A Simple Method for Calibrating a Radial Gate for Use as a Flow Measuring Device

G. Bonaiti, A. Karimov, G. Fipps

Abstract. *A simple method for the calibration and use of an existing radial gate as flow measuring device under submerged flow conditions is presented. Details on equipment and calibration methodology are discussed including: determining required gate opening parameters and flow conditions for which the method is valid. Flow is calculated with a submerged orifice equation using a constant drainage coefficient. This methodology was applied to a radial gate located in the United Irrigation District in South Texas. The gate was instrumented and monitored continuously over a three-month period. Measured versus predicted flow varied by less than 4%. The method was compared to a more complex equation which accounts for submerged flow conditions and results in a mean absolute relative error of 3%. Analysis of individual flow events revealed significant hysteresis when estimating gate opening from an actuator position signal. This accounted for a difference in the calculated flow of up to 0.13 m^3 s^{-1}.*

Keywords. *Flow meter calibration, Gate opening, Hysteresis, Submerged orifice equation.*

Flow measurement in irrigation canal systems provides important information on water availability, use, and losses. Replogle (2002) suggested that flow measurement is one of the most important factors for effective irrigation scheme management. Gensler et al. (2009) takes the idea farther and defines water measurement as the single most important component in irrigation scheme modernization, as "all operational decisions require sound knowledge of available water supplies and the demand throughout the system." In recent years, the development of automated irrigation systems has led to improved methods for water monitoring and control. Freeman and Burt (2009) reviewed practical experiences with state-of-the-art technologies for irrigation automation and concluded that it has great potential for collective irrigation modernization.

Nevertheless, irrigation districts do not often measure water flow within their delivery network and if they do, they frequently use antiquated methods that suffer accuracy. The main reasons are: measuring flow is not easy and it requires additional equipment and expense. Additionally, measurement is often only done at the main pump station. To encourage irrigation districts to implement flow monitoring programs, methods need to: be inexpensive and reasonably accurate (Wolter and Burt, 1997), use "novel application of existing technology and knowledge" (Replogle and Kruse, 2007), and target specific field conditions in a pragmatic way (Burt, 2011; Feist and Burt, 2014). One approach which is often less expensive than installing dedicated flow measurement structures or equipment is to use existing water control structures as measuring devices as long as site specific conditions are carefully evaluated (Wahl, 2004). To use radial gates for flow measurement, upstream water level, downstream water level, and gate position must be monitored continuously (USBR, 2001).

This article presents a case study for calibrating an existing radial gate for flow measurement. The study was carried out on a radial gate in the United Irrigation District of the Lower Rio Grande Valley in South Texas. Geologically, the region is a delta of the Rio Grande River and is characterized by small slopes. Bonaiti et al. (2010) collected and analyzed data from a radial gate installed in a main canal within the District. They found flow conditions were always submerged and gate operation had a very narrow range of water levels and gate openings. They were therefore able to estimate the flow using a submerged orifice equation with reasonable accuracy, assuming a constant drainage coefficient.

This article builds upon the work of Bonaiti et al. (2010) to examine issues related to calibration of existing radial gates for flow measurement in regions similar to the Lower Rio Grande Valley. The specific objectives are to:

- Identify and quantify sources of equipment error selection when using a radial gate as a flow measuring device in an open canal, and
- Identify suitable equations to estimate flow and compare their performances under the specific flow conditions.

Literature Review

Radial Gates

Radial gates require a relative small force for lift and operation, and they have good hydraulic discharge characteristics; thus, they often can be successfully calibrated for use

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as a flow measurement device (Bos, 1989; Wahl, 2004). To maximize accuracy, Bos (1989) recommended using radial gates with a horizontal, sharp bottom edge, measuring upstream water level in a rectangular approach channel having the same width as the gate, ensuring that the ratio of gate opening to water depth ratio does not exceed 0.8, and maintaining modular (free) flow. Wahl (2004) noted that the most difficult conditions are sites where the downstream channel is much wider than the radial gate. Shayan et al. (2014) determined that the type and angle of the radial gate seal significantly affected the contraction coefficient. Hard-rubber seals had the largest coefficient.

Bos (1989) identified the types of errors that can occur when calibrating radial gates and classified them as spurious, random, and systematic. A common systematic error occurs when estimating gate position. In particular, the same theoretical gate position can yield a different actual gate position when the gate is operated upward or downward. This is commonly referred to as hysteresis, and can be caused by a variety of reasons including measurement errors and mechanical equipment operational tolerances.

Flow Conditions

The first step in calibrating a radial gate for flow is assessing the flow conditions and water levels relative to the gate opening. Flow is defined as "free" when the discharge through the gate is controlled by the upstream water level, and "submerged" when the discharge is affected by both the upstream and downstream water level. Free flow is the ideal condition; flow measurement is subject to additional uncertainty when flow is submerged and at the threshold between the two flow regimes (Bos, 1989; Wahl, 2004). Several methods have been proposed to assess gate flow conditions (Bos, 1989; Lin et al., 2002). Bijankhan et al. (2011) presented an equation which distinguishes the flow conditions through a radial gate. Skogerboe (1965) proposed the following guidelines for calibrating submerged gates for flow: measure upstream water level at least 0.6 m away from the gate, measure downstream level at a location with full recovery of kinetic energy, and allow a minimum head differential of 6 cm between upstream and downstream locations. Robin (1939) found that in cases of deeply submerged gates, full recovery of kinetic energy may take place immediately downstream from the gate.

Equations

The submerged orifice flow equation is based on the Bernoulli equation and can be an effective method for calibrating radial gates (Buyalski, 1983; USBR, 2001). However, limitations exist. Ghetti (1980) showed that its application is limited to the case of slow and very submerged flow. Buyalski (1983) developed computer programs to overcome the complex discharge characteristics of radial gates and found that the discharge coefficient becomes difficult to determine when flow approaches the maximum designed capacity.

Clemmens et al. (2003) presented an equation referred to as the Energy-Momentum (E-M) method, which includes a momentum component to estimate the water level above the vena contracta under submerged flow conditions. Wahl (2004, 2005) and Wahl and Clemmens (2005) found that the E-M method is dependent on the relative gate opening over the upstream water level. Wahl also identified several issues potentially affecting the E-M method, including: errors in the dataset utilized to develop the equation, hydrostatic forces on channel walls, shape and velocity of the vena contracta, suitable location for measuring downstream water level and boundary friction on the channel floor. He therefore suggested the use of new computer programs to solve most of these issues. Lozano et al. (2009) examined the sources of error in applying the conventional discharge equation (based on the energy equation) and the E-M methods to rectangular sluice gates under submerged flow conditions. He found that the most significant errors were in the calculation of the discharge coefficient, which is sensitive to the head differential and the vertical gate opening.

Bijankhan et al. (2011, 2013) presented an equation which is valid for flow conditions through a radial gate in the transition zone between free and submerged flow. The equation integrates the submergence ratio in the computation, and introduces the maximum allowable tailwater depth permitting free flow in the formulation. The equation can be used for both free and submerged flow conditions and was found to improve the accuracy of calibration of radial gates for flow measurement.

Dent (2004) calibrated an empirical relationship that relates flow and gate opening as a function of the difference in head across the gate under submerged flow conditions. He used a large amount of field data, and reported an accuracy of 3% to 5%. He recommended the use of this relationship only within the range of operation covered by the historical data set, and to refine calibration continuously. A similar approach was followed by Corsi and Schuler (1995). They used discharge measurements to develop field-verified submerged-orifice discharge coefficient relationships for 11 radial gates, and recommended using such relationships only for conditions for which the relationships are valid.

Materials And Methods

Site Description

The United Irrigation District is one of 29 irrigation and water districts in the Lower Rio Grande Valley of Texas, and it has an authorized annual water use of about 6×10^7 m^3. The District delivers agricultural and municipal water to customers within its 15,000 ha service area through a 350 km network of canals and pipelines. As shown in figure 1, water is pumped from the Rio Grande River to the Bryan Main which is the main artery for the Northeastern portion of the District. Water flowing through this gate is approximatively 30% of the total water distributed by the District, and is delivered for irrigation and municipal water supply uses. Bryan Main is a trapezoidal concrete-lined canal with a flow rate capacity of 6.4 m^3 s^{-1}. Cross-section dimensions are 2.1 m depth, 5.5 m top width, 1.2 m bottom width, and side slopes of 1:1.

In 2009, the District installed a new radial gate (fig. 2), designed and fabricated locally, to improve water management efficiency by replacing an old sluice gate. The pre-existing submerged sluice gate structure was located about 40 m downstream from the Mission Main canal (fig. 1) and

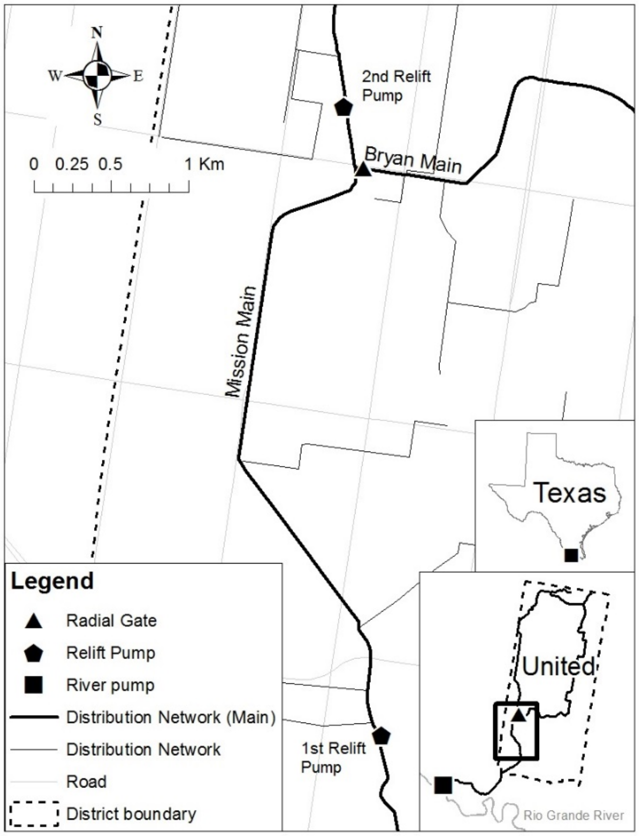

Figure 1. Location map.

was incapable of handling flow measurement capabilities due to constant fluctuations and turbulent flow conditions at upstream and downstream locations. The radial gate is located about 20 m downstream of the old sluice gate structure. The housing for the radial gate is a rectangular structure 7.3 m long and 3 m wide. The gate has a radius of 2.1 m, vertical height of 2.1 m, and pinion (pivot point) height of 1.1 m. The leaf edges have hard bar-shaped rubber seals, and the gate can open up to 1.5 m. The District operates and delivers water Monday through Friday all year long, and shuts down on weekends.

Figure 2. Radial gate and structure, before installation of monitoring instrumentation.

Equipment and Instrumentation

Figure 3 shows an instrumentation schematic of the experimental flow monitoring system. Two pressure transducers (Model: Acculevel, Keller America, Newport News, Va.) with 4-20 mA input/output control signals recorded water levels upstream and downstream of the gate. The upstream sensor was located 3 m from the gate pinion and installed in a 5.1-cm (2-in.) PVC stilling-well built into the vertical wall of the radial gate's rectangular control structure. The downstream sensor was located 9 m from the gate pinion in a 40.6-cm (16-in.) PVC stilling-well with the bottom open to the canal flow. The gate was powered by an electric motor, which could be operated manually or remotely with the use of a built-in gate position sensor in the actuator. The actuator was an Armaturen Und Maschinen Antriebe (AUMA) multi-turn actuator (Model SA 10.1-54B/GSD100.3, AUMA, Muellheim, Germany) with 4-20 mA input/output control signals. It features a single phase motor, 120 VAC, 60 Hz, two gear train limit switch with eight contacts, a dual position potentiometer, and an electronic position transmitter RWG (4-20 mA DC output). AUMA engineers provided initial calibration and set up. The control and data acquisition system consisted of a Campbell Scientific (Logan, Utah) CR 1000 data logger and a SDM-CVO4 control module, which were hard-wired to a computer in the District's office.

A Doppler flow meter (Model; Argonaut-SW, SonTek, San Diego, Calif.) was installed 10 m downstream of the radial gate and mounted on the middle bottom of the canal. The meter has three acoustic beams; one which points vertically up to measure water level, and two which point horizontally up and down stream at a 45° angle to measure water velocity. The Argonaut-SW specifications have a stated accuracy of ±0.1% for water level when used in depths less than 4.9 m, and ±1% of water velocity, for velocities up to 4.9 m s^{-1}.

Field Equipment Calibration and Verification

The downstream water level measurements were obtained with both the downstream pressure transducer and the Doppler flow meter. Readings from the pressure transducer were polled by the data logger at 5-s interval, and automatically averaged every 30 min. Readings from the Doppler flow meter were recorded at 2-min intervals, and later manually averaged to 30-min intervals. The two measurements were compared to verify consistency.

The actuator's control range (4-20 mA) was set to 0-100% scale in the data logger by adjusting mechanical switches which corresponded to a 0 to 1.5-m gate opening. The gate was then operated to different vertical open positions by varying the data logger input percentage, at 0.15-m intervals, moving the gate both upward and downward. At each data logger input percentage, the actuator position signal was recorded, and the vertical gate opening was manually measured. Data were compared to determine gate hysteresis.

A series of flow measurements using Price Type AA current meter was previously performed in the same location by Nazarov et al. (2006), together with recording with a Doppler flow meter (Argonaut-SW flow meter). They used a Scientific Instruments, Model 1210 Price Type "AA" Current

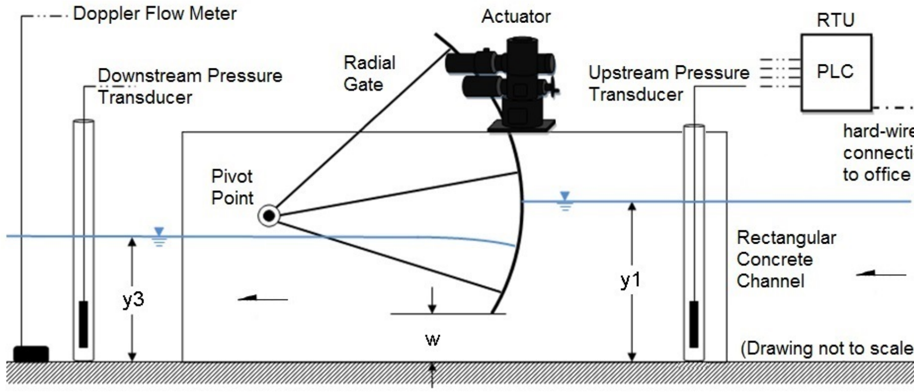

Figure 3. Schematic of the instrumentation installed at the study site to monitor flow: y_1 = upstream water level; y_3 = downstream water level; w = gate opening; RTU = Remote Terminal Unit; PLC = Programmable Logic Controller.

Meter, equipped with a Scientific Instruments Model 9000 Digimeter, and wading rods. Manufacturer specifications state that the meter is rated for measuring velocities from 0.08 to 2.44 m s^{-1}. Flow measurements were taken using the USGS two-point method were velocities are taken at 20% and 80% of total water depth of the canal cross-section (USBR, 2001). Readings from the Doppler flow meter were recorded in 2-min intervals. We conducted a second series of measurements in May 2010, following the same instrumentation, location, and procedure as Nazarov et al. (2006). All field data was analyzed to verify the accuracy of the Doppler flow meter under the conditions of the Bryan Main.

Field Study and Determination of Flow

The site was monitored over an 80-day period, from 13 January 2009 to 5 April 2009. Water levels as determined from both the Doppler flow meter and the pressure transducers were recorded continuously over this period. Other continuously recorded data were: gate opening (in the form of data logger input percentage and actuator position signal), and flow (measured with the Doppler flow meter). Water levels and gate openings were recorded with a polling interval set to 5 s and automatic averages every 30 min; Doppler flow meter readings were recorded in 2-min intervals and later manually averaged every 30 min.

Submerged flow conditions were verified by calculating the submergence ratio, as:

$$Sr = \frac{y_3 - y_{3(t)}}{y_{3(t)}} * 100 \tag{1}$$

where Sr = submergence ratio, y_3 = downstream level (m), $y_{3(t)}$ = transitional value of downstream level (threshold between free and submerged flow conditions). The threshold $y_{3(t)}$ was determined using the formula suggested by Lin et al. (2002), as follows:

$$\frac{y_{3(t)}}{w} = \frac{\delta}{2}\left(\sqrt{1+\frac{16y_1^2}{y_1\delta w+\delta^2 w^2}}-1\right) \tag{2}$$

where w = gate opening (m), δ = contraction coefficient, y_1 = upstream level (m). The submerged orifice flow equation was chosen to establish a head-discharge relationship for the radial gate and to calculate flow. This equation is derived from the general Bernoulli equation used to estimate flow through an underflow gate, and is applicable to radial gates in case of slow and very submerged flow (Ghetti, 1980), which may be written:

$$Q = w * L * C_d * \sqrt{2 * g * (y_1 - y_3)} \tag{3}$$

where Q = discharge (m^3 s^{-1}), w = gate opening (m), L = gate width (m), C_d = discharge coefficient, g = gravitational constant (m s^{-2}), $y_1 - y_3$ = head differential (m). Calculated flow was given at 30-min intervals, as that was the interval of data logger outputs (w, y_1, y_3).

To evaluate the accuracy of flow calculated with equation 1 compared to measured flow, we used two statistical methods. The first is represented by the coefficient of determination (R^2), obtained from regression functions interpolating all data (calculated vs. measured flow rate). The second is the relative sample standard deviation for individual events. Following Bos (1989), we treated the calculated flow and the measured flow as two samples from a population normally distributed, calculated as:

$$s = \frac{1}{\bar{x}}\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2} \tag{4}$$

where s = relative sample standard deviation, N = number of samples, x_i = sample (m^3), x = mean of all samples (m^3). Additionally, the mean absolute relative error (MARE) was used to evaluate the overall accuracy of the flow estimate, as follows:

$$MARE = \frac{\sum\left|\frac{(Q_{meas} - Q_{calc})}{Q_{calc}}\right|}{n} \tag{5}$$

where $MARE$ = Mean Absolute Relative Error, Q_{meas} = measured discharge (m^3 s^{-1}), Q_{calc} = calculated discharge (m^3 s^{-1}), n = total number of experimental data. The significance of hysteresis effects was determined by analyzing calculated versus measured flow during both the upward and downward motions of the gate. A parallelism test was carried out to compare the two linear regressions and slopes with an analysis of variance (ANOVA).

Flow was also determined with the method proposed by Bijankhan et al. (2013) which accounts for the varying submergence ratio, calculated by:

$$\frac{y_c}{w} = a_0\left(\frac{y_1}{w}\right)^{b1}\left(\frac{(y_1-y_3)/w}{\alpha\left(y_3-y_{3(t)}\right)/w+(y_1-y_3)/w}\right)^{b_2} \quad (6)$$

where y_c = critical depth, a_0, b_1, α, b_2 = numerical constants. Numerical constants were obtained by setting an objective function that minimized MARE, using the GRG (Generalized Reduced Gradient) nonlinear method available in the MS Excel Solver Add-in tool with default settings. The critical depth, y_c, is related to Q by:

$$y_c = \left(\frac{Q^2}{gb^2}\right)^{\frac{1}{3}} \quad (7)$$

where b = gate width.

RESULTS AND DISCUSSION

FIELD EQUIPMENT CALIBRATION AND VERIFICATION

Water Level Measurements

Downstream water levels ranged between 0.7 and 1.7 m, and were well within the Argonaut-SW factory accuracy limits. Water level obtained from the Doppler flow meter and the downstream pressure transducer resulted consistent, as demonstrated by the linear regression interpolating the data (slope=0.9927, intercept=0.0047, R^2=0.9999). Therefore, we did not correct pressure transducer readings, and directly used them in the flow calculation.

Actuator And Measured Vertical Gate Opening

The correlation between the data logger input percentage and the actuator position signal varied depending upon whether the gate was moving upward or downward (fig. 4). Values were very similar when the gate was operated upward, but the actuator position signal was higher than the data logger input percentage when the gate was operated downward. Both series of data were well fitted by a 2nd order polynomial regression, as demonstrated by the very high coefficient of determination (R^2=0.9998 for both regressions). This hysteresis phenomenon accounted for up to 0.61 mA, corresponding to 0.07 m difference in the actuator position signal for a given data logger input percentage. To exclude this type of error, we disregarded the data logger input percentage, and used the actuator position signal to estimate vertical gate opening.

The correlation between actuator position signal and measured vertical gate opening differed depending upon whether the gate motion was upward or downward (fig. 5). A detail box is shown in figure 5 that highlights the range of gate opening observed during the study period (0-0.5 m). The maximum hysteresis effect observed was a 0.024 m difference in measured vertical gate opening at an actuator position equal to 0.6 m. Hysteresis was likely due to

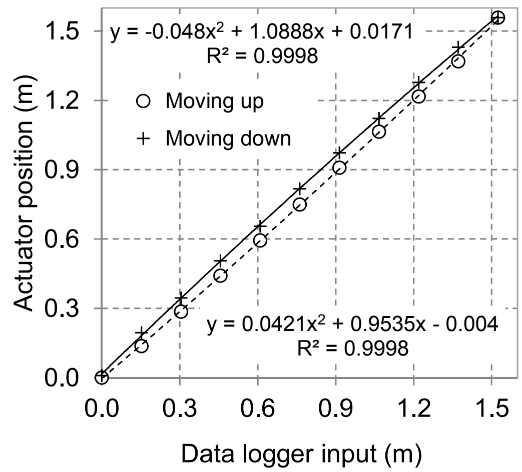

Figure 4. Correlation between gate openings as obtained from data logger input percentage and actuator position signal, during both upward and downward motion.

mechanical issues (internal friction and brakes on the motor were not able to completely stop the gate at the desired position). Figure 5 also shows that in both cases (upward and downward) the actuator position signal was greater than the measured vertical gate opening. As suggested by Bos (1989), errors which affect a group of measurements can be considered systematic, and must be treated separately from other errors. Separate expressions were developed for upward and downward movement of the gate using 2nd order polynomial regressions (table 1). These expressions fitted the data well and had high coefficients of determination (R^2=0.9996 and 0.9999 respectively for upward and downward motion). We then used the parameters of the equation to modify actuator position signal data, and then used the corrected values to estimate flow.

Flow Meter Calibration

Maximum flow measured in the canal with the Argonaut-SW meter was 3.3 m^3 s^{-1}, which corresponded to a velocity of 0.5 m s^{-1} and a water depth of 2 m. This high flow rate was forced in the canal in order to test the meter, but never occurred naturally during the study period. Regardless, both velocity and depth were well within the meter factory accuracy limits. Individual measures with the Price Type AA current meter ranged from 0.1 to 0.8 m s^{-1}, which were well within the factory accuracy limits of the Argonaut flow meter. The average flow rate measured with the Argonaut-SW was about 3% less than the average flow rate measured with the Price Type AA meter during both field tests conducted in 2006 and 2011. Flows measured with the Argonaut and the current meter in 2006 were 0.685 and 0.705 m^3 s^{-1}, respectively, and were 3.212 and 3.313 m^3 s^{-1}, respectively as measured in 2011. These results were used to calibrate flow measurements of the Argonaut-SW.

FLOW CALULATIONS

Table 2 shows the range in water levels and gate openings observed during the study period. The radial gate was completely closed every Friday evening, and opened again early Monday mornings, except twice in the second half of February. There was an average of about four gate movements per

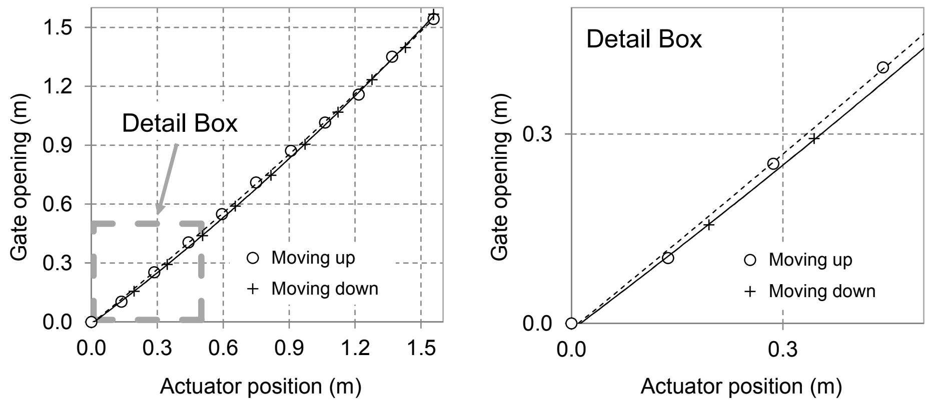

Figure 5. Correlation between gate openings as obtained from actuator position signal and actual vertical gate opening measurements, during both upward and downward motion. The detail box shows the range of gate opening observed during the study period.

week greater than 0.05 m, mainly Monday through Wednesday, with a maximum observed opening of 0.5 m. The downstream water level averaged 0.3 m lower than the upstream level. The submergence ratio as calculated with equation 1 ranged from 35% to 231%. The downstream water level was always above the threshold between free and submerged flow conditions ($y_{3(t)}$), as defined using a contraction coefficient of 0.6. In figure 6, the downstream water level and the threshold between free and submerged flow conditions are compared to upstream level, and are expressed as ratio to the gate opening.

Conditions were consistent with the recommendations presented in the literature for using a radial gate as a flow measuring device and for estimating flow with the submerged orifice equation. Furthermore, as stated by the District manager, the range of gate operation conditions observed during the study period were typical of the normal operation conditions during the entire year (Warshak, United Irrigation District, personal communication, 24 October 2016). As suggested by Bos (1989) and reported by USBR (2001), to prevent large discharge errors due to poor flow condition in the area just upstream from the measuring device, two cases should be distinguished: control width greater or less than 50% of the approach channel width. In the first case (our case) USBR (2001) recommends the following: "approaching flow should be tranquil… [and] 10 average approach flow widths of straight, unobstructed approach are required." The old gate structure which is located about 15 m upstream might, therefore, have slightly affected the accuracy of the results. Also the trapezoidal shape of the canal, as opposed to the rectangular shape of the gate structure, might have created additional interference. Both conditions were not further verified. Nevertheless, the authors believe that due to the slow flow velocities and very submerged flow conditions, these effects were minimal.

The calibration process had the objective to determine the value of C_d, and proceeded as follows: select an initial C_d value; calculate Q with equation 3 using measured gate opening (w) and water levels (y); compare calculated Q to measured Q over the study period; vary C_d until calculated Q (total cumulated at the end of the study period) matches measured Q. With a single discharge coefficient $C_d = 0.7$ the average error (relative standard deviation) between measured and calculated events was 2.8%, while the overall error (MARE) was 4%. Errors were calculated excluding the occasional measures obtained with the gate closed (up to 0.2 $m^3\ s^{-1}$), because no flow calculation was possible. This discrepancy was likely due to data polling and averaging, and the gate not closing perfectly, therefore any comparison would have been meaningless. For the error analysis we also removed the data related to the first hour of weekly operation; we believe that the larger errors observed in this phases are related to manual operation of the gate, which might have

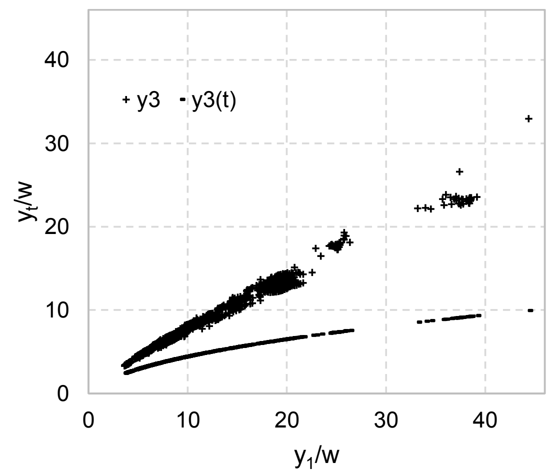

Figure 6. Downstream level (y_3) and threshold between free and submerged flow conditions ($y_{3(t)}$), compared to upstream level (y_1). Water level is expressed as ratio with gate opening (w).

Table 1. Parameters and coefficient of determination (R^2) identified for the regression equations fitting data series of actuator position signal vs. actual vertical gate opening for both upward and downward gate motion (second order polynomial regression $y = ax^2 + bx + c$).

Data series	a	b	c	R^2
Gate moving up	0.0577	0.9057	0.0088	0.9996
Gate moving down	0.1077	0.8389	0.0107	0.9999

Table 2. Range in conditions during the period of observation.

Parameter	Abbreviation	Max	Avg.	Min
Opening (m)	w	0.52	0.15	0.00
Upstream level (m)	y_1	2.13	1.65	1.19
Downstream level (m)	y_3	1.65	1.28	0.67
Upstream level – Downstream level (m)	y_1-y_3	0.85	0.37	0.00

interfered with correct data logger storage. Figure 7 shows the daily pattern of calculated and measured data. Maximum flow was 1.8 $m^3 s^{-1}$ and resulted slow and tranquil discharge, with an estimated average velocity of 0.3 and 0.4 m s^{-1}, respectively, upstream and downstream of the gate. The slow flow, together with the high submergence conditions, likely minimized the interference produced by the old sluice gate structure located upstream, and the trapezoid shape of the canal. Figure 8 shows the relation between individual events of calculated and measured flow. An interpolating linear regression function well fitted the data (R^2=0.9943).

Although the literature agrees on the fact that multiple discharge coefficients and more complex equations should be used to estimate flow through a radial gate under submerged flow conditions, our results produced an error range acceptable to District operations management. This might be explained by the very limited range of flow conditions generated by District operation, and is further supported by the very weak correlation between submerged ratio and error, as shown in figure 9. In only three cases out of a total of 2,686 the error was >20%, and correlation with submergence ratio was poor (R^2=0.1659) as shown in figure 9a. No correlation was found (R^2=0.0039) when considering only the months of March and April (>3/6/2009), when the canal was managed in a more consistent way as the irrigation season started (fig. 9b). Nevertheless, the figure shows that the highest errors are found with high submerged ratio, which in turn is related to small gate opening (fig. 10). Therefore, to improve flow estimate accuracy, we compared performances of the submerged orifice equation to the ones obtained with the equation proposed by Bijankhan et al. (2013), which integrates the submergence ratio in the computation.

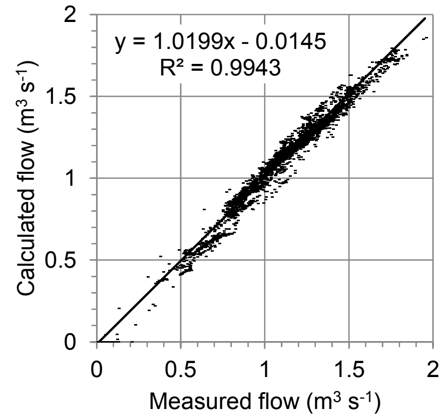

Figure 8. Calculated vs. measured flow for individual events, using the submerged orifice equation.

Our calibration results were consistent with the ones found by Bijankhan et al. (2013) when using Buyalski's (1983) experimental data for calibrating and evaluating the accuracy of their new proposed formula. Table 3 shows the constants obtained with a varying contraction coefficient, which could apply to our radial gate based on the literature as the gate angle increases (Henderson, 1966; Lin et al., 2002). When using a contraction coefficient of 0.6, MARE was 3% and the average relative standard deviation was 2.1%; therefore, both were smaller than what obtained with

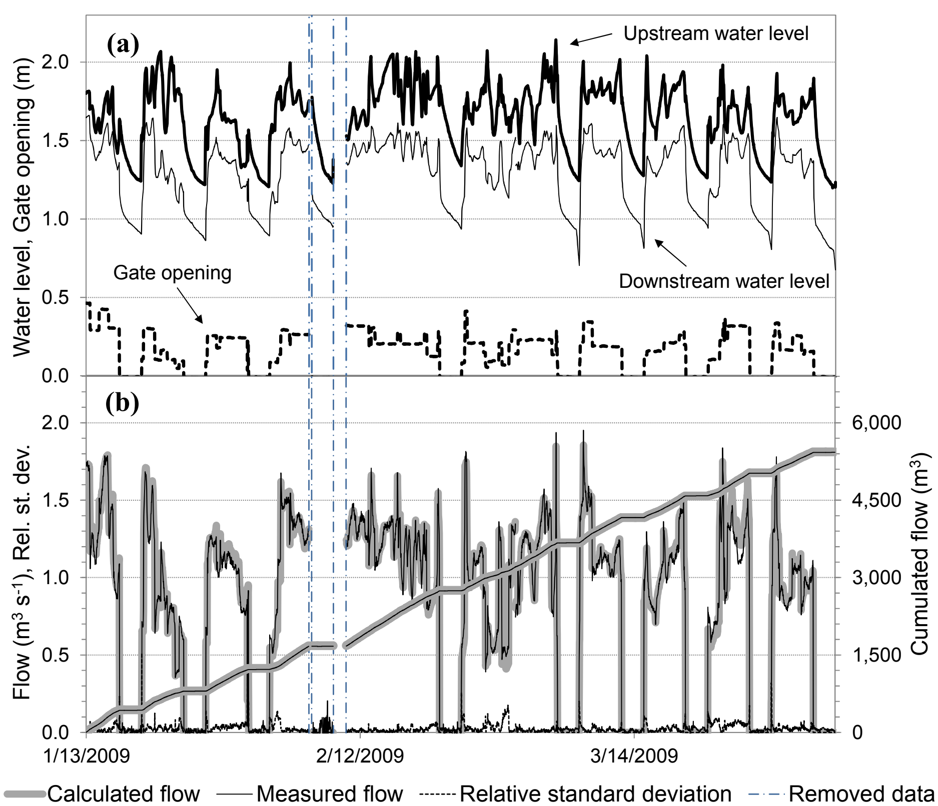

Figure 7. Daily pattern of calculated and measured data, including data removed for flow calculation. (a) Water level upstream and downstream the gate, and gate opening. (b) Daily and cumulated values of calculated and measured flow, and relative standard deviation.

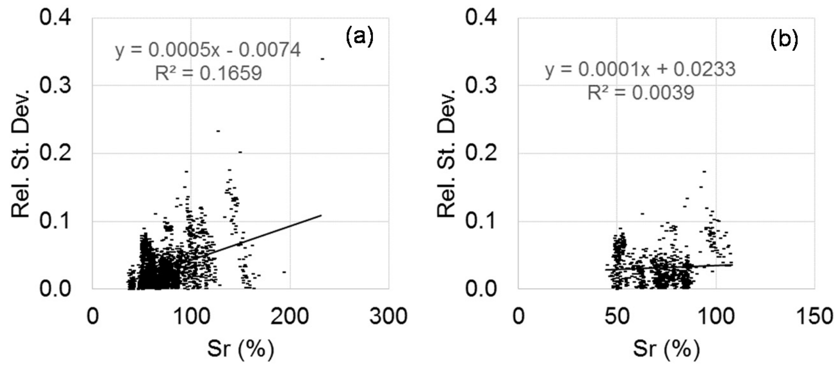

Figure 9. Correlation between submerged ratio (Sr) and error (Relative Standard Deviation). (a) Entire dataset. (b) Irrigation Season (>3/6/2009).

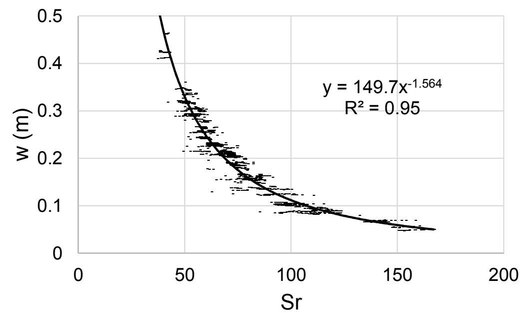

Figure 10. Correlation between submergence ratio (Sr) and gate opening (w).

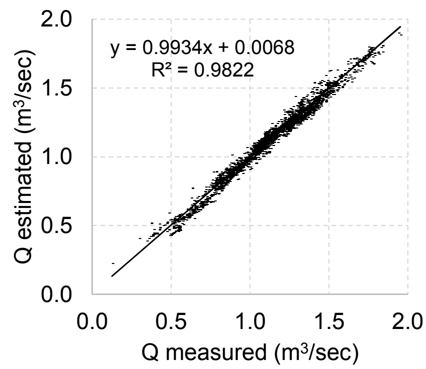

Figure 11. Calculated vs. measured flow for individual events, using the equation proposed by Bijankhan et al. (2013).

the orifice equation. The linear regression interpolating calculated versus measured flow events is shown in figure 11, and shows an accuracy consistent with figure 8. Calculated cumulative flow had a similar pattern to measured data (not reported), and a total of 5,373 m^3, which is 0.05% less than the measured total. Limited correlation was found again between the error (relative standard deviation) and the submerged ratio (R^2=0.2332), and no correlation was found when considering only the irrigation season (R^2=0.0067). Errors were once again analyzed excluding the occasional flow measured with gate closed, and in the first hour of weekly operation.

Results obtained with the Bijankhan et al. (2013) equation are consistent and further improved results obtained with the submerged orifice equation. This suggests that a calibration of the orifice equation is still possible with limited range of flow conditions, and that Bijankhan et al. (2013) equation can further help the District estimating flow in a larger range of flow conditions.

Effect of Hysteresis on Flow Rate Calculation

To quantify the effect of the hysteresis phenomenon on flow rate calculation, individual events of calculated and measured flows were compared before correction of actuator position signal for gate opening. Figure 12 shows two clearly identifiable groups of data which correspond to the upward and downward motion of the gate. Linear regressions fit the two groups well (R^2=0.9724 and 0.9825, respectively). Slopes were tested for parallelism and were found to be significantly different from each other (P=0.004). This confirms that gate hysteresis can be classified as a systematic error. We did not include the occasional measurements obtained with the gate closed. A different discharge coefficient (0.6) was used to calibrate the equation using this dataset before correction. As shown in the figure, the difference between the flows estimated by the two regression lines, for a given measured flow, increases with flow rate and ranges between 0.04 and 0.13 m^3 s^{-1}.

Table 3. Numerical constants calibrated using the Bijankhan et al. (2013) equation, and effects of varying the contraction coefficient.

Contraction Coefficient (δ)	a_0	b_1	α	b_2
0.60	0.736	0.459	1.996	0.357
0.65	0.705	0.470	1.958	0.358
0.70	0.677	0.481	1.958	0.356

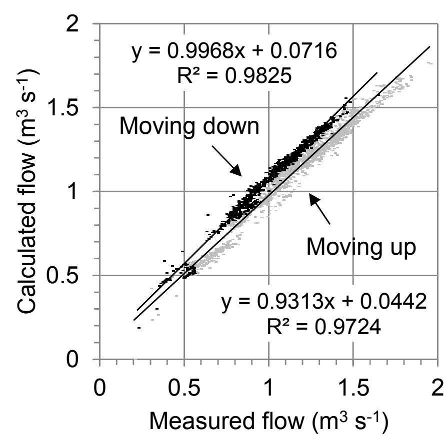

Figure 12. Calculated vs. measured flow for individual events before correction for hysteresis. Two groups of data are clearly identifiable and correspond to the upward and downward motion of the gate.

It was observed that relevance of hysteresis effect depended on specific events (fig. 13). As an example, the figure shows a comparison of flow calculated before and after correction for hysteresis, in two separate cases in March. In the week of 8-12 March (fig. 13A), flow calculated before correction has a higher relative standard deviation and looks clearly affected by gate movements, compared to measured flow. The figure shows that flow is underestimated after upward movement and overestimated after downward movement. The difference of weekly average flow (calculated vs. measured) is ±0.09 $m^3 s^{-1}$, and the difference of weekly cumulated flow (calculated – measured) is +10.6 m^3 which corresponds to the 2% of the cumulated weekly flow. After correction, flow estimate improves, even if gate movements appear to have still some effects. Differences of weekly average and cumulated flow are respectively ±0.03 $m^3 s^{-1}$ and +2.8 m^3 (0.6% of the cumulated weekly flow). In the week of 15-19 March (fig. 13B) the effect of correction is less evident, both on relative standard deviation and on calculated flow. The gate was moved mostly upward with smaller increments which may have helped the actuator do a better job in effectively positioning the gate. Nevertheless, comparison still shows a better result with corrected flow data. Before correction, the difference of weekly average flow (calculated vs. measured) is ±0.04 $m^3 s^{-1}$, and the difference of weekly cumulated flow (calculated – measured) is -7.4 m^3 which corresponds to the 2% of the cumulated weekly flow. After correction, differences of weekly average and cumulated flow are, respectively, ±0.04 $m^3 s^{-1}$ and +1.1 m^3 (0.3% of the cumulated weekly flow).

Conclusions

The radial gate observed in this study and its range of operating conditions were consistent with recommendations found in the literature for using a gate as a flow measuring device, and for estimating flow with the submerged orifice equation. Two conditions did not match recommendations, including an old gate structure located about 15 m upstream, and the rectangular shape of the gate structure which was different from the trapezoidal shape of the canal. Both conditions could have affected the theoretical condition of "undisturbed approaching flow" but were not verified. The authors believe that under the slow flow velocities and very submerged flow conditions during the study these effects were minimal.

The submerged orifice equation successfully estimated measured flow, with an average error (relative standard deviation) of 3.2% and mean absolute relative error of 4%. A constant coefficient of drainage (0.7) was used for the entire data set. Based on the District manager's judgment, condi-

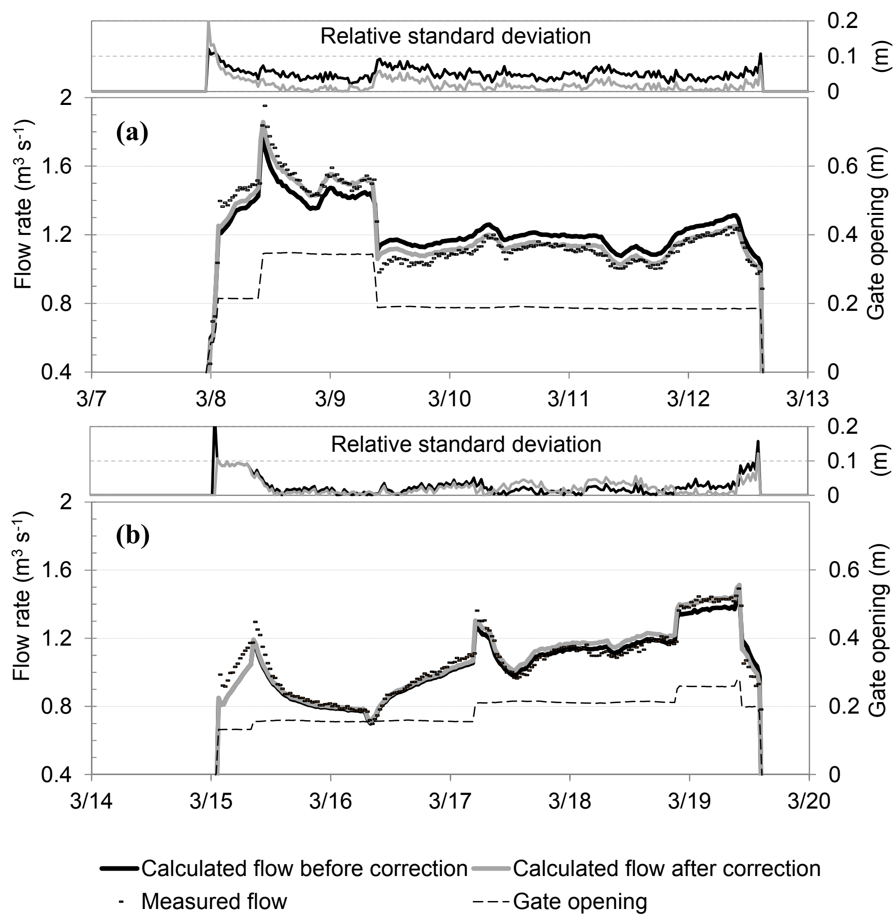

Figure 13. Comparison of flow calculated before and after correction for hysteresis, in two separate cases. (a) Week of 8-12 March. (b) Week of 15-19 March.

tions found in our study well represented what can be expected over an entire year and seasons. Therefore, the proposed calibration procedure and parameters provide a flow estimate that may be applied year-round and which has a reasonable accuracy meeting District needs. The equation proposed by Bijankhan et al. (2013), improved the estimate to a mean absolute relative error of 3%. By introducing the maximum allowable tailwater depth permitting free flow in the formulation, this equation should also provide the District with an accurate estimate for higher flow ranges. Therefore, it is recommended that the District conduct additional analysis to further calibrate both equations to a wider range of flow conditions.

Mechanical hysteresis in the radial gate controller also affected flow measurement. The actuator position signal for gate opening overestimated actual gate vertical opening, and differed when the gate was moved upward or downward. As a consequence, error varied week by week, and was dependent upon gate operation (i.e., frequency, amplitude, direction and increments of gate motion). Two second order polynomial regressions were identified to describe the relationship between actuator position and actual gate opening in both motions, and were used to correct gate opening when calculating flow.

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