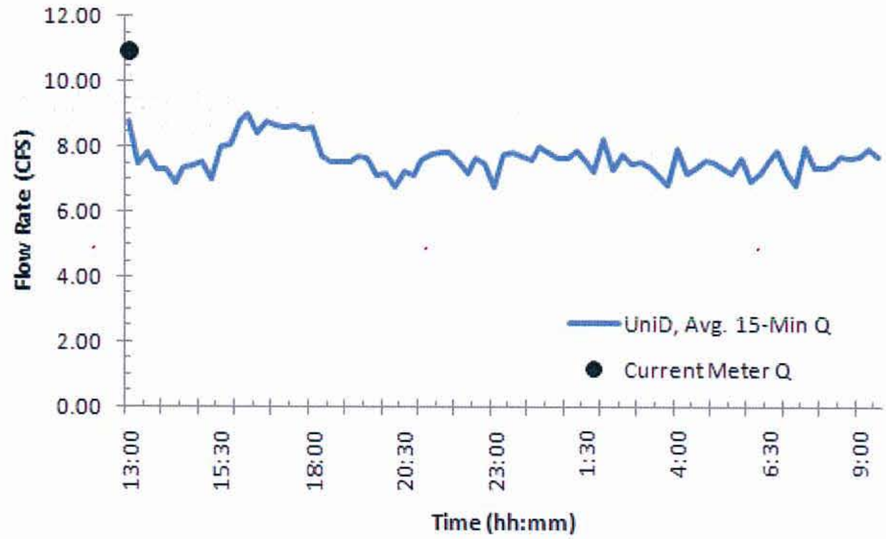

Figure 2 - Summary of Ovid Creek Flow Rate Data from June 25-26, 2008

S39 DIVERSION UPPER SALMON RIVER

In August of 2008 Department staff deployed a Unidata Starflow DFM system with Unidata's proprietary data logger (Starlog) on the S39 diversion ditch, which diverts water for irrigation from the Salmon River near Stanley, ID. The DFM was used to measure stream flows at three different stages to construct a rating curve relationship where the S39 ditch passes through a 36" diameter CSP culvert. Additional current meter measurements were taken to corroborate the DFM measurements. At the time of measurement the culvert was flowing partially full. *Figure 3* depicts the flow rate measurements from the Unidata DFM and current meter measurements.

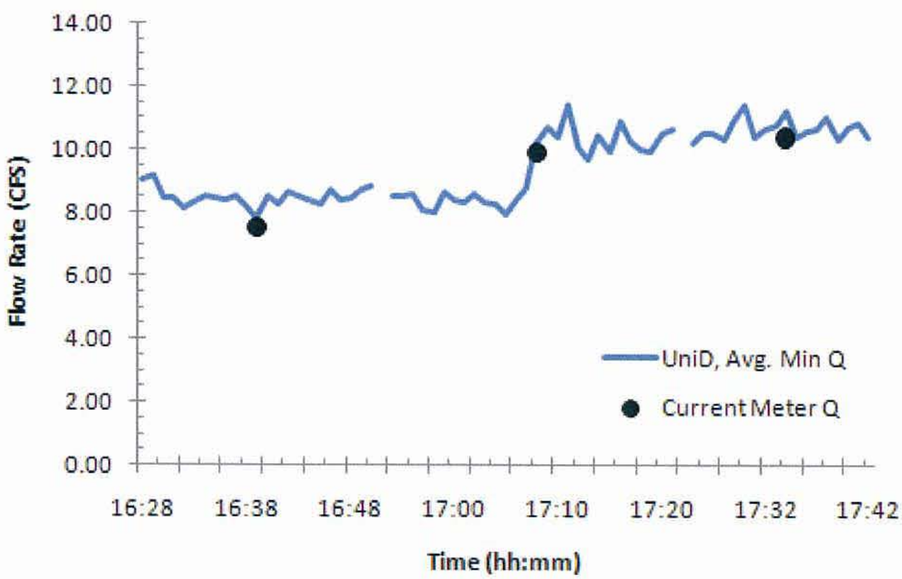

Figure 3 - Summary of S39 Diversion Flow Rate Data from August 14, 2008

HARTLEY DRAIN

In the Spring of 2009 the Department's Unidata Starflow DFM was paired with a Campbell Scientific CR200 data logger and installed in an 81x59 CSP Pipe – Arch (squash pipe) in the Hartley Drain near Star, ID. The CR200 data logger was employed to overcome the shortcomings associated with the use of a volatile memory type in Unidata's proprietary data logger – namely, when power is lost stored data is lost. The primary objective of the Hartley Drain deployment was to prove that a Inidata/CR200 paired system could be successfully deployed and maintained, with uninterrupted power for an extended period of time. It was intended to trouble shoot the proposed deployment of the same Unidata/CR200 paired system on the Nuffer Ditch later in the year.

Figure 4 depicts flow rate data and battery charge data for the DFM over the entire period that the system was deployed in the Hartley Drain and correctly measuring stream flow. Current metering of the stream flow in the Hartley Drain from February 20, 2009 is also depicted in the figure, to maintain a reasonable x-axis scale the current meter measurement corresponds to a date of March 13th. There is a permanent staff gage deployed by the Watermaster of District 63 at the Hartley Drain at the location of DFM deployment. Staff gage readings from February 20th (1.08') and March 12th (1.03') differed by 5/100th of a foot, suggesting there was little change in flow rate from the time the current meter measurement was taken and the time the DFM started to record stream flow. With this understanding, the percent error[8] in the DFM measurement was approximately 2.6%.

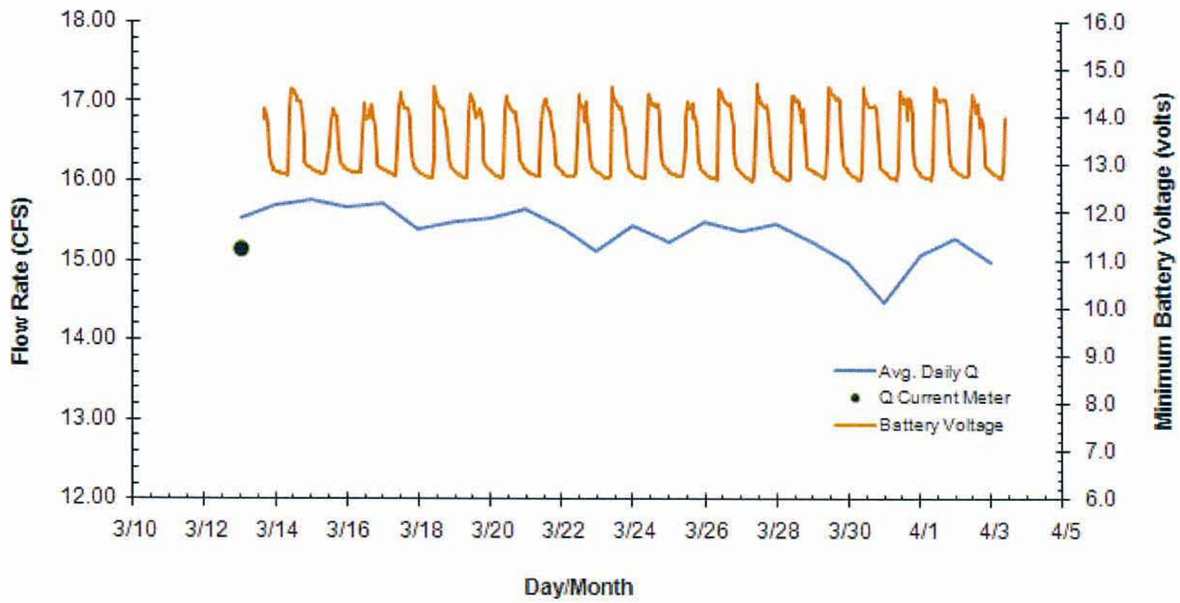

Figure 4 – Summary of flow rate measurements and battery charge from the Harley Drain DFM deployment.

[8] Throughout the entirety of this memo, percent error is calculated as E = abs(X – Y)/X, where X is adopted to represent the best possible value of the measured quantity (i.e. measurement obtained from a weir, current meter, etc.) and Y is the measurement obtained by the DFM. As a point of clarity, the above equation actually yields a percent residual, but for the scope of this paper the residual is referred to and treated as an error.

Another important finding of the Hartley Drain deployment, as evidenced in *Figure 4*, was verification that a 5 watt solar panel and 7 amp-hour battery could successfully power the Unidata/CR200 DFM package indefinitely, even during the relatively low sunlight months of February and March. Figure 5 depicts the deployment of the Unidata/CR200 DFM at the Hartley Drain.

Figure 5 – Deployment of the DFM system at the Hartley Drain. In the left hand picture the DFM enclosure and power supply can be seen mounted on the far side of the Drain, the permanent staff gage is located in the Drain just in front of the DFM system, the sensor is located in the squash pipe just visible on the left hand side of the frame, and Department Hydrologist Dan Nelson is seen current metering the Drain in the right side of the frame. The right hand picture is a close up of the enclosure, data logger, and power supply.

NUFFER DIVERSION

In the winter of 2008/2009 the Nuffer diversion was selected for a pilot program to introduce local water users[9] in the Central Division of the Bear River to the DFM technology. As part of the pilot program, throughout the irrigation season the Department maintained a Unidata Starflow DFM at the diversion for water measurement. Due to the use of volatile memory type in the Unidata system, the Department paired the Starflow with a Campbell Scientific CR200 data logger to avoid potential loss of data as a result of unanticipated interruptions in power. The Department also installed and maintained a second MACE Agriflow type DFM system at the site for three weeks to collect redundant and comparative water measurements. With the support of the Watermaster, periodic current meter measurements of the diverted irrigation water were also taken as corroboration of the DFM's accuracy.

Sensors from both DFM systems were deployed inside a 73x55 CSP Pipe – Arch (squash pipe) to provide for a well constrained cross sectional area of flow. Throughout the season Department staff observed steady and uniform flow conditions in the squash pipe. *Figure 6* depicts the deployment of both DFM systems on the Nuffer Diversion.

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[9] The group consisted of water users in the Pegram Area that divert water from the Bear River into the diversions colloquially known as the Nuffer, Miller, Ure, Jensen, Sorenson, and Smith.

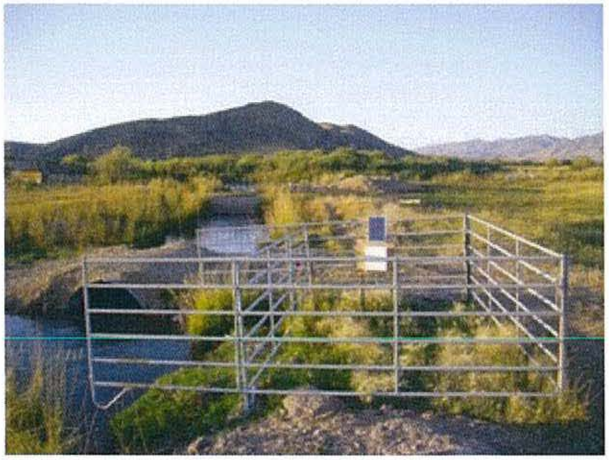

Figure 6 – Installation of DFM systems on Nuffer Diversion. Right hand picture depicts the Unidata DFM deployment, enclosure and power supply are located behind fencing for protection from cattle, squash pipe is located in stream adjacent to DFM system, and the diversion works can be seen in background approximately 100 feet upstream of the squash pipe. The left hand picture is a close up of the Unidata DFM system, note the weather proof container at the base of the fence posts where the MACE DFM system was temporarily housed.

Flow rate data were collected by the Unidata/CR200 DFM system for the entire irrigation season. Flow rate data were collected by the MACE DFM system for approximately three weeks. Current meter measurements were carried out by the Department and the Watermaster on five different occasions. *Figure 7* summarizes all flow rate measurement data collected on the Nuffer Diversion during the 2009 irrigation season.

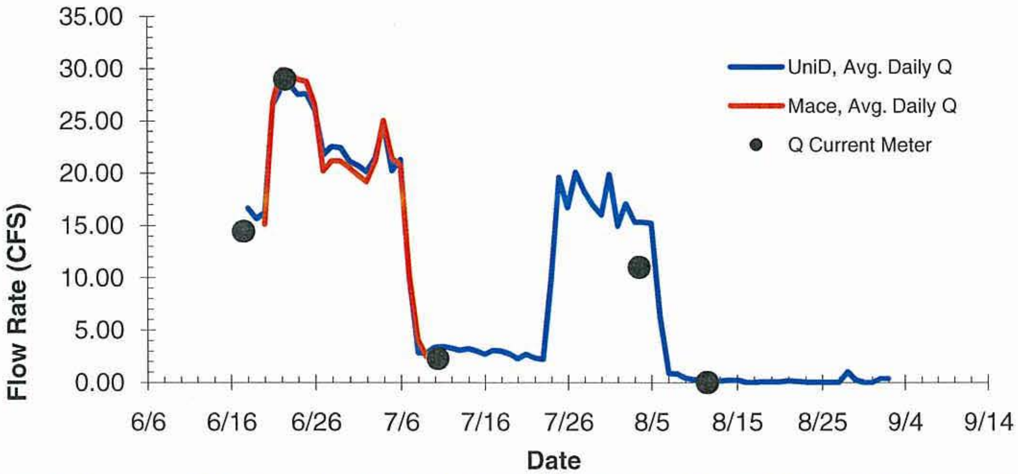

Figure 7 – Summary of flow rate data collected on the Nuffer Diversion for the 2009 Irrigation Season. Low flow conditions from approximately 7/8/09 – 7/23/09 represent a closure of the head gates during the first cutting of pasture hay. Low flow conditions from approximately 8/7/09 – 9/2/09 represent closure of the head gates and drainage of the Nuffer Ditch while the railroad carried out operation and maintenance of improvements, including culverts and bridges, in their right-of-way parallel to and crossing the Nuffer Ditch.

BRIDAL VEIL SPRINGS

In July of 2009 the Department deployed a MACE DFM system into twin 36" diameter corrugated steel pipes to evaluate the efficacy of using DFM technology to monitor the flow rate of the Bridal Veil Springs complex. The twin culverts passed the full flow of the springs just upstream of where the spring complex discharges into the SeaPac Hatchery's lower fish rearing raceways.

Because spring water is the surface discharge of ground water, it can be exceedingly pristine (devoid of any suspended solids) and thus potentially a poor candidate for measurement via DFM technology, which requires particulate in the stream flow to reflect or scatter sound waves. In order to be effective, DFMs require the stream flow being measured to have at least 100 ppm of acoustically reflective particles greater than 75 microns in diameter (MACE 2009). Two common standards of practice for evaluating the presence and concentration of acoustically reflective particles would be to measure the turbidity[10] by means of a nephelometer or to measure the concentration of total suspended solids[11] from a water sample. Another means to evaluate the concentration of acoustically reflective particles in a stream flow, which relies on tools readily available to Department staff, is the measurement of the signal-to-noise[12] (STN) ratio determined by a FlowTracker[13] (current meter). STN ratios equal to or greater than 10 dB are indicative of a stream flow well suited for flow rate measurement by a DFM.

A STN ratio of 28.8 dB was measured in the Bridal Veil springs flow at the location of the deployed MACE DFM. Although there were two culverts there was only one MACE velocity/depth sensor. To overcome this condition, measurements were first collected in one pipe, and then the sensor was moved to the second pipe where measurements were then collected. The flow rates from both pipes were summed to arrive at a total flow. Due to this method, an instantaneous combined flow rate was never taken. A current meter measurement of the spring flows from April 2009 was used to evaluate the effectiveness and accuracy of the MACE DFM. Because of the large elapsed time (four months) between the current meter and DFM measurements, and known seasonal fluctuations in spring flow, a general order of magnitude comparison is the only way the current meter measurement can be defensibly used to evaluate the MACE DFM. The results indicate that the DFM was quite capable of measuring pristine spring flows and obtained a reasonable flow rate value; however, a precise evaluation of measurement accuracy is not afforded by the data collected. The measurement results and error analysis are presented in *Table 2.*

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[10] Turbidity is the measure of the light transmitting properties of water and is a function of suspended and colloidal material within the sample (Lindeburg 1999). Turbidity in excess of 5 NTUs is an indication that there is more than likely sufficient material within the stream flow for a DFM to function accurately. A typical clear lake is approximately 25 NTUs whereas visibly muddy canal or river water can exceed 100 NTUs.

[11] Total suspended solids (TSS) are defined as the material remaining on a standard glass-fiber filter, after a water sample has passed through it (Lindeburg 1999). The filter is weighed before filtration, dried at 103-105 deg-C, and weighed again, the gain in weight divided by the total sample weight represents the concentration of TSS.

[12] Signal-to-noise (STN) ratio is a measure of the strength of a reflected acoustic signal relative to the ambient noise level of the sensor and is primarily a function of the amount and type of particulate in the water. For best operating conditions of acoustic wave based flow measurement devices, STN should be equal to or greater than 10 dB (SonTek 2004).

[13] The FlowTracker ADV is an acoustic Doppler velocimeter manufactured by SonTek/YSI Inc. that attaches to a wading rod and is used by Department staff to measure 2D and 3D flow rate measurements of open stream channels (current metering). For more information on the FlowTracker visit www.sontek.com.

Table 2 – Summary of Bridal Veil Spring Flow Measurements

DFM Left Culvert, Q (CFS)	DFM Right Culvert, Q (CFS)	DFM Combined Q* (CFS)	Flow Tracker, Q** (CFS)	% Error
11.6	11.9	23.5	34.1	31.0%

*DFM Flow Measurement taken on July 15, 2009 w/ a MACE Agriflow DFM.

**Curent meter measurement taken on April 9, 2009 with a SonTek Flow Tracker

HOAGLAND TUNNEL

In July of 2009, in an attempt to assess further the ability of DFM systems to record accurate flow rates in pristine water environments, the Department deployed a MACE DFM system in the Hoagland Tunnel spring. The DFM was originally deployed at the entrance to a rectangular concrete flume immediately downstream of the daylight point of the spring. A FlowTracker was used to assess the STN ratio at this location, measuring values in the range of 4-6 dB. The MACE DFM system was not capable of accurate velocity measurement at this location. The MACE DFM was then moved downstream approximately 20 feet to the outlet of the concrete flume. Between the inlet and the outlet there is a 90-degree angle in the flume or stream channel, which moderately aerates the stream flow. At the downstream end of the flume a STN ratio of approximately 18 dB was measured; at this location the MACE device was able to accurately measure velocity. Qualitative analysis of this deployment indicates that there is a level of water quality (pristinelyness) that can be encountered in the water measurement duties of the Department for which a DFM system will be incapable of accurately measuring flow rates. As such, consideration should be given to water quality at any proposed DFM measurement site, and steps should be taken to quantify the water quality prior to deployment and evaluate the anticipated effectiveness of a DFM at that location.

CUB RIVER IRRIGATION DISTRICT – UPPER DIVERSION MIDDLE DITCH

On April 7, 2009, in the company of the WD 13A Watermaster, Department staff visited the Cub River Irrigation District's upper diversion of their middle ditch. The Watermaster introduced staff to the recently installed Greyline AVFM-II at the upper diversion dam of the middle ditch and provided instruction on accessing the control house and obtaining instantaneous measurements from both the Greyline's digital display and via the dial in phone number.

The Greyline system was installed in the winter/spring of 2009 as a permanent measurement device for the diversion. *Figure 8* depicts the outside and inside of the control house where the Greyline digital display read out, data logger, power supply, and telemetry apparatus are all housed. The sensor is installed in a 36" diameter round pipe, approximately 100 feet from the entrance of the pipe located at the diversion works adjacent to the control house. *Figure 9* depicts the entrance of the pipe at a no flow (May 2009) and low flow (June 2009) condition. During Department staff's first visit to the site no water was being diverted. Staff returned to the diversion site on three different occasions throughout the irrigation season, during all three return visits the middle ditch was current metered for evaluation of the accuracy of reported flow rates by the DFM system.

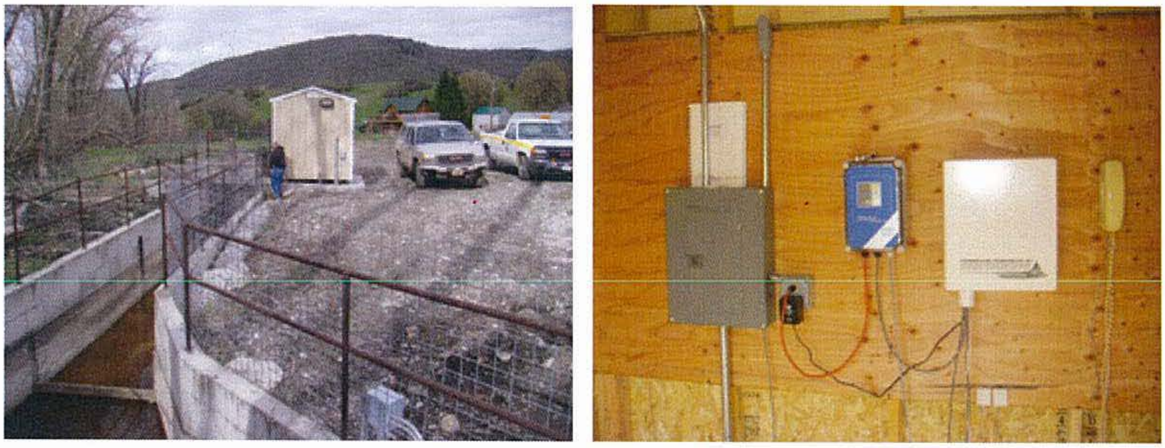

Figure 8 – Cub River Irrigation District's upper diversion of the Middle Ditch. The back of the control house is depicted in the picture to the left and the inside of the control house is depicted in the right hand picture.

Figure 9 – Inlet conditions at the Upper Diversion the Middle Ditch at no flow (left) and low flow (right).

Table 3 summarizes current meter measurements and flow rate measurements from the Greyline DFM during the Department's three site visits. Review of the data indicates an unacceptably high error, increasing in magnitude with higher flows. *Figure 9* indicates that even at low flows there is a large degree of turbulence at the entrance to the pipe. It is likely that there is still considerable turbulence or at least the effects of turbulence at the location of the DFM 100 feet downstream of the entrance. Turbulence undermines the accuracy and precision of a DFM in multiple ways; it can lead to non-uniform flow conditions, it can lead to unsteady flow conditions, it disrupts the predictability of the velocity profile, it can lead to partially full flow conditions where a full flow programming scenario has been assumed, and it can lead to the excessive entrainment of air into the stream flow. Some bubble entrainment in the stream flow is acceptable and even desirable as sound wave scatterers. However, too much air entrainment changes the density of the stream flow and subsequently the rate at which sound travels through the medium thus influencing the accuracy of the measurement of velocity (Unidata 2008). For best results DFM sensors should be sighted in locations of minimal turbulence (Greyline 2009).

Table 3 – Summary of CRID Upper Diversion of the Middle Ditch Current Metering and DFM Flow Rate Results with Percent Error Between the Two Readings also Presented.

Date	Current Meter: Flowtracker, Q* (CFS)	Greyline DFM, Q** (CFS)	% Error
6/17/2009	10.1	11.9	17.8%
7/9/2009	33.2	15.0	54.8%
9/10/2009	14.3	15.5	8.4%

*These values were obtained at a cross section located approximately 15 feet downstream of the first daylight point of the middle ditch (1/4 of a mile from the DFM).

**These values represent an average of instantaneous flow rates taken every mintue for 10 consecutive minutes.

LAST CHANCE CANAL

In the fall of 2008 the Last Chance Ditch Company and the Watermaster of Basin 65 installed a MACE DFM system at the diversion of the Last Chance Canal. Approximately 100 yards downstream of the diversion works the Last Chance Ditch flows underneath North Plaza Road through three deformed 36" diameter CSP culverts. A velocity/depth sensor was installed in all three culverts which feed back to a MACE FloPro data logger housed in a steel box on the east side of the ditch. At the time of Department staff's site visit, all three culverts were flowing full. Despite a few minor, easily correctable issues, the west and east culverts appeared to be collecting reasonable depth (wrong units in display), velocity (wrong sign in west culvert), and flow rate measurements (wrong sign in west culvert). Assuming that the flow in the Last Chance Ditch approximately flows in equal proportions between all three culverts, as confirmed by the similarity of observed measurements of the east and west culverts, the central culvert velocity sensor appeared to be malfunctioning by measuring velocities and flow rates significantly less than the other two. Assuming the central culvert flow rate is equivalent to the average of the east and west culvert flow rates allows for the approximation of the combined flow. At the time of the site visit a flow measurement was also taken with a StreamPro[14] for verification. *Table 4* summarizes flow rates and percent error from measurements taken during the site visit.

[14] The StreamPro is an acoustic Doppler current profiler manufactured by Teledyne RD Instruments, which is a tool for velocity and discharge measurement in shallow streams utilized by the Department. For more information regarding the StreamPro visit www.redinstruments.com.

Table 4 - Last Chance Ditch DFM and StreamPro Flow Measurements from September 9, 2009.

Date	MACE DFM Q (CFS)	StreamPro Q (CFS)	% Error
9/3/2009	62.05	77.5	19.9%
9/3/2009	83.66 *	77.5	7.9%

*Value corrected for erroneous central culvert flow rate reading.

REVIEW OF FINDINGS

Table 5 is a summary of all deployed DFM measurements summarized in the memo for which there was a corresponding corroboration measurement. The average error between the DFM flow rate measurement and the corroborating measurement was 15.5%, with a standard deviation of 17.4%, and a minimum and maximum error of 1.7% and 54.8% respectively.

Table 5 – Summary of All DFM Flow Rate Measurements Where Corroborating Measurements were Taken with a Summary of Percent Error.

Date	Site	DFM	Channel Desc.	DFM, Q (CFS)	Current Meter, Q (CFS)	% Error
6/25/2008	Ovid Cr.	Unidata	36" Diam. Culv.	8.76	10.92	19.8%
8/14/2008	S39 Diversion	Unidata	36" Diam. Culv.	7.80	7.53	3.6%
8/14/2008	S39 Diversion	Unidata	36" Diam. Culv.	10.17	9.91	2.6%
8/14/2008	S39 Diversion	Unidata	36" Diam. Culv.	11.23	10.38	8.2%
3/13/2009	Hartley Drain	Unidata/CR200	81x59 Pipe Arch	15.53	15.13	2.6%
6/17/2009	Nuffer	Unidata/CR200	73x55 Pipe Arch	16.68	14.45	15.4%
6/17/2009	Nuffer	MACE	73x55 Pipe Arch	15.58	14.45	7.8%
6/17/2009	Cub River	Greyline	36" Diam. Culv.	11.90	10.1	17.8%
6/22/2009	Nuffer	Unidata/CR200	73x55 Pipe Arch	28.50	29.00	1.7%
6/22/2009	Nuffer	MACE	73x55 Pipe Arch	29.61	29.00	2.1%
7/9/2009	Cub River	Greyline	36" Diam. Culv.	15.00	33.20	54.8%
7/10/2009	Nuffer	Unidata/CR200	73x55 Pipe Arch	3.43	2.28	50.5%
7/10/2009	Nuffer	MACE	73x55 Pipe Arch	2.40	2.28	5.3%
8/3/2009	Nuffer	Unidata/CR200	73x55 Pipe Arch	15.31	11.00	39.2%
8/11/2009	Nuffer	Unidata/CR200	73x55 Pipe Arch	0.22	0.00	N/A
9/3/2009	Last Chance Ditch	MACE	3x 40" Diam. Culv.	83.66	77.5	7.9%
9/10/2009	Cub River	Greyline	36" Diam. Culv.	15.5	14.3	8.4%

SOURCES AND MAGNITUDE OF ERROR

Two graphs addressing error are presented in this section. The first graph, *Figure 10,* is an X-Y scatter plot of flow rate and error. As can be seen from the graph, there appears to be no distinguishable pattern to the plotted points, suggesting that percent error is not a function of flow rate. The data might suggest that DFMs are more accurate in larger flows (>20 CFS), which would be anticipated, however, this would be a tenuous conclusion based on the paucity of measurements in this category. The second graph, *Figure 11,* is a bar chart of percent error by model type. It would be tempting to draw overarching conclusions from this chart to assist in the recommendation of model types by the Department. However, the study is not comprehensive enough to support those types of conclusions. In very few instances were different model types installed in the same locations and scenarios. Specifically in the instance of the Greyline deployment, data was collected at only one location. Never the less, the data are presented for the reader's consideration, with the hope that underlying circumstances be considered.

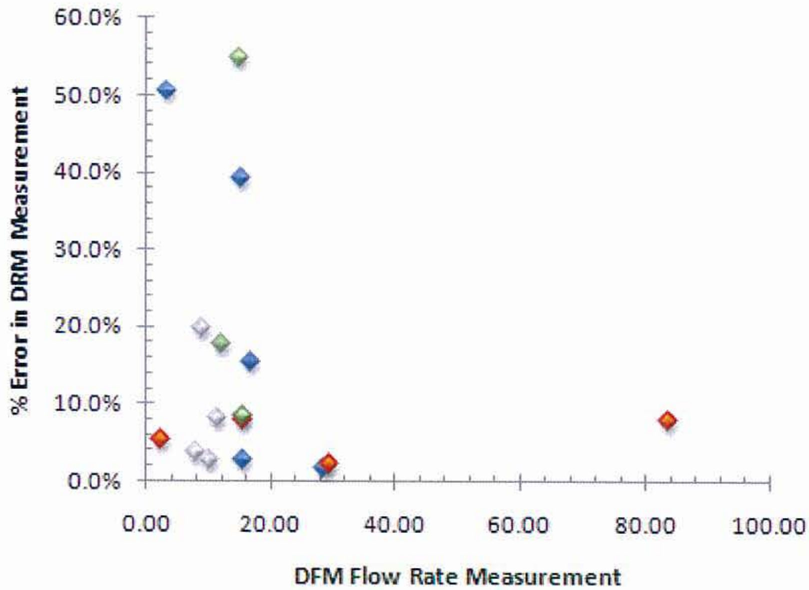

Figure 10 – X-Y Scatter Plot of DFM Measured Flow Rate and Percent Error. The Greyline DFM is represented by green diamonds, the MACE DFM by red diamonds, the UniData DFM with proprietary data logger by grey diamonds, and the UniData/CR200 combination by blue diamonds.

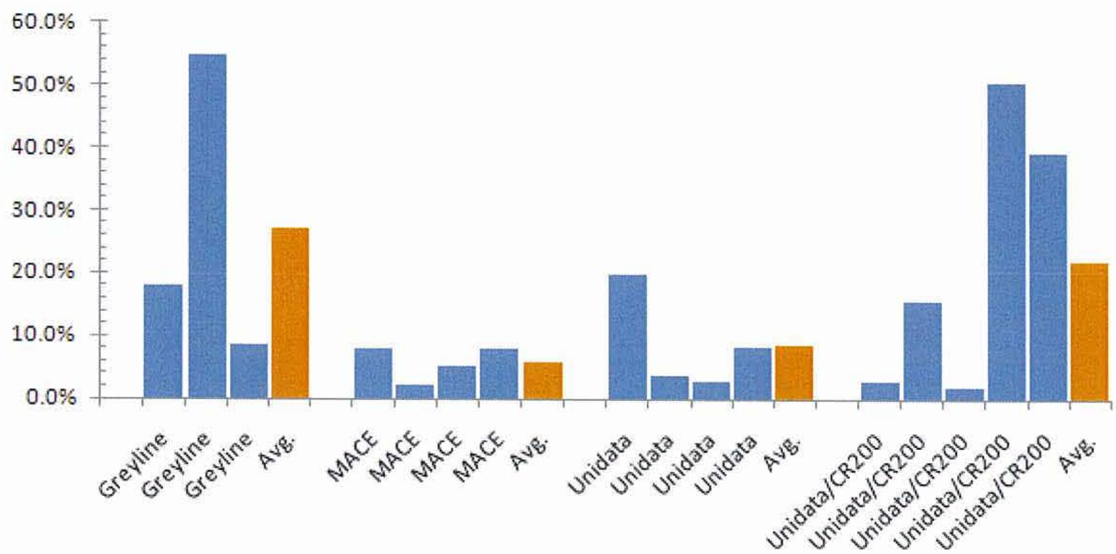

Figure 11 – Column Chart of Percent Error by DFM Model Type. Orange columns represent average percent error for the model type.

Analysis of percent error versus channel type was also considered. There were roughly an equal amount of data for circular pipe conditions, and non-circular pipe conditions (squash pipe). Because the relationship of a circular pipe is supported directly by all of the DFMs considered, while non-circular channel types rely on the depth versus area relationship to be defined and properly programmed into the DFM by the user, there was an expectation that non-circular channels would be associated with higher measurement error. However, this was not borne out by the findings of this research; the error for both channel types was roughly equal: 16.5% for circular cross sections and 15.6% for non-circular sections. Unfortunately, amorphous open channel cross sections were not evaluated in this memo, with all DFM deployment sights residing in some type of corrugated metal pipe. It would be a worthwhile endeavor to investigate the accuracy and precision of DFM's in these scenarios with future deployments.

It should be noted that if the measurements with the three largest percent errors (54.8%, 50.5%, and 39.2%) are excluded from the data set the average error drops to 8.0% with a standard deviation of 6.1% and a maximum error of 19.8%. There are plausible justifications for the exclusion of the 54.8% (Greyline, Cub River) and the 39.2% (Unidata/CR200, Nuffer) measurements. In the case of the Greyline data point (54.8%) it was observed that the inlet condition of the diversion was highly turbulent at low flows, and likely much worse at high flows. Turbulent enough, that the ability of the DFM to accurately measure flow rate in the conditions observed is highly suspect. In the instance of the Unidata measurement point (39.2%), the corroborating measurement was carried out by the Watermaster, and not the Department Staff responsible for other current meter measurements at the sight. Differences in technique, uncertainty analysis, and measurement locations between the Watermaster and Department staff could potentially explain the error. For the last data point with a percent error of 50.5% (Unidata/CR200, Nuffer), flows in the ditch fluctuated between 1-30 CFS. This is an extreme range of flows for a measurement device to accurately measure across. In the instance of this data point, the DFM measured 3.43 CFS and the current meter measurement was 2.28 CFS. In this situation this magnitude of error isn't as significant when you consider that at higher flow rates (15-30 CFS), the DFM measured flow with a much greater degree of accuracy.

Assess Performance Evaluation Objectives

The first objective of the Departments efforts was to assess the accuracy and precision of un-calibrated Doppler flow meters in low energy, typical energy, and high energy scenarios. Low energy scenarios consist of diversions where there is insufficient energy or head in the system to allow for a traditional gravity driven measurement device, such as a weir or Parshall flume to properly function. The Nuffer diversion was specifically selected as a DFM deployment sight due to its low-energy characteristics and the assertions of the water users that a traditional weir or Parshall Flume could not function. Investigations by the Department in the past indicate that a combination of low bed slope and vegetative growth in the Nuffer can induce back water effects in the channel leading to extremely low energy conditions at certain times during the irrigation season (IDWR 2008). The Cub River Irrigation Diversion deployment sight represents a high energy condition, as evidenced by the extremely turbulent nature of flow at the inlet. The remainder of the DFM deployment sights evaluated fall into the category of typical or standard energy diversions. As presented in the previous section, the DFMs observed were quite capable of taking accurate measurements in potentially low energy and standard energy diversions. However, in high energy flow conditions, the turbulent nature of the flow regime seemed to be the primary factor in large inaccuracies in DFM measurements, which is consistent with Manufacturer literature.

The Department's second performance evaluation objective was to assess the accuracy and precision of un-calibrated Doppler flow meters in various water quality environments. The stream channels measured varied widely in water quality from pristine springs to visibly muddy irrigation water. *Table 6* summarizes the variation in STN values encountered across the deployment sights. It is worth noting that there was six orders of magnitude difference in STN values across the entire range of measured waters.

Table 6 – Summary of Water Sources and Signal-to-Noise Ratios

Water Source	STN Ratio (dB)	STN Ratio (unitless)
Hoagland Tunnel Spring	5.0	3
Ovid Creek	12.9	19
Bridal Veil Spring	28.8	759
Upper Salmon River	33.9	2,474
Hartley Drain	43.3	21,380
Nuffer Ditch	50.6	114,815

Of the sites investigated by the department only the Hoagland Tunnel Springs possessed water quality sufficiently devoid of acoustically reflective material to render a DFM incapable of measuring velocity, and in this instance, simply moving downstream a short distance ensured sufficient material had been entrained in the stream flow to allow for accurate measurements. Despite the DFM's ability to measure flow over an extreme STN range, and the unlikely event that this will be a limiting factor, water quality should be a consideration of water users deploying DFM systems, both in assessing the water quality itself and in selecting the location of water measurement.

The final performance evaluation objective of the Department was the assessment of the ease in programming, installing, and maintaining continuous flow measurement and data logging capabilities with a Doppler flow meter system. Except in two instances, all of the DFM deployments reviewed in this evaluation were installed and maintained by Department Staff. In one instance the DFM system was installed by a consulting firm specializing in water measurement and hydrology and maintained by an Irrigation District. In another instance the DFM system was installed and maintained by the Watermaster of WD 65, generally regarded as one of the more technically advanced and sophisticated Districts in the State. In all instances, the DFMs were configured, deployed, operated, and maintained by personnel that can be considered professionals in the field of providing and measuring water, which is to say they are not typical laypeople in these matters. Even so, when reported flow rate measurements are taken at face value there is an unacceptably high average percent error of 15.5% across the evaluation study.

In the deployments considered there are numerous examples of programming error, sight selection error, and power interruption. While some DFM models are simpler to program and deploy then others, they all require an advanced understanding of hydrology, water measurement principles, electronics, programming, and general trouble shooting. When, as in the case of the Unidata/CR200 system, you combine the componentry of a manufacturer's DFM package with nonproprietary data logging and power supply componentry, which can be needed to support non-volatile memory data collection and telemetry, the problems are only exacerbated. For long term, or permanent deployment of these systems where there is not a local source of continuous power, power supply issues including the long term maintenance of solar panels, charge regulators, and most importantly batteries will further impede the continuous measurement of water. Unlike a weir or flume, when there is no power there is no means of measuring flow. These are not water measurement devices that you can install and walk away from; they require on-going care, maintenance, and operation by a knowledgeable dedicated user.

Conclusions & Recommendations

If output flow rate data from the un-calibrated devices evaluated by the Department are taken at face value, an overall measurement error of 15.5% was observed with error equal to or greater than 40% encountered at 18% of the measurements sites. With review and processing of flow rate data, overall measurement error drops to 8.0% with a maximum error of 19.8% at one location. In order to be deemed an acceptable measurement device Department standards require measurement accuracy of open channel devices to be ±10.0% of a trusted standard current meter measurement.

When properly configured and deployed the Department confirmed that DFM devices could provide accurate water measurement in a host of open channel scenarios, including very low energy systems. They were found to be capable of measuring flow over a wide range of water quality types, including the vast majority of situations likely to be encountered in agricultural irrigation settings. The digital read-out display of flow parameters is a feature especially appreciated by users, even though care must be given when relying on these measurements to set head gates as they represent an instantaneous reading, which when evaluated was found to fluctuate by approximately ±8.0% about the mean. The data collection of continuous flow rate parameters is also a valuable characteristic of these systems.

That being said, the proper configuration and deployment of DFM systems can be challenging, even when undertaken by professionals in the field of water measurement. Based on the findings from this evaluation, DFM systems may not be appropriate for individual water users, or laypeople in the field of water measurement. When viable, individual water users should always give preference to the selection of a standard or traditional gravity measurement device. More sophisticated water use entities such as Irrigation Districts, Canal Companies, Water Districts, and the Department, may give strong consideration to the selection of a DFM for permanent water measurement when more traditional devices are not practical or there is a compelling motivation for the use of a DFM.

When DFMs are selected and implemented as a permanent water measurement device, careful consideration should be given to the selection of a measurement location. DFM devices are only accurate when a stable relationship between the mean channel velocity and the mean velocity of reflective particles within the pathway of transmitted acoustic waves can be established over the entire range of anticipated flows (Laenen 1989). Unsteady flow, non-uniform flow, turbulent flow, water temperature gradients, and fluid density gradients will all undermine the strength of the relationship between mean channel velocity and mean acoustic path velocity resulting in inaccurate flow measurement. In a separate study the department found that under ideal conditions velocity measurements from DFMs were within 2.1% of a corroborating measurement; under less than ideal conditions the percent discrepancy increased to 8.7% (IDWR 2010). Some of the inaccuracies in flow measurement encountered by the Department in this performance evaluation can be attributed to the location of DFMs where the previous characteristics of velocity and flow were not sufficiently constrained.

Immediately after installation, measurements from the DFM device should always be verified by a secondary trusted means of water measurement over the entire range of anticipated flows. Periodic verification measurements should continue throughout the operational lifetime of the device to establish the devices ongoing ability to provide accurate measurement. If a DFM device is not capable of consistently obtaining flow rate measurements within ±10.0% of the known flow rate, modification of the device must be undertaken. All of the DFMs considered in this evaluation support the in-situ calibration of the device to allow for the development of a site specific relationship for flow measurement. However, calibration is only a feasible means of increasing accuracy for channels in which the stage-discharge relationship is constant throughout the entire season of use. As an example, accuracy will not be improved by calibration in systems where back water effects are prominent due to vegetative growth or downstream gates as the device can only be calibrated to one flow condition out of the potentially many that may exist over the entire regime of flows. In instances where calibration will not improve measurement accuracy, the location of the DFM may need to be reconfigured to address those detrimental characteristics effecting measurement, or the DFM may need to be relocated to a more suitable point of measurement.

When a DFM has been selected for use in water measurement, the following items should be thoughtfully considered when deciding on a DFM package and water measurement location:

- Power Supply: Is local permanent AC power available at the measurement location? Different DFM packages have different power requirements, and different DFM packages have different memory types where power can be an issue. The availability of permanent AC power versus a remote DC power supply should be taken under consideration when selecting the DFM package and measurement location.

- Data Collection: Is permanent data collection required? All of the DFMs considered came with proprietary data loggers that had different capacities, features, and functions. The data collection needs of the sight should be considered when selecting a DFM Package.
- Telemetry: Is the telemetrization of the DFM anticipated? None of the DFMs considered supported telemetry in their base packages. The telemetrization of a site is an indicator that a separate data logger and larger power supply may be needed.
- Number of Channels to be Measured: Different DFM packages more readily support the measurement of multiple channels than others do. When selecting a DFM package consideration should be given to the number of flow channels being measured.
- Channel Type: What is the channel type? Is it physically constrained or likely to change with time? Can a relationship between depth of flow and cross sectional channel area be easily defined that is stable over the entire range of diverted flows and channel conditions? All of these factors should be considered when selecting a measurement location. The simpler (rectangle, circle, etc.) and more permanent (steel, concrete, etc.) the channel geometry the better.
- Channel Velocity: Is the velocity distribution across the width of the channel uniform? DFMs measure velocity at a single static location in the channel. Flow characteristics and DFM sensor location must be such that the single velocity measurement is representative of the entire channel.
- Flow Type: What are the flow conditions at the measurement sight? Are they uniform? Are they steady? Both are requirements for accurate DFM measurements. Do they change over the course of the season? Are they overly turbulent? Answers to all of these questions should be understood when selecting a measurement sight.
- Water Quality: What is the water quality of the stream flow? It is unlikely this will affect the selection of most measurement locations, however, when dealing with extremely high water quality sources (springs or well water) a measurement of water quality and verification of DFM efficacy at the location should be considered.
- Verification of Measurement Accuracy: All deployed DFMs should be regularly verified for measurement accuracy over the entire range of anticipated flows.
- Calibration/Reconfiguration/Relocation: All of the DFMs considered allow in-situ device calibration. As necessary DFMs should be calibrated, reconfigured, or relocated to assure accurate flow rate measurement, with measurements routinely demonstrating an average percent error of 10.0% or less.

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