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FLOW MEASUREMENT OPTIONS FOR CANAL TURNOUTS

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ABSTRACT

Volumetric record-keeping, billing, and allocations at irrigation district delivery points (turnouts) are the norm, rather than the exception for most California irrigation districts. However, many older districts are just beginning these efforts, and other districts are trying to improve existing hardware and procedures. Volumetric accounting with high accuracy and a reasonable price presents unique engineering challenges for irrigation districts because of the variety of existing structures and configurations at irrigation delivery points. Because it is likely that irrigation districts will attempt to utilize existing devices, or slightly modify them, there is a need for standardized installation and/or calibration. This paper discusses three efforts to adapt, improve, and/or calibrate existing technologies for flow rate and volumetric metering of canal turnouts.

INTRODUCTION

In the most basic form, all irrigation turnouts, or delivery points, serve two purposes:
- Starting and stopping the flow of water
- Control of delivered flow rates – typically provided by a mechanism such as a valve or gate. In other cases, the turnout mechanism is adjusted wide open, and the turnout flow rate is determined by something such as the number of alfalfa valves or sprinklers open downstream.

Modern turnouts are also capable of:
- Flow measurement – an instantaneous quantification provided by various methods.
    - For some turnouts, a supplementary device measures the flow rate (with various levels of accuracy) and displays the result digitally or with an analog gauge.
    - More frequently, field measurements of the mechanism’s opening, upstream and (sometimes) downstream water levels are applied to an equation or rating table. In these cases, the turnout structure itself is used as the flow measurement device, without auxiliary equipment.
- Volumetric totalizing – an accumulation of the flow measurement over time. The accumulation can be completed by either:
    - Automatically mechanical or electronic methods, or
    - Manually “averaging” multiple, discrete flow measurements over an irrigation event.

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Regulations now mandate that in the near future, many California agricultural irrigation turnouts must be configured to provide flow measurement and volumetric totalizing of delivered irrigation water. Furthermore, the measured quantities must also meet specific accuracy standards for new and existing flow measurement devices (CA SBX77 2009).

In most cases accurate flow measurement requires, among other things, satisfactory hydraulic conditions both upstream and downstream of the flow measurement location. For this reason, flumes are not recommended immediately downstream of a bend in the canal. Similarly, propeller meters are not recommended for installations immediately downstream of a partially closed butterfly valve. In these examples, it is unlikely that the instantaneous flow measurement would reflect the actual flow rate.

From an engineering perspective, achieving flow measurement and automatic volumetric totalizing within acceptable accuracy stipulations has become relatively straight-forward for most pipeline turnouts because:

- The hydraulic conditions upstream and downstream of the flow measurement device can be easily "standardized" with a length of straight pipe. The exact length of straight pipe required by each product is specified by the manufacturer. If there is too little room to fit straight pipe lengths or a skewed flow profile cannot be corrected with straight pipe, commercially available "straightening vanes" can be installed to correct poor upstream hydraulic conditions.
- The round pipe cross section provides a clean and an easily calculated flow area.
- There are numerous commercially available "flow meters" (utilizing various technologies) that provide flow measurement and *automatic* volumetric totalizing with more than acceptable accuracies. Many can also be delivered with factory calibration certificates traceable to the National Institute for Science and Technology (NIST).
- If the piping system is designed properly, the flow meter can be easily removed and re-calibrated by the manufacturer or other entities.
- Flow meters can be easily installed with standard, commercially available fittings.

For the reasons above, meeting flow measurement and volumetric totalizing regulations for new or existing pipeline turnouts has become more of an economic analysis than an engineering topic. A variety of irrigation districts simplify the challenge by requiring that farmers install accessible, properly installed magnetic or propeller meters downstream of their filter systems when the farmers install a drip/micro system.

Conversely, meeting flow measurement mandates for canal turnouts is more complex. Although there are good solutions for new canal turnouts, there are very few new canal turnouts being constructed and it is prohibitively expensive to replace each non-conforming structure at the district level. As such, the remainder of this paper will focus on the options for utilizing existing structures for flow measurement as well as options for retrofitting existing canal turnout structures to meet flow measurement regulatory obligations.

A major constraint for canal turnout flow measurement is access to existing physical configurations. In general, most canal turnout structures and accompanying gate/valve mechanisms are installed in the canal. The structure discharges into a buried pipe under a canal access road. The buried pipe may or may not daylight on the farm side of the access road with various arrangements. This physical configuration limits flow measurement options to one side of the buried pipe or the other, and many districts have limited (or no) jurisdiction to install devices on the farm side of the turnout.

The size and placement of a flow measurement device is also constrained by other factors. The device cannot obstruct normal canal maintenance operations, or be vulnerable to damage from access road traffic (Burt 2010). In addition to these factors, flow measurement devices are also susceptible to typical problems experienced in most open channel applications such as sedimentation, trash and biological debris, and vandalism. Despite these challenges, canal turnout flow measurement has been successful at various levels.

Most existing canal turnouts fit into one of the following categories:

- Simple canal gate that was never designed to provide a means of flow measurement or volume totalizing.
- A "rated" gate to which a prescribed formula or rating table is used in conjunction with field measurements such as the upstream and downstream water levels, and the gate opening. Examples include:
    - ARMCO metergate
    - IID jack gate
    - Constant head orifice
- A simple canal gate, combined with an auxiliary and dedicated flow measurement device including:
    - Open propeller meters
    - Portable or permanent Acoustic Doppler Velocity Meters (ADVMs) and similar electric devices
- Relatively new, complete gate and flow measurement packages (e.g., the Rubicon SlipMeter)
- Pumps, which for the purposes of this paper are considered pipeline turnouts

This paper discusses three specific efforts to work with existing structures to improve accuracy. The three examples are:

1. Verifications of ARMCO meter gate rating tables for standard and non-standard installations
2. A calibration system and procedure for IID jack gates
3. Pilot installations of an adjustable, flow measurement orifice for non-standard canal turnouts

METERGATE CALIBRATIONS

Overview

Metergates are the most common canal turnout structure in California irrigation districts (ITRC 2002), although many (if not most) do not have a proper downstream stilling well. Since the early 1900's metergates have been commercially available from various manufacturers as an integrated canal turnout package, functioning as both a flow control and flow measurement device. Metergates are standard round canal gates with a specific configuration, as shown in Figure 1, which serves to "standardize" the downstream hydraulic conditions for field measurements.

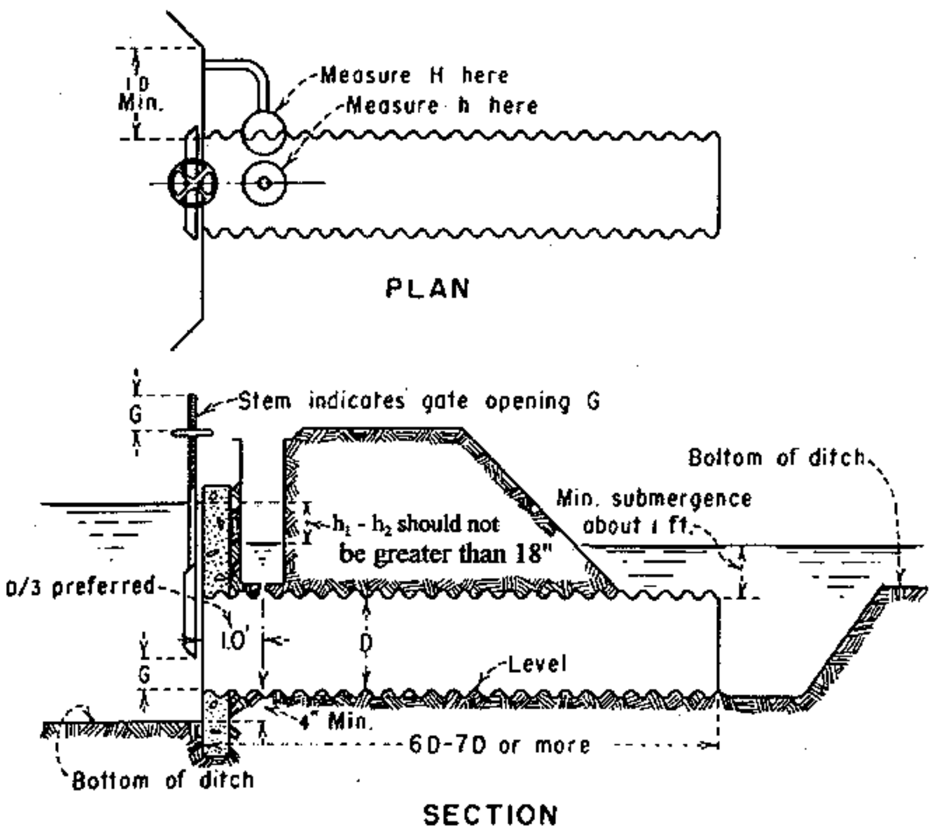

Figure 1. Metergate installation requirements (USBR 1997). Recommended modifications are noted in Burt and Howes (2014).

Flow Measurement. The difference in head pressure between the upstream and downstream sides of the gate mechanism and the gate opening are determined during an irrigation event and applied to manufacturer-provided rating tables (USBR 1997).

Volumetric Totalizing. The irrigation water volume delivered during an irrigation event can be calculated with the following equation:

$$V = \sum_{i=1}^{n}(Q_i \times t) \times \frac{3600}{43560} \qquad \text{Equation (1)}$$

Where,
V = volume delivered (Acre-feet)
Q_i = instantaneous flow measurements (ft^3/sec)
n = number of observations made
t = times between measurements, (hours)
3600/43560 = conversion factor

Calibration Evaluation

Many existing metergate installations do not meet the prescribed installation requirements; for example, the downstream water level measurement connection is often not installed 12" downstream of the gate face. For these and other non-standard metergate installations, applying the standard rating tables provides an unknown flow measurement uncertainty.

ITRC evaluated standard metergate rating tables for both standard and non-standard installations (Howes and Fulton 2013). Round and square gates of various sizes were included in the evaluation.

Results. A summary of the results from the evaluation is provided below (Burt and Howes 2014):

1. A high level of flow measurement accuracy (+/-5%) was found if all of the following conditions are met:
    a. The gate opening is between 20% and 75%
    b. The top of the gate is submerged by a minimum of one-half the gate opening
    c. The location of the downstream water level measurement is between 4" to 12" downstream of the face of the gate
2. A downstream water level measurement location between 4" and 12" downstream of the gate face does not have a significant effect on the flow rate obtained using the existing rating tables unless the gate is open more than 70-75% (percent of fully open).
3. Supply canal (tangential) water velocities did not seem to have a significant impact on the flow through the turnout gates. Supply channel velocities up to 1.9 feet per second (fps) were examined.
4. Higher flow measurement uncertainty (error) occurred at gate openings less than 20%.
5. Optimum range of operation for the highest accuracy was an opening between 20% and 75% under most conditions. Smaller gate openings seemed to be more problematic than larger gate openings.
6. Increased flow measurement uncertainty occurs if the upstream gate face is not submerged by at least one-half the gate height (or diameter). USBR recommends upstream gate submergence of at least a full gate height (or diameter).

During the evaluation, practical installation and operational recommendations were developed for metergates:

1. The buried pipe downstream of any metergate needs to remain full to enable downstream water level measurements.
2. Upstream submergence of at least one-half the gate height (or diameter) is required.
3. The true gate opening needs to be known. This is typically different than simply measuring the vertical gate movement from the seating position because of:
    a. Tolerances between the gate stem and the gate face. There is almost always measurable "slop" (0.25" or more) in the stem-gate connection.
    b. Overlap of the gate face to the actual opening. To fully seated (closed) position, most round and square canal gate faces must overlap the flow area opening.
4. The true gate zero should be marked by a grinder or other permanent means other than a marker or paint.
5. A stilling well should be installed on the downstream water level measurement location. The stilling well provides dampening of water level fluctuations due to turbulence. The stilling well should be:
    a. At least 6"-8" in diameter with a small access hole to the buried pipe of approximately ¾" diameter. Not only does this combination of sizes provide for adequate dampening, but also:
        i. The larger diameter allows easier measurements. The operator can actually see the water level and use a standard tape to measure down.
        ii. The larger diameter allows for cleaning the stilling well, such as removing sediment, trash, leaves, and other debris.
    b. The top of the stilling well should be equal in elevation to the top of the gate frame. This ensures that a single reference plane is available to the operator to measure the upstream water level (down from the gate frame) and the downstream water level (down from the top of the stilling well).

Discussion. The results of the evaluation indicated that with the proper installation, preparation and operation techniques, metergates could achieve acceptable accuracies for both flow measurement and volumetric totalizing.

- The delivered flow rate can be measured within acceptable accuracies using rating tables as long as various key conditions are met. The ITRC rating tables also provide flow measurements with improved uncertainties for less-than-ideal gate openings (less than 25% or greater than 75%).
- Delivered volumes of water can meet required accuracy standards with sufficient periodic flow measurements. The minimum frequency of those periodic measurements must be determined by local conditions, such as the variability in the water level of the supply canal.

IID GATE CALIBRATION SYSTEM

The typical canal turnout for Imperial Irrigation District (IID) is a jack gate. The name is derived from the lifting mechanism. A typical IID jack gate is shown in Figure 2.

Figure 2. A typical IID jack gate

For flow measurement, the difference in head pressure between the upstream and downstream sides of the gate mechanism and the gate opening are measured during an irrigation event and applied to gate discharge equations. It is difficult to determine the validity of the equation and its coefficients without verification. Furthermore, different equations and sets of measurements are required for submerged and free flow conditions.

Various theoretical and analytical methods have been proposed to determine the correct coefficients based on field-measured ratios such as the relative opening using momentum or energy conservation approaches (Belaud et al 2009); however, these are likely too complex for utilization in the field. Rather, it was proposed that the general submerged and free flow gate discharge equations could be used (or rating tables) to provide sufficiently accurate flow measurement if the discharge coefficient was determined empirically. The general gate discharge equation for a submerged flow condition is shown as (USBR 1997):

$$Q = CA\sqrt{2g\Delta H} \qquad \text{Equation (2)}$$

Where,
C = discharge coefficient
A = open flow area (ft^2)
g = acceleration of gravity, (ft/sec^2)
ΔH = head differential across the gate (ft)

For gates that operate in free-flow conditions, the following general equation is used:

$$Q = CA\sqrt{2gH} \qquad \text{Equation (3)}$$

Where,
C = discharge coefficient
A = open flow area (ft^2)
G = acceleration of gravity, (ft/sec^2)
ΔH = upstream head (ft)

Through in-situ field testing, the discharge coefficient could be determined. It was thought that such an approach would not only simplify the flow measurement process compared to other methods, but also provide verified field data as an improvement over theoretical equations.

Characterization Overview

Transitioning flow conditions and the variety of (i) side contractions, (ii) bottom contractions, and (iii) hydraulic entrance conditions further complicate the use of theoretical equations and coefficients. Because it would also be economically infeasible to standardize all IID jack gates through replacement, it was determined that characterizing jack gates could be a possible solution to meet district-level flow measurement obligations.

In cooperation with Sawtelle and Rosprim, a Corcoran, CA fabrication firm, ITRC modified a "moon-buggy" pumping system that would be used to calibrate individual IID jack gates. The pumping system is shown in Figure 3.

Figure 3. Pumping system for IID jack gate characterization

Fundamentally, the pumping system can be used to characterize canal turnouts by delivering water through the gate, and pumping the water back to the supply canal while measuring the flow rate with redundant, certified flow meters.

More specifically, the characterization process was conducted as follows:

1. The supply canal would be configured to provide relatively good water level control via weir flow, and the water level was manually adjusted to be close to the high water mark. Therefore, slight fluctuations in the canal water level would be a smaller percent of the total submergence of the gate.
2. A removable dam was installed in the farm ditch approximately 60 feet downstream of the turnout gate.

3. The suction piping of the pumping system was set approximately 20-40 feet downstream of the turnout gate.
4. The discharge piping of the pumping system was set to return into the supply canal.
5. The true gate zero was determined.
6. The gate was slowly opened to deliver a historic maximum flow, and the pumping system flow rate was adjusted via hydraulic Vernier controls.
7. The pumping system flow rate was adjusted so that the farm ditch had little freeboard, but a consistent depth.
8. Once the farm ditch water level had stabilized at the maximum flow rate, multiple flow meter readings and gate water level measurements were recorded over a period of 10 minutes.
9. The gate position was adjusted to lower the flow rate, and the process was repeated.
10. The field data was recorded at a total of three flow rates: a historical maximum, a medium flow rate, and the historical minimum flow rate.

The field measurements were entered into a spreadsheet that was set up to automatically calculate a discharge coefficient at the particular flow rate and gate opening. Equation (4) is rearranged from Equation (2) for a submerged flow condition:

$$C_d = \frac{Q}{A\sqrt{2g\Delta H}}$$ Equation (4)

Results

To train IID staff on the characterization operations, a full gate characterization was completed. A jack gate was characterized at three different flow rates. Using Equation (4) the results from the completed characterization are shown in Table 1.

Table 1. Results of completed jack gate characterization

	High Flow	Medium Flow	Low Flow
Submerged (Y/N)	Y	Y	Y
Measured Flow Rate (CFS)	11.09	7.25	3.96
Δ H (ft)	0.26	0.34	0.48
Flow Area (sq. ft)	3.81	1.90	0.78
Discharge Coefficient, Cd	**0.715**	**0.815**	**0.912**

The three discharge coefficients can then be plotted to develop an equation to solve for interpolated discharge coefficients for any expected flow rate. The plot is shown in Figure 4. A linear trendline was developed so that discharge coefficients can be interpolated with a reasonable level of accuracy (R^2 = 0.9988), for flow rates typical of the specific canal turnout.

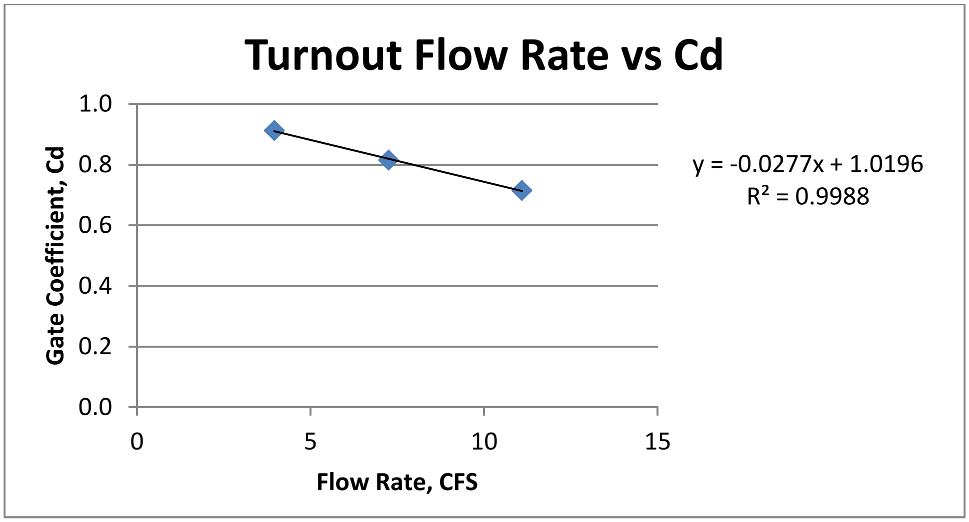

Figure 4. IID jack gate – flow rate versus discharge coefficient

Discussion

Some jack gates transition between free flow and submerged flow conditions. The transition between flow conditions can occur between low and high flow rates, or be caused by fluctuating downstream conditions throughout irrigation events.

For these transitional flow condition turnouts, it can also be difficult to properly identify the flow condition, and can be confusing to operators. For these sites, it would be recommended that a hydraulic "bump" be installed downstream of the jack gate to raise the water level downstream of the gate for a short distance. This would ensure the gate operates under submerged flow conditions for typical delivered flow rates.

Flow Measurement. The pumping system was successful in developing individual discharge coefficients, which could be used in conjunction with the appropriate gate discharge equation and field measurements. It is expected this method would provide flow measurement within the stipulated accuracies for existing gates.

However, many of the same practical and operational recommendations developed by ITRC from the metergate evaluation also apply to the use of gate discharge equations for jack gate flow measurement, including:
1. Determining a true gate zero opening position
2. Permanently marking that position
3. Providing a single reference plane for water level measurements for submerged flow gates

In addition, ITRC recommended that jack gate turnouts could be categorized by similar hydraulic conditions such as:
- Submerged, free-flow, or transitioning conditions
- Suppression or contraction on the gate sides
- Suppression or contraction on the gate bottom

By categorizing gates, the total number of characterizations could be significantly decreased. A second gate characterization was started as part of the training, but was not completed with ITRC support.

Volumetric Totalizing. Similar to the metergate, operators must take one or more instantaneous flow measurements and apply those to Equation (1) to determine the delivered irrigation water volume per irrigation event.

Challenges. A complete turnout characterization took approximately 6 hours; however, much of that was focused on IID staff training on the transportation, operation and data analysis. It is likely that after a few iterations, two complete characterizations could be completed in less than 8 hours with a team of 2-3 operators/engineers, if the two turnouts were somewhat close together along the same channel.

Safe transportation along a canal access road was possible with a standard 1-ton truck; however, over-the-road transport required a semi-truck and trailer with “oversize” flags.

Cost. The complete pumping system, parts and accessories cost approximately $110,000. Although the initial capital investment is relatively large, the cost per turnout is much lower in such a large district. Furthermore, the pumping system can be, and probably will be, used for other district operations such as dewatering canals.

ADJUSTABLE ORIFICE PLATE

There are many existing California canal turnouts that were never designed to provide flow measurement, or never installed properly to meet certain conditions. For these installations, districts will need to either replace the structure or install an auxiliary device to provide accurate flow measurement and volumetric totalizing.

For these structures, ITRC examined the applicability of an adjustable orifice plate with a key feature – a datalogger with single pressure transducer that measured the differential head across the orifice. There is nothing new about using orifice plates upstream of a flow control gate – this application was designed for the case of frequently varying flow rates into a turnout that would not be properly measured by the district operators. The plate can be installed without replacing the existing structure, keeping everything on the irrigation district side of the access road. The orifice plates can be installed vertically or parallel with a canal’s side slope, upstream of an existing canal turnout, as shown in Figure 5.

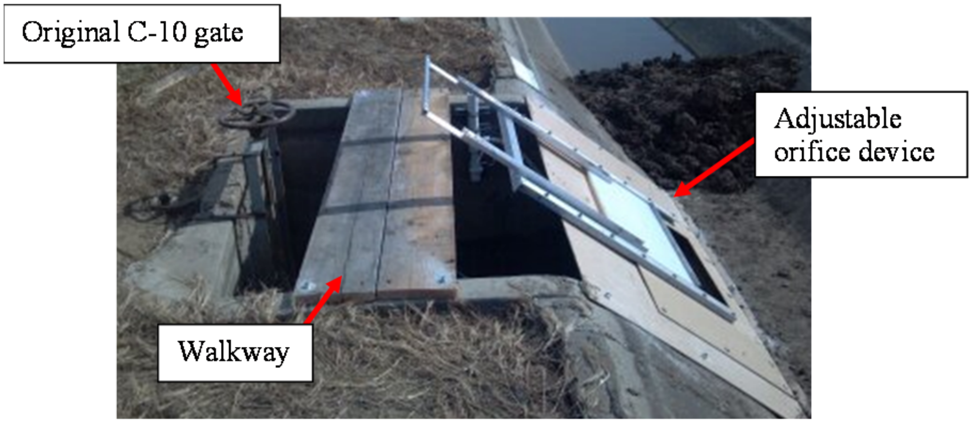

Figure 5. Orifice plate configuration with an existing non-standard metergate

Orifice Plate Overview

The orifice plate approach combines a standard USBR submerged orifice discharge equation with the physical configuration of a constant head orifice (CHO). The discharge equation is the same as Equation (4), for a submerged flow gate, with the exception of the discharge coefficient. Provided the following conditions are met, a C_d of 0.61 can be used (USBR 1997):

- The upstream edges of the orifice should be straight, sharp, and smooth.
- The upstream face and the sides of the orifice opening need to be vertical.
- The top and bottom edges of the orifice opening need to be level.
- Any fasteners present on the upstream side of the orifice plate and the bulkhead must be countersunk.
- The face of the orifice plate must be clean of grease and oil.
- The thickness of the orifice plate perimeter should be between 0.03 and 0.08 inches. Thicker plates would need to have the downstream side edge chamfered at an angle of at least 45 degrees.
- Flow edges of the plate require machining or filing perpendicular to the upstream face to remove burrs or scratches and should not be smoothed off with abrasives.
- For submerged flow, the differential in head should be at least 0.2 feet.
- Using the dimensions depicted in Figure 6, P > 2Y, Z > 2Y, and M > 2Y.

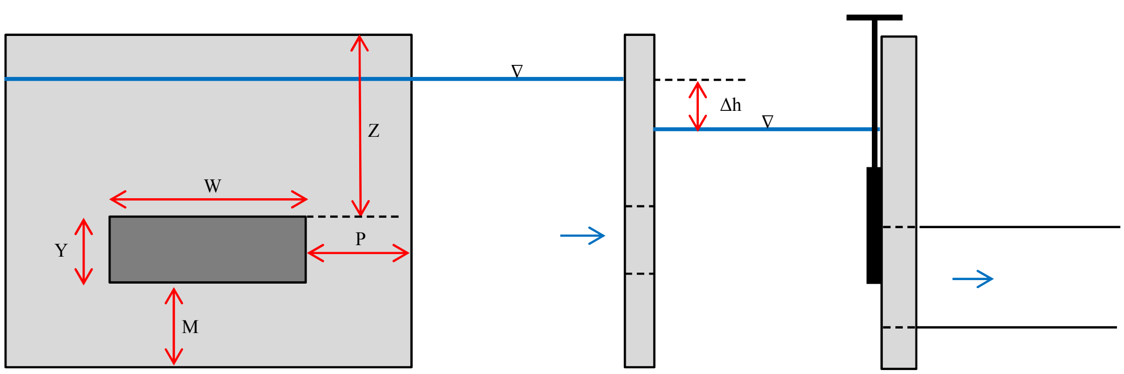

Figure 6. Submerged orifice dimensional requirements

It was proposed that the orifice area be made adjustable so that a range of flows could be delivered, while maintaining a measurable head differential across the orifice (0.2' minimum).

Operators could then use a rating table to choose an appropriate orifice opening to meet the irrigation demand, such as the one as shown in Table 2.

Table 2. Orifice plate rating table

	Width of Orifice Opening, ft											
	2.5											
	Height of Orifice Opening, ft											
	0.5	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.5
Flow Rate, CFS	Change in Head, ft											
30.0											1.04	0.96
25.0									1.04	0.86	0.72	0.67
20.0							1.04	0.82	0.67	0.55	0.46	0.43
15.0					1.04	0.77	0.59	0.46	0.38	0.31	0.26	0.24
10.0			1.04	0.67	0.46	0.34	0.26	0.21	0.17	0.14	0.12	0.11
9.0			0.85	0.54	0.38	0.28	0.21	0.17	0.14	0.11		
8.0		1.19	0.67	0.43	0.30	0.22	0.17	0.13	0.11			
7.0		0.91	0.51	0.33	0.23	0.17	0.13	0.10				
6.0	0.96	0.67	0.38	0.24	0.17	0.12						
5.0	0.67	0.46	0.26	0.17	0.12							
4.5	0.54	0.38	0.21	0.14								
4.0	0.43	0.30	0.17	0.11								
3.5	0.33	0.23	0.13									
3.0	0.24	0.17										
2.5	0.17	0.12										
2.0	0.11											
1.5												
1.0												

The orifice can be adjusted and locked in place with pins at discrete orifice opening intervals (0.1'), as shown in Figure 7.

Figure 7. Adjustable orifice

Flow Measurement. The existing canal gate would then be used to start and adjust the delivered flow. The flow rate can be manually measured by using an incorporated stilling well, as shown in Figure 8.

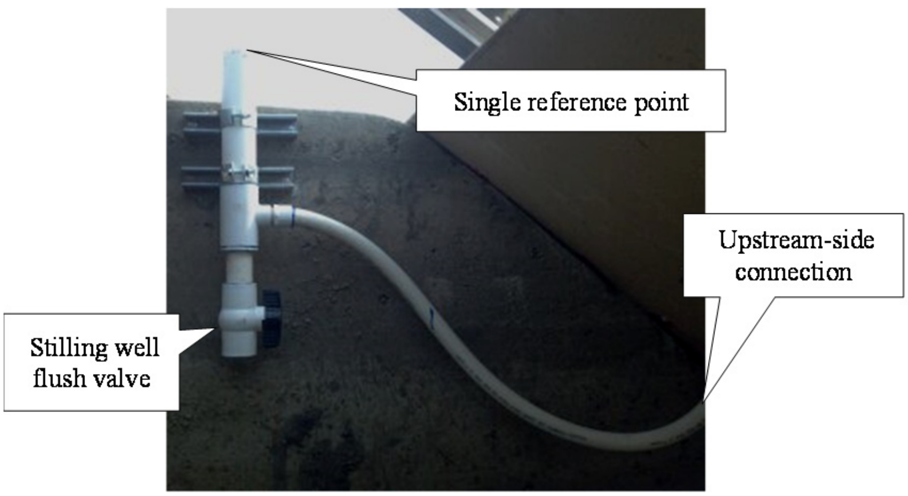

Figure 8. Stilling well configuration, installed downstream of the orifice plate

With the orifice width fixed and the orifice height known, the head differential is measured by two methods. Manual head differential measurements are taken at the top of the stilling well. The upstream water level is measured from the top of the stilling well to the water level inside. The downstream water level is also measured from the top of the stilling well to the surrounding water level. In addition, a differential pressure transducer and data logger is installed to record the head differential measurement over time.

Volume Totalizing. Manual flow measurements could be averaged and the volume totalized using Equation (1). The data logger provides a redundant record of instantaneous flow measurements at 2.5 minute intervals. The spreadsheet data can then be manipulated using a computer program such as Microsoft Excel® to calculate delivered volumes.

Results

Flow Measurement. ITRC installed two orifice plates with single pressure transducers: one at Patterson Irrigation District (PID) and a second in Merced Irrigation District (MID). During the first season, problems with the differential pressure transducer were found. However, the PID installation has continued to operate over two complete irrigation seasons. The PID data was retrieved and plotted. The PID flow measurement results using Equation (2) and a discharge coefficient of 0.61 are shown in Figure 9.

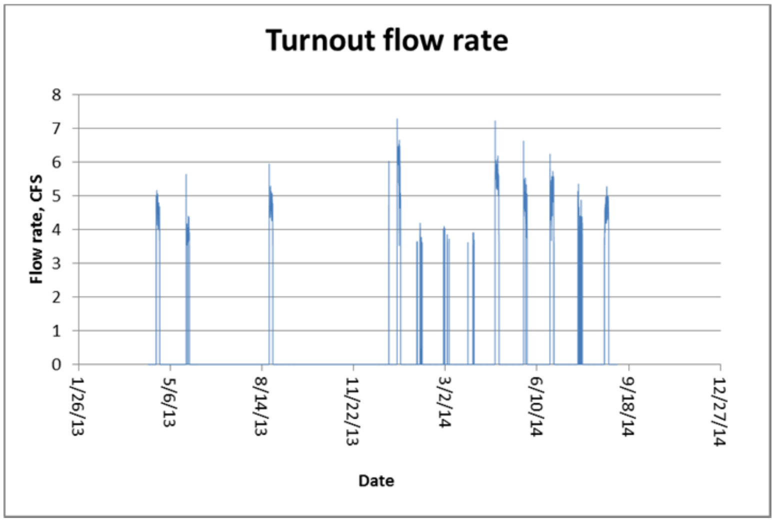

Figure 9. PID orifice plate flow measurement data

Volume totalizing. Using the same spreadsheet, the delivered volumes were calculated and accumulated over two irrigation seasons. The volumetric results are shown in Figure 10.

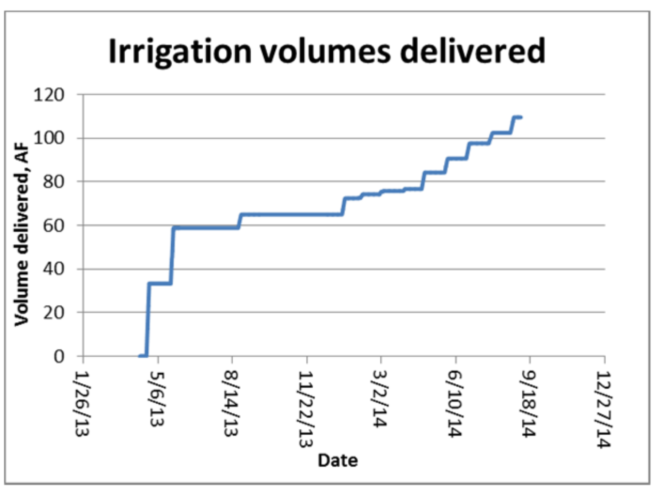

Figure 10. PID orifice plate volumetric data

The turnout delivered roughly 65 acre-feet during the 2013 irrigation season and 55 acre-feet during the 2014 irrigation season.

Discussion

Although the orifice plates were not calibrated at a flow measurement facility, their configuration provided a method of applying standard discharge equations to non-standard canal turnouts. Further evaluation may be conducted in the future regarding the discharge coefficient in both the vertical orifice and slanted orifice orientations.

Challenges. The Telog data logger utilized for these and other trials has proven to be a rugged and dependable tool for research. However, data retrieval requires a field visit, as well as a proprietary cable and program installed on a laptop. Recent technological advances have become readily available for these applications such as wireless communication, cloud-based databases, and automated reporting. However, that advanced technology would do little to resolve most of the challenges experienced during this experiment.

The most challenging aspect to the expanded implementation of the orifice plate trials was finding adequate sensing products. There are very few manufacturers of submersible, differential pressure transducers of the type used in this experiment. Even fewer of these available products are sufficiently rugged for the application. One of the two GE Druck pressure transducers experienced significant drift over the first season. It has since been removed until another solution can be found. Future testing of orifice plates for flow measurement will likely include various other sensing technologies.

Cost. Each orifice plate cost roughly $6,000 to fabricate and install in the field. The cost of construction could likely be decreased with less expensive materials and local fabrication shops.

CONCLUSION

Various methods are available to irrigation districts that can provide canal turnout flow measurement and volumetric totalizing that conform to regulatory standards. However, the variety of existing canal turnout structures, their hydraulic conditions, and specific local considerations will likely result in an equally varied implementation of flow measurement and volumetric totalizing across California.

Regardless of the method used for flow measurement and volumetric totalizing, there will likely be further challenges in the future for irrigation districts to aggregate and organize the large amounts of volumetric data.

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