

## USING WINGATE TO DEVELOP PRACTICAL DISCHARGE EQUATIONS FOR GATED OUTLETS AT YELLOWTAIL AFTERBAY DAM

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### ABSTRACT

Three gated outlet systems at Yellowtail Afterbay Dam were analyzed to develop discharge curves and equations needed for an automated gate control system that will regulate flow rates in the Bighorn River and the Bighorn Canal. Radial gates mounted on the dam's ogee crest spillway were analyzed using established empirical methods, while vertical slide gates in the river sluiceway and canal sluiceway systems were analyzed using the WinGate computer program. Analytical results were used to develop simplified gate-rating equations that will be practical to apply in the gate control system.

**Keywords:** slide gates, water measurement, gate control

### INTRODUCTION

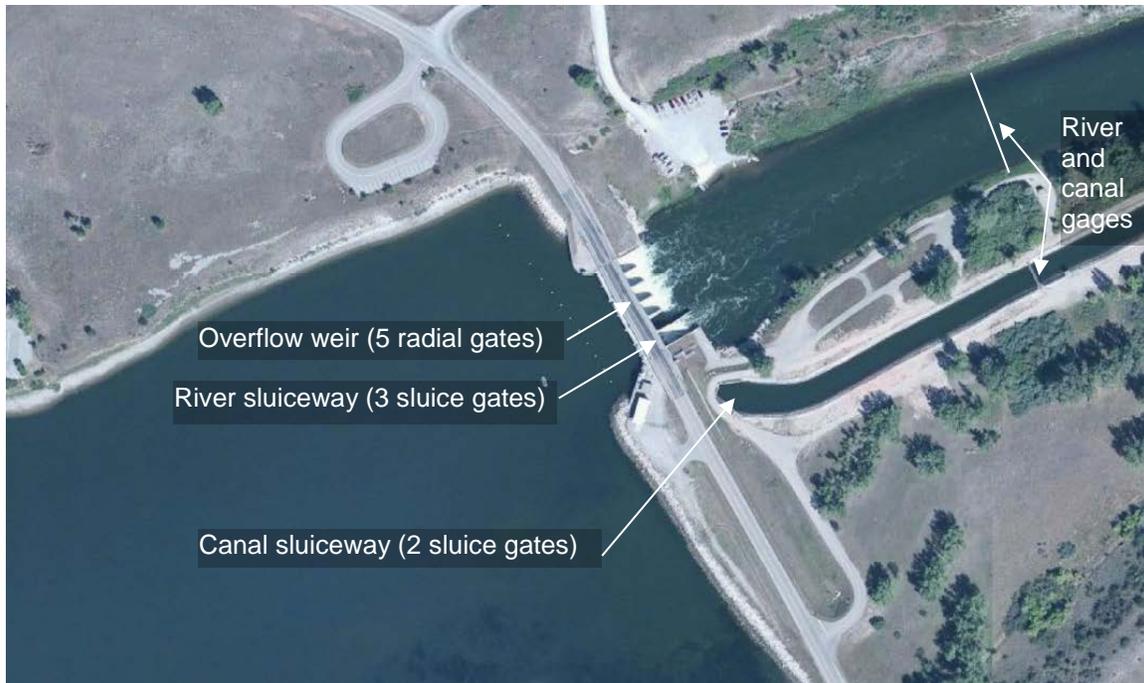
Yellowtail Afterbay Dam is a 72-ft high concrete gravity dam with earthen embankment wings located on the Bighorn River in southern Montana, 2.2 miles downstream from Yellowtail Dam near St. Xavier, MT. The dam provides reregulation storage below Yellowtail Dam and Powerplant to stabilize flows in the Bighorn River, and also is the point of diversion for flows into the Bighorn Canal, which conveys irrigation water along the east side of the valley of the Bighorn River as it proceeds toward Hardin, MT.

Three gated outlet systems release water from the dam into two waterways:

- An **overflow weir** section equipped with five 30-ft-wide by 13.5-ft-tall radial gates releases water into the Bighorn River. Flows through this structure can be gate-controlled, or the gates can be raised out of the water to allow free weir flow over the dam crest, which is at elev. 3179.50 ft. Maximum discharge past the overflow weir is about 25,000 ft<sup>3</sup>/s at reservoir elevation 3192.0 ft.
- The **river sluiceway** uses three 10-ft-wide by 8-ft-tall vertical slide gates to release water into the Bighorn River at the right end of the overflow weir. The gate sill elevation is 3157.0 ft, and the maximum discharge capacity is 8,100 ft<sup>3</sup>/s. Flow through the river sluiceway is always gate-controlled.
- The **canal sluiceway** contains two 10-ft-wide by 8-ft-tall vertical slide gates that release water to the Bighorn Canal. The gate sill is at elev. 3167.0 ft. Maximum discharge capacity of the canal sluiceway is 750 ft<sup>3</sup>/s. Flow is normally gate-controlled, but at unusually low reservoir elevations, weir flow is possible.

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**Figure 1. — Aerial view of Yellowtail Afterbay Dam showing the three outlet systems that release water to the Bighorn River and Bighorn Canal.**

Flows in the Bighorn River below the dam and in the Bighorn Canal are measured at river gage sites operated by the Bureau of Reclamation and incorporated into the U.S. Geological Survey gaging network. Gage 06287000 (Bighorn River near St. Xavier, MT) is located in the Bighorn River about 780 ft downstream from the Afterbay Dam. This gage has provided daily discharge data since October 1, 1934. A second gage is located in the Bighorn Canal approximately 720 ft downstream from the end of the canal sluiceway stilling basin. Reclamation's Hydromet system provides daily average flows at both gages as well as reservoir elevations for the Afterbay Dam pool from October 1, 1985 to present. Hourly and 15-minute interval data are also available for many parameters through the project's SCADA system.

The original operational scheme for Yellowtail Afterbay Dam called for the dam outlets to be operated to maintain a steady discharge in the river downstream from the dam, as indicated by the river gage. However, seasonal growth of algae in the river and other factors cause the river gage rating to shift significantly over time, making it difficult to maintain steady outflows from the dam. There is also a history of high total dissolved gas levels in the Bighorn River below the Afterbay Dam. The river sluiceway is the primary generator of the high dissolved gas concentrations. To control total dissolved gas levels, it is desirable to operate the dam outlets to generally maintain a 25% – 75% split of flows released through the river outlet works and the overflow weir, respectively, although this flow split ratio is subject to adjustment.

These two issues prompted the development of a new Afterbay Automated Gate Control System (AAGCS) that was designed to set river flows by calculating discharges through the gated outlets. The system was also intended to maintain the desired flow split for

control of total dissolved gas in the river. Unfortunately, during commissioning of the new system, fluctuations in the river elevation exceeded allowable limits during power peaking, and gates operated excessively while attempting to maintain the set point.

As a result, implementation of the AAGCS was suspended and Reclamation's Technical Service Center was asked to review the control system and make recommendations for modifications that would improve system performance. A preliminary review identified issues related to control algorithms, control stability, and flow measurement accuracy. Sources of potential inaccuracy in the existing discharge equations were identified for each of the gated outlets and the report recommended a review of the gate-flow equations and development of accurate, physically-based equations as needed. The project to develop new discharge equations for all three outlet facilities is described fully in Reclamation research report HL-2013-01 (Wahl 2013). This paper focuses on the application of the WinGate computer software to the two sluiceway systems.

### BACKGROUND INFORMATION

The investigation began with a review of polynomial equations that had previously been developed for the automated control system. For each of the three outlet systems, these equations compute discharge as a function of gate settings and relevant water levels. In addition, the Standing Operating Procedures for the dam provide graphical rating curves for the overflow weir and river sluiceway, based in part on a 1:24-scale physical model study of the dam (Arris 1965) performed during its original design. A second 1:24-scale physical hydraulic model study of the river sluiceway (Young 1982) also provides an alternative rating curve for the river sluiceway gates. No rating curves were known to exist for the canal sluiceway gates.

The Bureau of Reclamation Hydromet system provides operational data for the site using station name BHSX (Bighorn River near St. Xavier, MT). The system can be accessed on the Internet at <http://www.usbr.gov/gp/hydromet/>. Daily values of several useful parameters are available from October 1, 1985 to present. Key variable names are shown in Table 1.

**Table 1. — Available Hydromet data for Yellowtail Afterbay Dam.**

	<b>Real-time data</b>	<b>Historic daily values</b>
Forebay elevation	FB	FB
River gage height	GH	GD
River gage shift	HH	HH
River discharge	QR	QRD
Total discharge (river + canal)	Q	QD
Canal gage height	CH	GJ
Canal gage height shift	HJ	HJ
Canal discharge	QC	QJ

## **OVERFLOW WEIR**

The Standing Operating Procedures for Yellowtail Afterbay Dam (SOP) provides a rating curve dated July 1966, showing both free weir flow and gate-controlled flow. The free weir flow curve (gates out of the water) is based on a 1:24-scale physical hydraulic model study that included the weir crest, but did not include functional gates (Arris 1965). The source of the curves for gate-controlled flow is unknown.

Because the engineering basis for the gate-controlled flow equations is not known, the decision was made to develop new equations using either existing operational data or an accepted analytical method. Unfortunately, a review of the available data raised questions that could not be resolved regarding the accuracy of historic gate position measurements. This uncertainty made it impossible to utilize currently available historical data for discharge calibration purposes and forced the application of an analytical method.

The method used to develop new discharge equations for the overflow weir was that described in U.S Army Corps of Engineers Hydraulic Design Criteria Charts 311-1 to 311-5 and also presented in *Design of Small Dams* (Reclamation, 1987). For details on the application of this method to Yellowtail Afterbay Dam, see Wahl (2013).

## **RIVER SLUCEWAY**

### **Existing Methods for Determining Discharge**

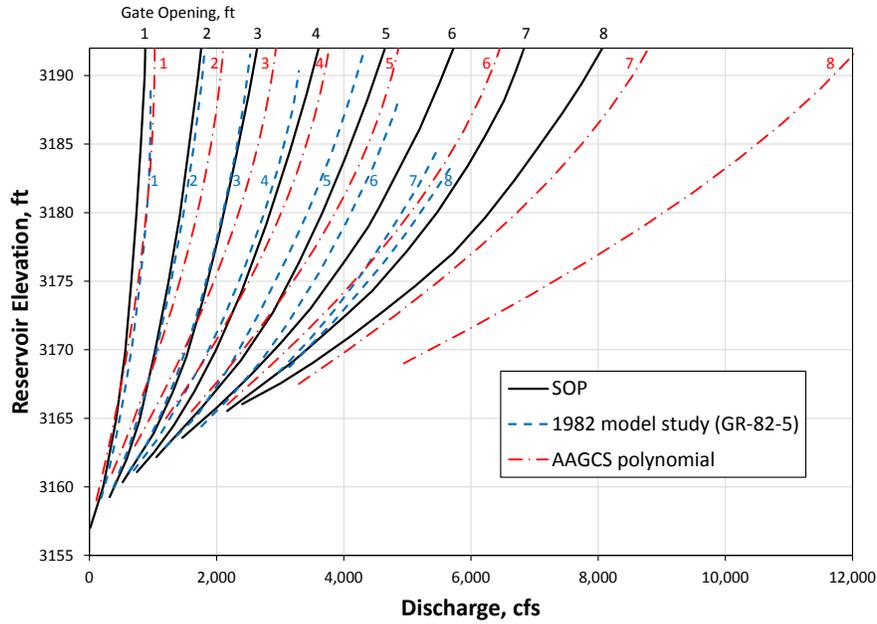
Three methods for computing discharge through the river sluiceway are currently available. The SOP provides a rating curve based on the original hydraulic model study (Arris 1965) and field data of unknown origin, a second rating curve was developed during the 1982 physical model study (Young 1982), and polynomial equations were developed for the automated gate control system.

Figure 2 shows the SOP discharge curves, the 1982 model study curves, and the curves produced by the AAGCS polynomial equation. For gate openings of 4 ft or less there is good similarity between the SOP and 1982 model study curves, but for higher gate openings the latter model study curves indicate lower discharges, which is attributed to the inclusion of a larger forebay in the 1982 model. The polynomial equations indicate significantly higher discharges than the other two sets of curves, especially at high reservoir levels and large gate openings. There is a huge disparity for gate openings of 6 ft or more. There is no plausible explanation for the polynomial curves indicating that the sluiceway discharge at an 8-ft gate opening is almost double that of a 6-ft opening.

### **Effective Discharge Coefficients**

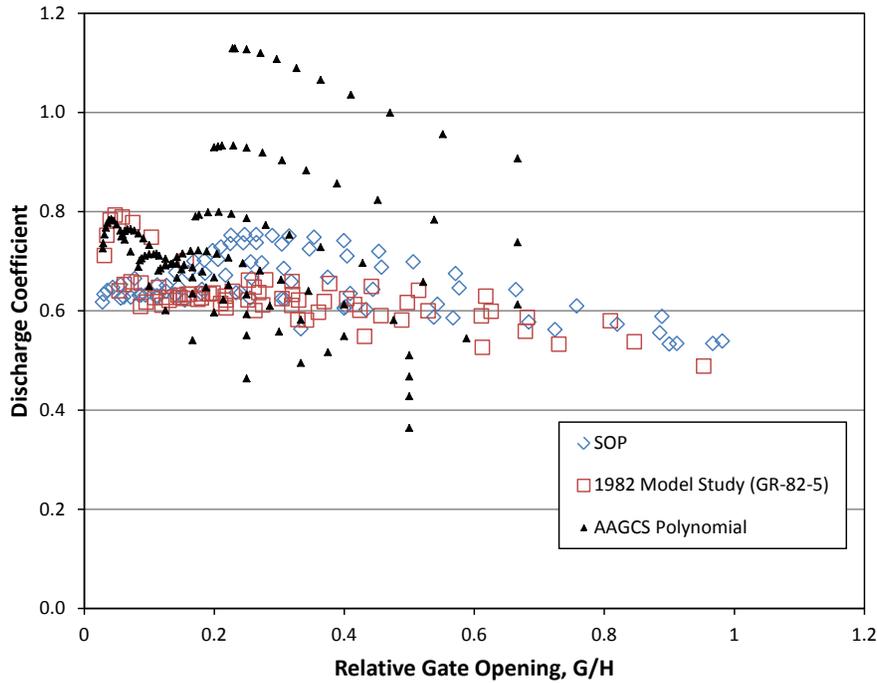
Discharge curves for vertical sluice gates should generally exhibit the behavior of an orifice flow equation:

$$Q = C_d GL \sqrt{2gH} \tag{1}$$



**Figure 2. — River sluiceway discharge curves.**

with a discharge coefficient that is relatively constant near a value of 0.6. To further evaluate the discharge curves shown in Figure 2, effective discharge coefficients were computed from data points digitized from the original curves. The head term in the orifice equation was computed relative to the center of the gate opening. The variation of these discharge coefficients with relative gate opening is shown in Figure 3.



**Figure 3. — Effective discharge coefficients for previously established river sluiceway rating curves.**

The discharge coefficients for the SOP and 1982 model study curves behave somewhat as expected. The model study data in particular show a steady value close to 0.6, except for the data points associated with the 1 ft gate opening, which was noted to have a suspicious shape in the 1982 model study report. In contrast, the AAGCS polynomial shows dramatic variation of the discharge coefficient and values exceeding 1.0 that are not physically realistic.

### Analytical Discharge Curves

The discharge curves and equations compared in Figure 2 all base the gate discharge on just the gate opening and the upstream reservoir elevation, so they are assuming that free flow occurs through the sluice gates. However, a review of the river gage records and the resulting tailwater conditions below the dam shows that river stages could be high enough to cause submergence of the sluice gates, since the gate seat is at elevation 3157.0 ft and tailwater levels vary from about 3157 to 3165 ft. Although submergence is possible, tailwater levels above the gate seat elevation do not guarantee submerged flow, since the momentum of the flow through the gate opening may be strong enough to sweep the tailwater away from the gate exit and allow the gate to flow free. The most likely condition for gate submergence would be combinations of high discharge through the overflow weir (causing high tailwater in the river) and low discharge through the sluiceway. Future operations will maintain a steady ratio of the sluiceway and overflow weir discharges, and it is not immediately apparent that this will yield submerged flow conditions at the sluiceway.

To evaluate the potential for submergence, flow through the sluiceway gates was analyzed using the new WinGate computer program (Wahl and Clemmens 2012; Clemmens et al. 2012). This program was developed for the purpose of calibrating radial gates and vertical slide gates in canal check structures using the energy-momentum (E-M) method. The program can be applied to these sluice gates since they seat on a horizontal surface, as opposed to an ogee crest. The program solves the energy equation from the upstream pool to the orifice opening beneath the gate and the momentum equation from there to the downstream canal. The combined use of the energy and momentum equations makes the method well suited to accurate modeling of flow in the transition zone from free to submerged flow.

The WinGate analysis made use of historic Hydromet data to model a realistic set of circumstances. Daily values of total river flow, river gage height, and upstream reservoir elevation were obtained from 10/1/1985 to 2/3/2013. These data were filtered by comparing the river flow rates and net river gage height data (gage height plus gage shift) to the river gage rating equation. About 87% of the net gage height values matched the values expected for the corresponding river discharges within  $\pm 0.01$  to  $\pm 0.03$  ft, while 13% varied from the expected values by amounts up to  $\pm 2$  ft. The latter data were excluded from analysis on the assumption that the mismatch to the river gage rating curve indicated that operations on that day were highly transient, and thus average daily values did not accurately represent the conditions.

For the data retained, the total river discharges were used to compute the flow through the overflow weir and sluiceway that would have been set on that date, if the 25% – 75% flow split rule had been applied. WinGate was then used to solve for the sluice gate openings needed to obtain the computed sluiceway flow, using the river gage height as the tailwater elevation just downstream from the sluiceway stilling basin. This neglects the small head loss that occurs in the river reach between the end of the stilling basin and the river gage location, but is a reasonable approximation. The WinGate analysis considered that the reservoir upstream from the sluice gates was only as wide as the gates themselves, so that the velocity heads in the reservoir approaching the sluice gates would be realistic, since WinGate was modeling only the sluiceway and not the simultaneous flow through the overflow weir structure.

The analysis showed that the required sluice gate setting for about 80% of the cases produced a submerged, gate-controlled flow condition, while 20% produced free gate-controlled flow (meaning that the tailwater level was too low to affect the discharge, even though it may have been above the gate seat elevation). When total river discharge was greater than 5225 ft<sup>3</sup>/s (sluiceway discharge > 1306 ft<sup>3</sup>/s) the sluiceway was always in free flow, and when the river discharge was less than 2475 ft<sup>3</sup>/s (sluiceway discharge < 619 ft<sup>3</sup>/s) the sluiceway was always submerged. When the river discharge was between these limits, either flow condition was possible. The exact threshold for submergence is a complex function of the gate opening, upstream head, and tailwater elevation and requires a momentum analysis like that performed in WinGate. The situation is also complicated by the fact that the river gage elevation for a given river discharge is not constant due to algae growth in the river and other factors that create the need for adjusting the river gage relation seasonally through the use of shifts. Finally, if flow

splits other than the 25% – 75% condition were used, the ranges in which free and submerged flow are possible would vary. It should be emphasized that although this analysis was performed assuming the 25% – 75% flow split, this assumption was made only to obtain a realistic range of operating conditions; the results should be applicable to other flow split ratios.

For the submerged flow cases, WinGate also provides output of the calculated discharge if free flow had existed, and an analysis of these data showed that the effects of submergence were typically small; the median discharge reduction from the free flow value was only 0.29%, and 99.5% of the cases had errors smaller than 2.5%. This shows that when submergence occurs, the river tailwater levels are typically just above the threshold needed to cause submerged flow. Although ignoring submergence would cause mostly small errors, the maximum error was 4.73%, and all errors were in the same direction, so it seemed worthwhile to seek a way to account for submergence.

The sluiceway discharges computed with WinGate were used to back-calculate effective discharge coefficients for use in basic orifice equations for free and submerged flow. For free flow the head is measured relative to the center of the gate opening, and for submerged flow the head is the difference between the reservoir level and the river level at the gaging station. Figure 4 shows the variation of the discharge coefficients as a function of the relative gate opening. Note that the relative gate opening is defined as the ratio of the gate opening to the upstream head *relative to the gate sill elevation* (not the gate centerline). Although the orifice equation for computing free discharge uses head referenced to the center of the gate opening, the discharge coefficient proved to be more closely related to the sill-referenced head.

The variation of the discharge coefficient for free flow is very slight, and this is consistent with experimental and numerical simulations of flow through vertical sluice gates (Belaud et al. 2009). The submerged flow discharge coefficient varies more significantly and in a different manner, increasing with relative gate opening. This is partly due to the change in the definition of the head term for submerged flow, and also due to the fact that this coefficient is accounting for the lumped effects of several empirical factors affecting submerged flow (e.g., momentum effects in tailwater channel) that are included in the WinGate analysis.

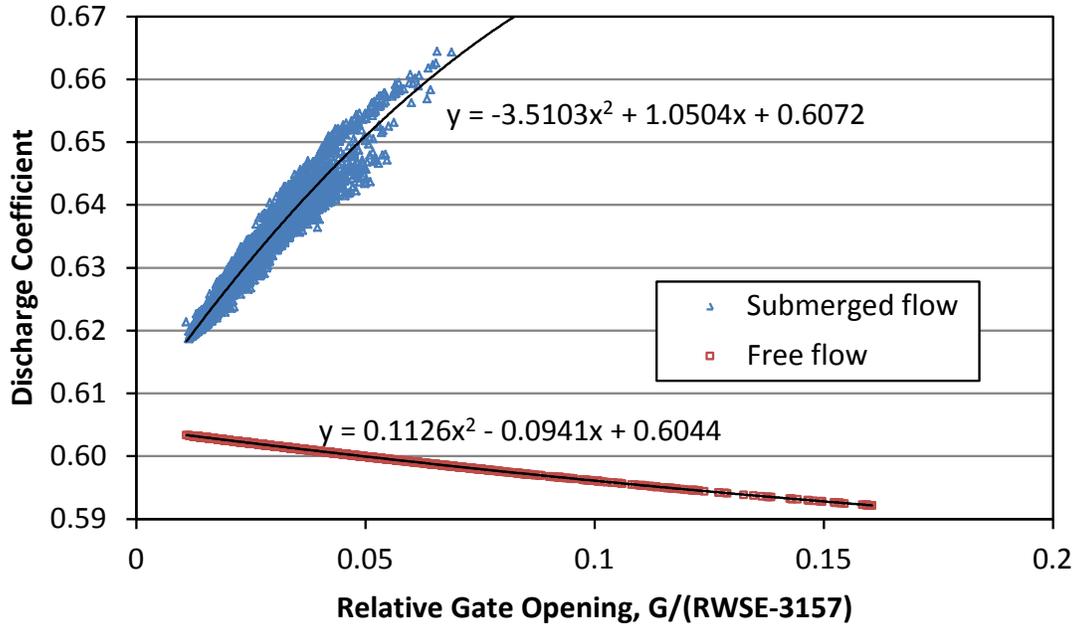


Figure 4. — Discharge coefficients for river sluice gates based on the WinGate analysis.

To compute discharge through the sluiceway using the information in Figure 4, the following steps can be performed:

1. Compute relative gate opening

$$G^* = \frac{G}{RWSE - 3157} \quad (2)$$

2. Compute free-flow discharge as

$$C_{d,free} = 0.6044 - 0.0941(G^*) + 0.1126(G^*)^2 \quad (3)$$

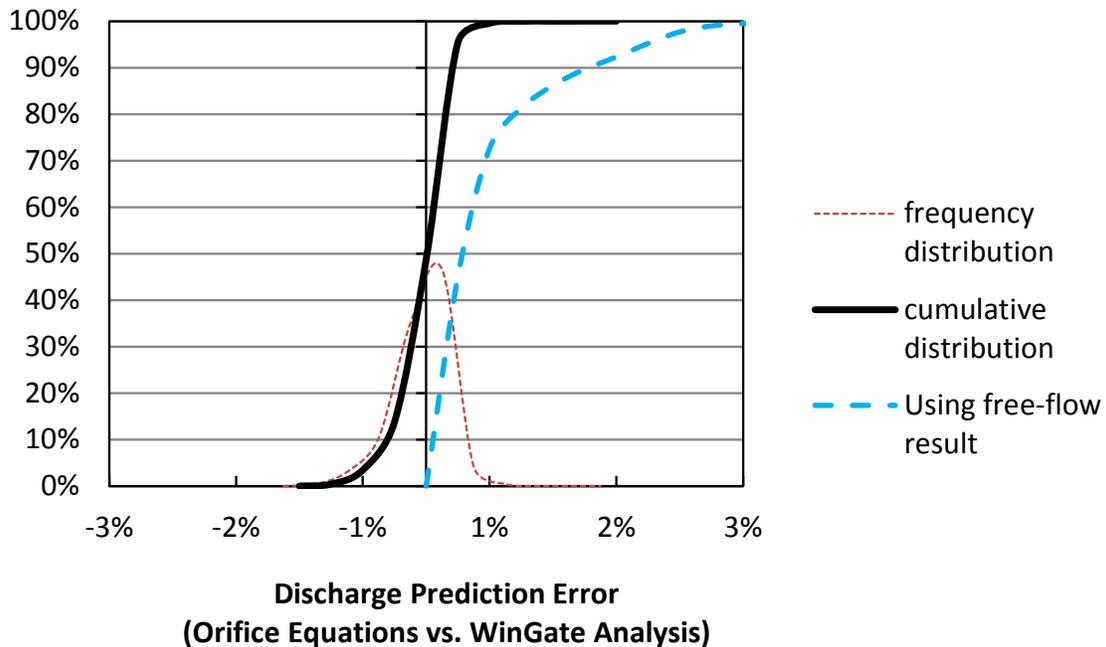
$$Q = (3)(C_{d,free})(10)G\sqrt{2g(RWSE - 3157 - G/2)}$$

3. Compute submerged-flow discharge as

$$C_{d,submerged} = 0.6072 + 1.05(G^*) - 3.51(G^*)^2 \quad (4)$$

$$Q = (3)(C_{d,submerged})(10)G\sqrt{2g(RWSE - h_{gage})}$$

where  $h_{gage}$  is the elevation of the water surface at the river gaging station. The final result is the minimum discharge computed by the two methods. Figure 5 shows the resulting discharge prediction errors and demonstrates that this approach does a good job of distinguishing between free and submerged flow and provides a reasonable representation of the flows predicted by the WinGate analysis.



**Figure 5.** — Discharge prediction errors using minimum of free-flow and submerged-flow orifice equations. The errors that would occur by always assuming free flow are also shown.

The control system will also need to solve for the gate setting required to obtain a target discharge. For this purpose, free flow conditions should be assumed and the discharge coefficient can be set to 0.6 as an initial value. The gate setting can then be determined from the free-flow orifice equation. Once this has been done, the discharge coefficients for free and submerged flow can be refined and the equation controlling the final result can be determined. Multiple iterations may be needed to reach convergence.

Figure 6 shows a new set of discharge curves that was generated for the sluiceway using the results of the WinGate analysis. Since there is a range of ambiguity for free versus submerged flow and the effect of submergence is slight in the vast majority of cases, the curves were generated using only the free flow equations. The resulting curves most closely match the 1982 model study curves and indicate somewhat lower discharges than all of the previously developed curves. When submerged flow conditions exist, the discharges would be reduced further, but only by a small amount in most cases (0 to 2%).

There is significant difference between the various discharge curves beginning at gate openings greater than 4 ft, but the practical importance of large gate openings may be small. The WinGate analysis using the 1985-2013 Hydromet data showed that the sluice gate setting to achieve the 25% – 75% flow split objective would be less than 4 ft on 99.5% of the days analyzed (see Figure 7).

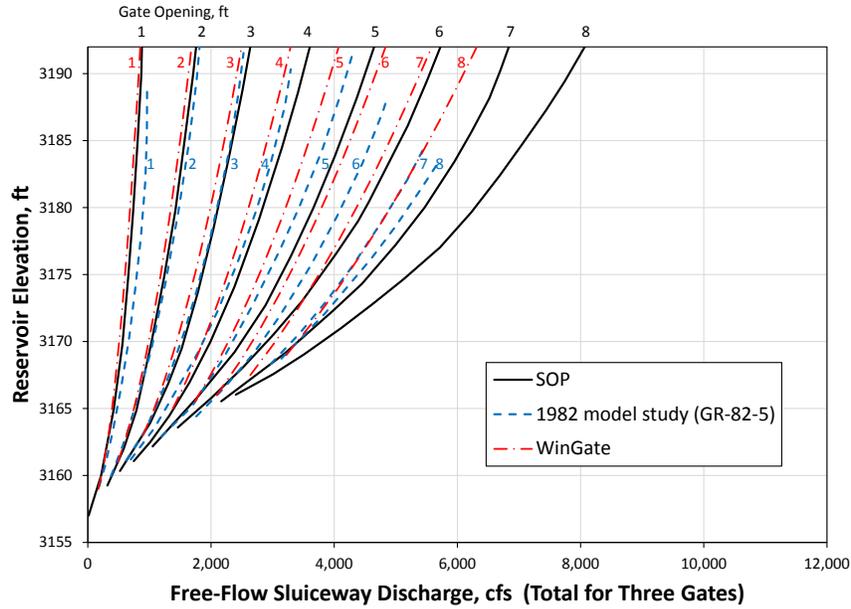


Figure 6. — Discharge curves generated from WinGate analysis.

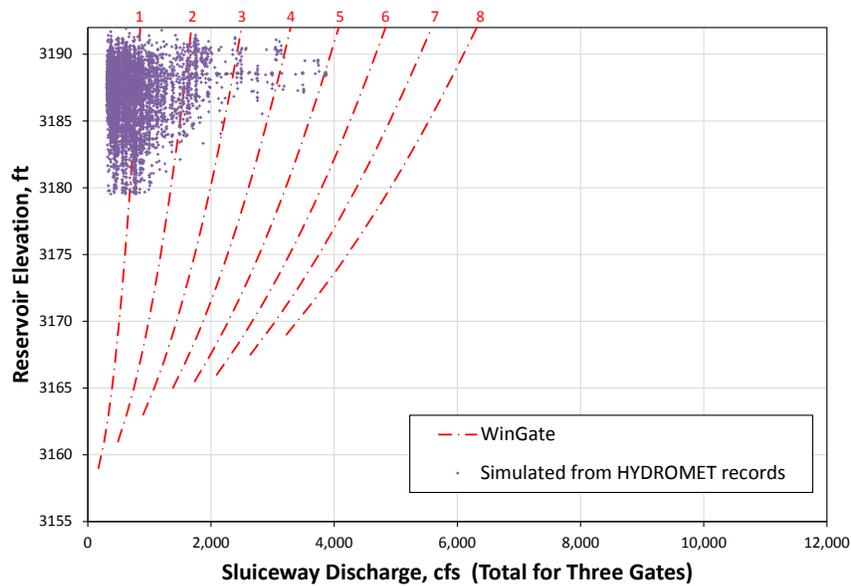


Figure 7. — Sluiceway operating conditions simulated for 1985-2013 period from Hydromet data.

**Comparison to Field Data**

There are few field data values available for testing the discharge equations and curves. The SOP discharge curve provides 7 data points, and an additional 6 data points are available, which were reportedly used to develop the AAGCS polynomial equations, but their original source is unknown. Table 2 shows the available data and the discharges computed by different methods. The WinGate discharges are significantly lower than the discharges predicted by the other methods, as expected.

**Table 2. — Field data for discharge through the river sluiceway.**

Reservoir elevation, RWSE, ft	Gate opening, G, ft	Observed discharge, ft <sup>3</sup> /s (three gates)	Predicted discharges and % differences from observed		
			AAGCS Eqn.	WinGate	SOP
Data used to develop AAGCS equations (unknown origin)					
3186.38	0.838	896	807 (-10%)	653 (-27%)	670 (-25%)
3186.38	1.483	1509	1501 (-1%)	1146 (-24%)	1225 (-19%)
3185.99	3.44	2943	3030 (+3%)	2572 (-13%)	2750 (-7%)
3185.33	4.074	3492	3497 (+0%)	2983 (-15%)	3250 (-7%)
3185.80	4.643	4100	4063 (-1%)	3406 (-17%)	3800 (-7%)
3184.00	5.41	4750	4786 (+1%)	3788 (-20%)	4400 (-7%)
Data from SOP discharge curve					
3169.25	2	1013	1032 (+2%)	956 (-6%)	1000 (-1%)
3184.42	3	2445	2623 (+7%)	2189 (-10%)	2300 (-6%)
3174.75	4	2424	2483 (+2%)	2251 (-7%)	2450 (1%)
3169.75	5	2424	2376 (-2%)	2254 (-7%)	2450 (1%)
3189.42	5	4460	4721 (+6%)	3901 (-13%)	4450 (0%)
3179.83	6	4481	5023 (+12%)	3779 (-16%)	4500 (0%)
3174.83	7	4552	5450 (+20%)	3731 (-18%)	4600 (1%)

Despite the large differences from the few field observations, the WinGate discharge curves are believed to offer the best estimate of discharge for the sluiceway. The inconsistent behavior of the discharge coefficients in the other methods has already been discussed and gives good reason for discrediting them. The WinGate curves are physically-based and reflect the most current research on sluice gate discharge characteristics. There are potential sources of error in the WinGate analysis, such as unique site-specific approach flow conditions and head losses that may not be accurately accounted for, but most such factors would tend to reduce the discharges, and WinGate is already predicting lower flows than the other methods. The one factor that could cause the WinGate discharges to be too low for a given reservoir level is not correctly accounting for high velocity head in the reservoir due to the simultaneous operation of the overflow weir with the river sluiceway. If a consistent bias between the new equations and field-measured flows is found in the future, adjustments could be made to the WinGate-based discharge curves.

### **BIGHORN CANAL SLUICEWAY**

The canal sluiceway contains two 10-ft-wide by 8-ft-tall vertical slide gates that release water into the Bighorn Canal. The gate sill elevation is 3167.00 ft, and the maximum discharge capacity of the canal sluiceway is 750 ft<sup>3</sup>/s. Flow is normally gate-controlled, but for unusually low reservoir elevations, weir flow may be possible.

A rating curve for the sluiceway gates is not provided in the SOP for Yellowtail Afterbay Dam. Discharge in the canal is measured at a gaging station located about 720 ft downstream from the start of the canal. Hydromet records define the rating curve at the gaging station. About 90% of the available daily readings fit the rating within  $\pm 0.25$  ft, with the other 10% scattering widely around the curve defined by the bulk of the data.

A complex polynomial equation developed for use with the automated gate control system was reviewed and found to be seriously flawed in several ways (see Wahl 2013 for details).

### WinGate Analysis

Hydromet data for the canal sluiceway were obtained from October 1, 1985 to October 10, 2012. The data set was filtered to retain only those data that fit the rating curve defined by the bulk of the data, with outliers considered to be days on which steady flow did not prevail, so daily average values provided a poor representation of real conditions. With the filtered data, WinGate was used to compute sluice gate settings that were required to obtain the recorded value of canal discharge with the given upstream reservoir and downstream canal water levels. As described previously, WinGate performs a momentum analysis that can accurately account for the effects of gate submergence. The results from WinGate were then used to compute effective discharge coefficients for a simplified submerged orifice equation that would be practical for use in the automated gate control system. It is notable that the data set contained no records of conditions for which weir flow was likely.

The WinGate analysis showed that the gates always operate in a submerged flow condition, and the reduction of discharge due to submergence varies from about 5% to 28% of the free-flow discharge.

The WinGate results were used to compute submerged-flow discharge coefficients for a basic orifice equation:

$$Q = C_d GL \sqrt{2g\Delta H} \quad (5)$$

where  $Q$  is the discharge in  $\text{ft}^3/\text{s}$ ,  $C_d$  is the discharge coefficient,  $G$  is the gate opening,  $L$  is the gate width,  $g$  is the acceleration due to gravity, and  $\Delta H$  is the difference in elevation between the upstream reservoir and downstream canal.

The discharge coefficients were related to both the relative gate opening,  $G/H_1$ , and the submergence ratio,  $H_3/H_1$ , where  $H_1$  is the upstream head and  $H_3$  is the downstream head, both measured relative to the gate sill elevation. Thus,  $H_1 = RWSE - 3167$  and  $H_3 = Y_{\text{canal}} - 3167$ , where  $RWSE$  is the upstream reservoir water surface elevation and  $Y_{\text{canal}}$  is the water surface elevation in the canal. Note that this submergence ratio is a simple parameter that does not perfectly reflect the submergence conditions at the gate itself, since the water level at the back side of the gate leaf will be different from that in the downstream canal, but it is straightforward to compute and useful for operational computation purposes. Figure 8 and Figure 9 show the relationships to each parameter. Both relations appear to be promising for predicting discharge coefficients, but an even better relation was found using an equation fitting software tool designed for analysis of 3D surface functions, TableCurve 3D. This relation is:

$$C_d = \frac{1}{1.6503 - 1.769\sqrt{G/H_1} + 0.7717(H_3/H_1)} \quad (6)$$

Figure 10 shows the results when predicting  $C_d$  using equations based on  $G/H_1$ ,  $H_3/H_1$ , and both parameters together. The only region where the two-parameter relation performs poorly is when the predicted  $C_d$  value is less than 0.62. When this is the case, the equation shown in Figure 8 based on  $G/H_1$  should be used.

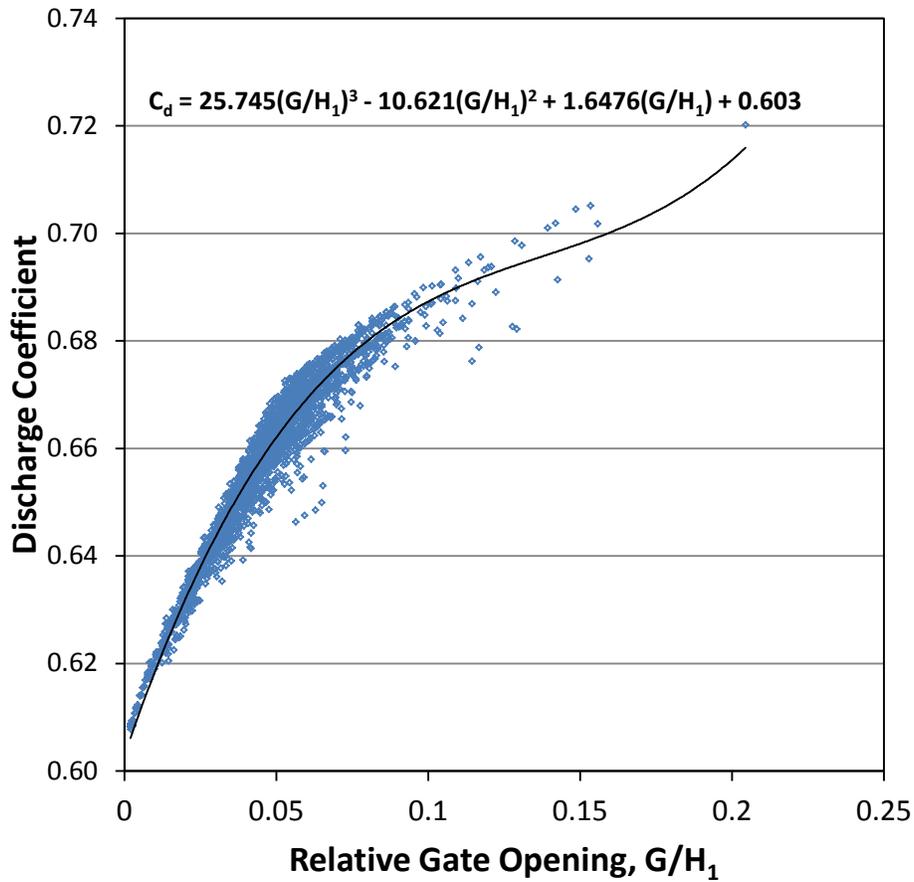


Figure 8. — Relation between canal sluiceway discharge coefficients and relative gate opening.

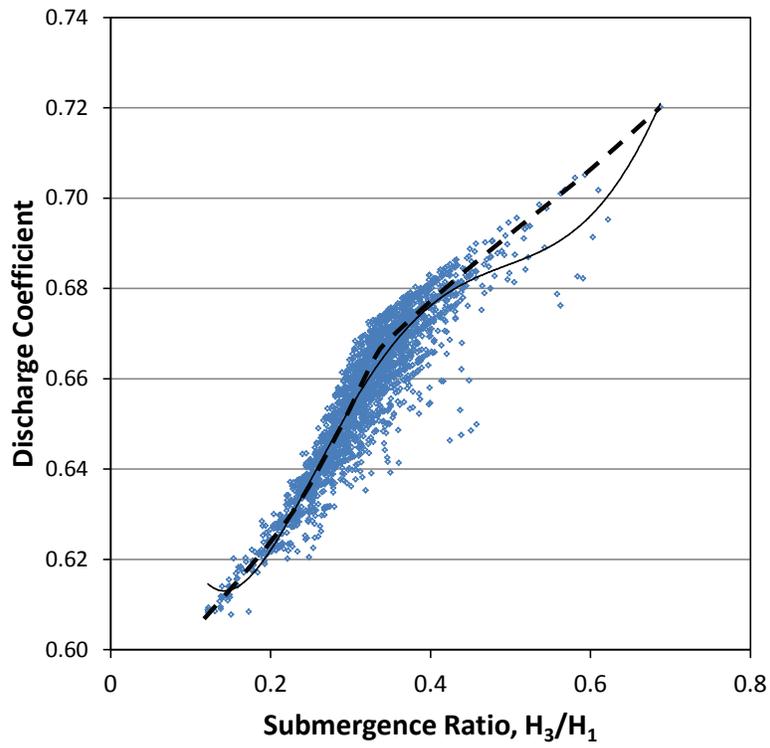


Figure 9. — Relation between canal sluiceway discharge coefficient and submergence ratio. The solid line is a fifth-order polynomial curve fit, and the dashed line is a manual curve fit (by eye).

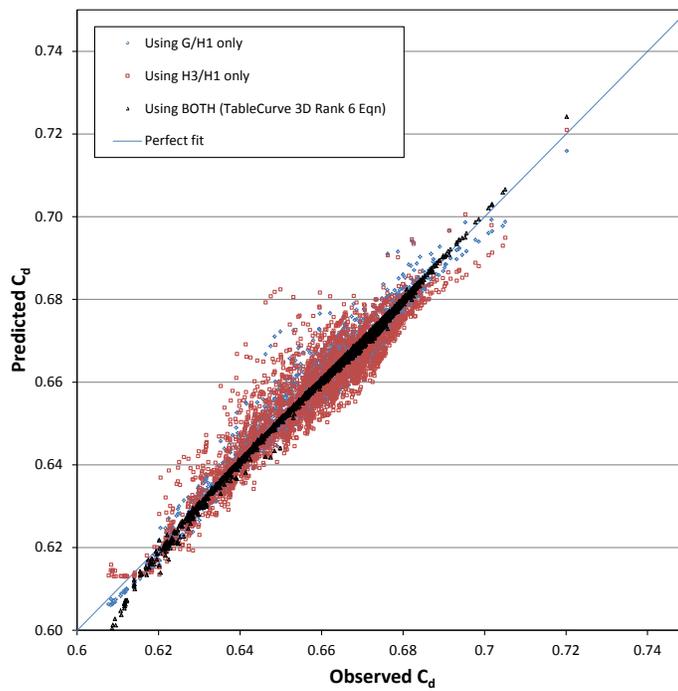


Figure 10. — Performance of several functions that can predict values of discharge coefficients for the canal sluiceway.

**Sources of Uncertainty in WinGate Analysis**

The WinGate computer program is a physically based model designed to calibrate canal sluice gates for accurate discharge measurement. It applies the energy equation to the upstream side of the gate and includes empirical factors that account for energy loss approaching the gate, assuming a streamlined approach channel. At the gate opening, the program applies empirical relations for estimating the contraction coefficient of the flow through the gate opening. Downstream from the gate, the momentum equation is applied, with empirical relations that estimate the hydrostatic and drag forces on downstream channel boundaries. Each of the empirical relations is a source of uncertainty, as are the assumptions of streamlined approach flow and no interaction with the adjacent river sluiceway and overflow weir. The greatest source of uncertainty in the model results is probably the estimation of flow forces on the sloped apron downstream from the gate, which leads into the stilling basin. The canal check gates that WinGate was designed to analyze typically do not have such sloped aprons or discharge into a stilling basin, so this specific downstream channel configuration has not been studied during the development of WinGate. If the forces on this surface are not accurately modeled in WinGate, there will be a systematic error in the computed discharge. The relative size of this error should be consistent throughout the operating range, so a future calibration adjustment is possible.

The analysis used to develop the new gate equations made use of the prevailing relationship between canal discharge and canal depth, which establishes the tailwater condition below the sluice gates. It was noted that the prevailing tailwater curve is about 2 ft higher than that which was expected based on the original design parameters of the canal. The reason for this difference is presently unknown. A second analysis was carried out in which the tailwater curve was set at the design level, and in this case the sluiceway would experience free orifice flow for a significant range of operating conditions. Thus, it should be noted that if tailwater conditions at the site change in the future due to canal maintenance activities or canal rehabilitation projects, that may change the equations needed to accurately predict sluiceway discharges.

**Weir Flow**

Although the Hydromet records indicate that weir flow through the canal sluiceway is highly unlikely, the potential for it does still exist. If the reservoir level upstream from Yellowtail Afterbay Dam is extremely low, it may be necessary to raise the canal gates out of the water to deliver as much water into the canal as possible. However, a simple estimation of free weir flow ( $Q=3.09LH^{1.5}$ ) through two gates or through one gate (assuming the other gate is closed) shows that in either case the tailwater levels produced in the canal are higher than the reservoir levels needed to obtain a given flow rate. Thus, it is impossible for free weir flow to exist, and the weir will always be submerged by the tailwater if the gates are raised out of the water. In this condition, flow will actually be controlled by the canal cross section and the canal gaging station will offer the best means for estimating the flow rate. The present rating equation for the gaging station was obtained from analysis of the Hydromet data:

$$Q = -0.2182h^3 + 60.91h^2 - 5278.5h + 145915 \quad (7)$$

where  $h$  is the net (shifted) canal gage height relative to elevation 3100 ft. (i.e., if the canal water level is at elevation 3170.0 ft,  $h=70.0$ ).

### **Recommended Equations for Canal Sluice Gate Discharge**

Discharge through the canal sluiceway should be computed using the orifice equation, Eq. (6), with the discharge coefficient computed from Eq. (7), unless the value computed there is less than 0.62. In that case, the discharge coefficient should be computed instead with the equation shown on Figure 8.

If the reservoir elevation and canal elevation are both lower than the gate lip elevation, then the gates will not control the flow and the discharge should be determined at the canal gaging station using Eq. (8).

When it is necessary for the control system to compute the gate opening needed to deliver a target discharge into the canal, an iterative solution of the orifice equation is required, since the discharge coefficient is dependent on the gate opening. The current value of the gate opening could be used as an initial guess at the new gate opening and the calculations then proceed as described above. Alternately, the discharge coefficient could be assumed to have a value of 0.66 for the first cycle of calculations (the median of the values obtained from the WinGate analysis).

## **CONCLUSIONS**

The WinGate computer program was effectively used in this study to develop discharge rating equations for two sets of vertical slide gates. The results of the WinGate analysis were used to develop simplified rating equations that will be suitable for use in the automated gate control system. The river sluiceway gates can operate in either free or submerged flow, and a method was developed for identifying the controlling discharge equation. The canal sluiceway gates will operate in a submerged condition at all times (assuming current tailwater levels are maintained). An empirical equation was developed to predict the submerged flow discharge coefficient as a function of both the relative gate opening and relative submergence.

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