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**Hydraulics Laboratory Technical Memorandum PAP-1090**

# Discharge Curves for Helena Valley Canal Headworks

**Helena Valley Unit, Pick-Sloan Missouri Basin Program**
**Montana**

**U.S. Department of the Interior**
**Bureau of Reclamation**
**Technical Service Center**
**Hydraulic Investigations and Laboratory Services Group**
**Denver, Colorado**

**May 2014**

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**U.S. Department of the Interior**
**Bureau of Reclamation**
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# Background and Purpose

The Helena Valley Regulating Reservoir ("DAM AND RESERVOIR" in Figure 1) provides intermediate storage along the Helena Valley Canal as it conveys water from Canyon Ferry Reservoir on the Missouri River to irrigable lands near Helena, Montana. Releases from the regulating reservoir into the downstream canal reach are made through a headworks structure located in a dike extending beyond the left abutment of Helena Valley Dam. This headworks structure contains two 6-ft wide by 6.5-ft high vertical slide gates that discharge into twin concrete box culverts that serve as hydraulic jump stilling basins leading to the head of the canal. The safe maximum discharge for the downstream canal is 350 $ft^3/s$. The headworks structure and gates are sized to permit full releases to the canal even at low reservoir levels, so releases that far exceed the canal capacity are possible at high reservoir levels.

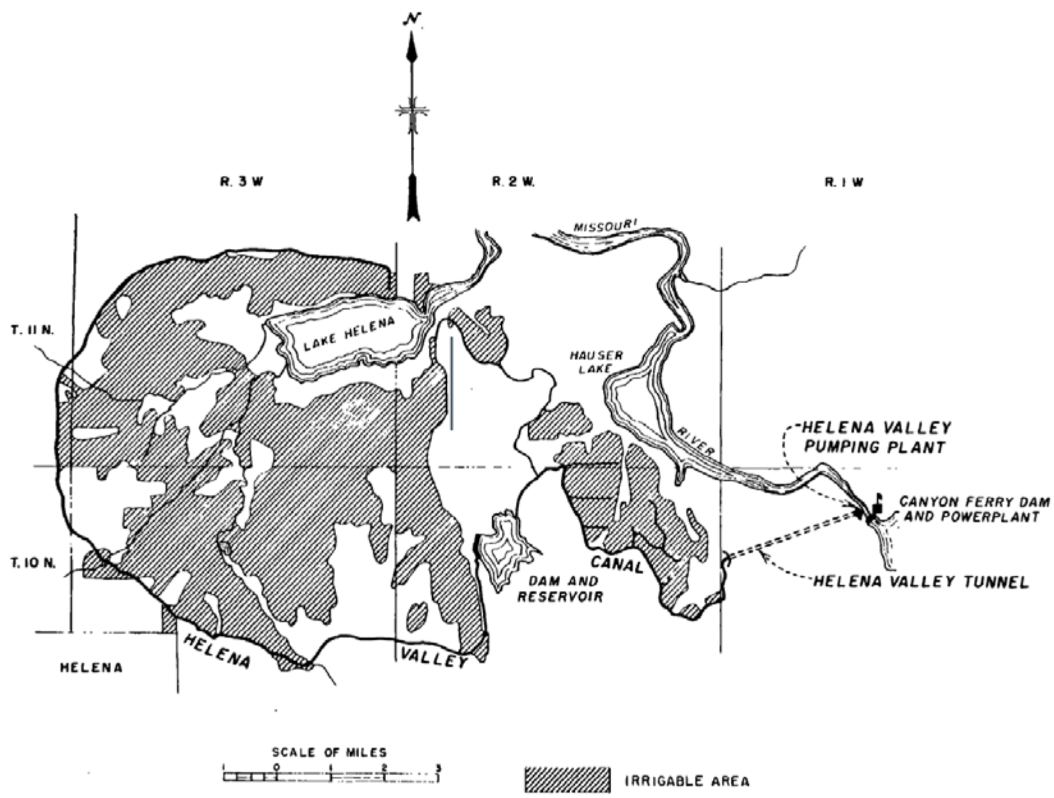


Figure 1. — The Helena Valley Unit (from *Project Data*, Water and Power Resources Service 1981)

To facilitate accurate releases of water from the regulating reservoir into the canal, the Montana Area Office requested the development of a set of discharge curves for the headworks structure. This technical memorandum describes the development of these discharge curves using the analytical computer program, WinGate. This software uses the energy and momentum equations to model the flow through vertical slide gates and radial gates used in canal check structures and headgate facilities. The software was developed jointly by staff of the Bureau of Reclamation Hydraulics Laboratory (Denver, CO) and the U.S. Department of Agriculture's Arid Lands Research Center (Maricopa, AZ). WinGate is described in two recent technical papers (Clemmens and Wahl 2012; Wahl and Clemmens 2012).

# Model Setup

The WinGate computer program models the headworks structure as a complete unit with an approach channel, both individual gates, and a tailwater channel. The shape and size of the upstream and downstream canals are specified, as well as the elevation differences between them. The gates and their sill elevations are defined, along with the width of the piers separating them from one another. Drawing 596-D-118 included at the end of this report shows the general arrangement of the structure in both plan and sectional elevation views.

For modeling purposes the upstream channel was considered to be the 16-ft base-width trapezoidal approach channel leading from the reservoir into the headworks structure. Transition and fluid friction losses in this section were assumed to be negligible, so the water surface elevation in the main body of the reservoir directly represents the head applied to the upstream side of the gates. The gate section was defined with the two 6-ft-wide vertical slide gates and an 8-inch-wide pier between them. (Note that the pier width varies from 8 inches to 2 ft, but is 8 inches for most of the length of the upstream gate chamber.) The downstream channel cross section was defined at the exit of the concrete box culvert and stilling basin structure, sta. 626+18.52. At this section the channel is rectangular with a width of 14 ft and includes the center 8-inch pier. The corner fillets in the box culvert section were neglected; they occupy only 0.5 to 1 percent of the downstream channel cross section, depending on the flow rate.

For most operating conditions the gates will operate in free flow with no submergence of the exit side of the gates; water released from the gates will flow down the sloped apron at a supercritical depth, and a hydraulic jump will develop at a downstream location in the stilling basin. For some flow conditions the downstream side of the gates will be submerged by a hydraulic jump that occurs immediately at the exit of the gates. The WinGate computer program is able to evaluate whether the tailwater level in the stilling basin is sufficiently high to cause this submergence, which will reduce the discharge through the gates.

Once the geometry of the headworks structure and other pertinent hydraulic details were defined in the software, a tailwater curve for the downstream side of the headworks structure was developed by applying the Manning equation to the downstream canal. Design drawing 596-D-118 provided the canal cross section size, shape, elevation and bed slope downstream from the headworks structure, as well as the design tailwater flow depth at maximum discharge. These data were used to compute the channel roughness, $n$=0.025; this information was used to compute tailwater depths for the full range of discharges.

# WinGate Modeling

WinGate can be used in an interactive manner to simulate single flow conditions, or it can be used in a batch mode to analyze multiple flow scenarios. The latter capability is useful for the development of complete rating curves. To begin, tailwater depths were determined for specific canal discharges based on the downstream canal properties. A batch data input file was prepared for WinGate that allowed it to solve for the gate opening needed to release specified discharges into the canal at incremental reservoir elevations and the associated tailwater levels for each discharge. The input data spanned the range of flows from 50 to 350 $ft^3/s$ and reservoir levels from 3805 ft to 3820.5 ft. This analysis considered two operating schemes for the headworks. In dual-gate operations both gates were set to the same gate opening. For single-gate operations the entire canal discharge was supplied through one gate and the other gate was fully closed. A total of 228 different flow conditions were analyzed in this way using WinGate. About 60 percent of the dual-gate cases produced free flow, while 40 percent produced submerged flow (at low reservoir heads or small gate openings). All of the single-gate cases produced free flow, although submerged flow is possible for single-gate operation at very small gate openings.

## Analysis of WinGate Results

The data produced by WinGate were next used to develop simplified relations that could be used to predict the effective discharge coefficients of the slide gates in free and submerged flow conditions at any desired gate opening or flow rate. For this purpose, the free and submerged flow cases were modeled using orifice equations as follows:

$$Q_{free} = C_{d,free} A\sqrt{2gH_1} \qquad (1)$$

$$Q_{subm} = C_{d,subm} A\sqrt{2g(H_1 - H_3)} \qquad (2)$$

The subscripts *free* and *subm* indicate free and submerged flow conditions, respectively, $Q$ is the discharge in $ft^3/s$, $C_d$ is the discharge coefficient, $A$ is the area of the gate opening (product of gate width and vertical opening) in $ft^2$, $g$ is the acceleration due to gravity (32.2 $ft/s^2$), $H_1$ is the upstream reservoir head above the gate sill elevation in feet, and $H_3$ is the tailwater elevation above the gate sill elevation in feet. The gate sill elevation is 3799.40 ft. For each of the flow conditions modeled in WinGate, the data were used to solve for the discharge coefficient. These coefficients were then analyzed to develop useful relationships that could be used to compute discharge curves. The free flow discharge coefficients were a direct linear function of the relative gate opening, $w/H_1$, where $w$ is the vertical gate opening (Figure 2).

$$C_{d,free} = -0.2258(w/H_1) + 0.6026 \quad (3)$$

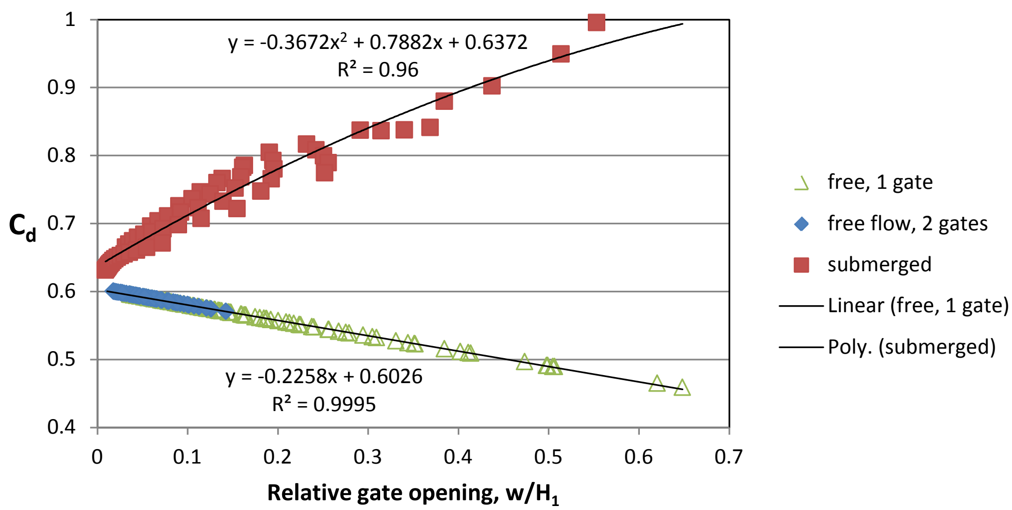


Figure 2. — Discharge coefficients versus relative gate opening.

The submerged flow discharge coefficients were related to both $w/H_1$ (Figure 2) and the relative submergence, $H_3/H_1$ (Figure 3). Several potential predictive relationships were studied using the curve-fitting software TableCurve 3D and the most useful relationship was

$$C_{d,subm} = 4.4152 - 3.800\left(e^{-w/H_1}\right) - 1.7141(H_3/H_1)^2 \quad (4)$$

where $e$ is the base of natural logarithms, approximately $e$ = 2.7183. Figure 4 shows predictions of submerged flow discharge coefficients made using eq. 4 and other simpler relations (functions of $w/H_1$ or $H_3/H_1$, individually).

## Discussion

The values of the discharge coefficients shown in the preceding figures may appear unusual to some readers. A typical discharge coefficient for a vertical slide gate in free flow is about 0.6. The data shown here start at that value, but decrease significantly for large gate openings. This is due to the fact that the discharge equation used here is based on the total head above the gate sill. Another common definition for free flow utilizes the total head above the centerline of the gate opening. With that definition, free flow discharge coefficients at large relative gate openings would be larger. The approach taken here is appropriate because it is simple to apply and leads to a very consistent relation that can be used to predict the discharge coefficient for any gate setting.

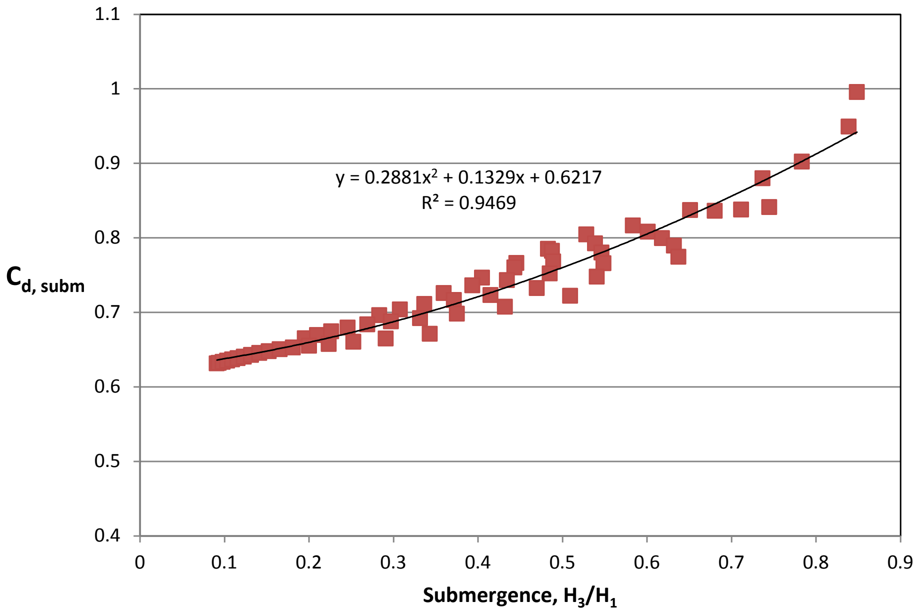


Figure 3. — Submerged flow discharge coefficients versus submergence.

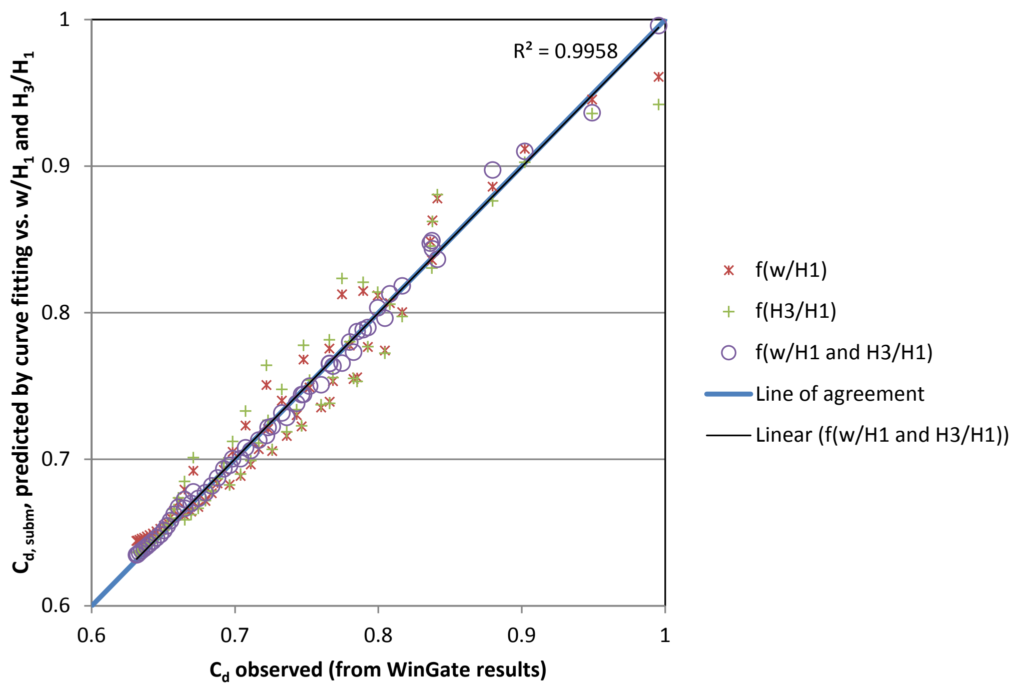


Figure 4. — Predictions of submerged flow discharge coefficient as functions of relative gate opening, submergence, and a combination of both factors (eq. 4).

The discharge coefficients for submerged flow are larger than the typical 0.6 value. This is consistent with research that has shown increased discharge coefficients in submerged flow (e.g., Belaud et al. 2009); the increased discharge coefficient is accompanied by a decrease in effective head due to the tailwater that provides backpressure against the gate, so actual discharges are still reduced when gates become submerged. The discharge coefficient values that are very near to 1.0 are associated with cases in which the gates are nearly out of the water, there is almost zero head difference ($H_3$-$H_1$) across the gates, and the gates are barely affecting the flow.

# Development of Discharge Curves

The relationships developed above provide the tools needed to readily create discharge curves for the canal headworks structure. The equations are more useful for this purpose than the WinGate program itself because the desire when developing rating curves is to determine the discharge for specified combinations of gate opening, upstream head and downstream head. However, until the discharge is known, the downstream head cannot be determined. Thus, to use WinGate to develop the discharge curve data would require iterative runs of WinGate followed by determination of tailwater levels (using the Manning equation) and repetition until the solution converges. A more tractable approach is:

1. Start with a known reservoir head and gate opening, and make an initial rough estimate of the expected discharge, and compute its associated tailwater elevation (using the Manning equation);
2. Use equations 1 through 4 to compute the free and submerged flow discharge estimates;
3. The minimum of the two is the new estimate of discharge;
4. Repeat the process until the discharge converges to a final value.

This solution process was readily automated in an Excel spreadsheet, but convergence was difficult to obtain in some cases. This was overcome by relaxing step 3. After finding the minimum of the free and submerged flow estimates, the new best estimate of discharge was made equal to a weighted combination of the original estimate (from step 1) and the newly calculated value, with the weighting factor adjustable in the spreadsheet. With this refinement, the process was readily completed, producing the discharge curves shown in Figure 5 and Figure 6. The figures do reflect the influence of tailwater and potential gate submergence, although they only directly show the flow to be a function of gate opening and upstream reservoir level. On both figures the approximate regions of free and submerged flow are indicated. However, for single-gate operation the submerged flow range is limited to extremely small gate openings and the effects of submerged are slight, so good results can be obtained by simply assuming that free flow always applies. The discharge curves for large gate openings at low reservoir levels are truncated at the point at which the gate is expected to be out of the water and unable to control the flow.

# Uncertainties

The WinGate computer program is an analytical tool that applies the energy and momentum equations to determine the discharge characteristics of gated check structures. Although there is a strong theoretical basis for its analysis, the model also includes empirical factors that account for energy loss, velocity distribution effects, drag forces, and other hydrodynamic forces on channel boundaries. These factors have been developed through laboratory studies that do not fully represent specific characteristics of the Helena Valley Canal headworks structure. For example, site-specific approach flow conditions and the shape of the curved apron immediately downstream from the gates may cause WinGate's discharge estimates to be different from actual discharges. Laboratory research studies performed during the development of WinGate suggest that free flow discharge uncertainty of about ±3 percent can be obtained, while submerged flow uncertainty is typically ±5 to ±10 percent. Field calibration and verification tests would be needed to confirm the accuracy of these curves.

# Conclusions

In the absence of field testing, the discharge curves provided in Figure 5 and Figure 6 give the best available estimates of the discharge characteristics of the Helena Valley Canal headgate structure. These curves can be used in their printed form, or the iterative solution process described in the **Development of Discharge Curves** section of this technical memorandum can be used to compute discharges for other gate settings.

Appendix A provides an alternative means for directly computing discharges that may be more practical for some future purposes in which iterative calculations are problematic, such as automation of discharge calculations in a SCADA system (Supervisory Control and Data Acquisition). The procedure is not iterative, but does require the computation of several complex polynomial equations for dual-gate operations. For single-gate operations, the non-iterative free-flow solution is sufficiently accurate for all purposes.

Field tests could help to confirm or improve the accuracy of the discharge curves developed here. These tests would require the measurement of the upstream reservoir head, gate opening, and discharge in the downstream canal over a range of operating conditions. Tailwater elevations could also be recorded to help verify that the tailwater levels computed during this study were accurate, but this is not absolutely required. Discharge measurements could be obtained using traditional current-metering (i.e., stream gaging) techniques, or newer technologies, such as miniature boat-mounted acoustic Doppler current profilers (ADCP).

# References


Belaud, G., L. Cassan, L., and J.-P. Baume, 2009. Calculation of contraction coefficient under sluice gates and application to discharge measurement. *Journal of Hydraulic Engineering*, 135(12):1086-1091.

Clemmens, A.J., and T.L. Wahl, 2012. Computational procedures used for radial gate calibration in WinGate. 2012 World Environmental and Water Resources Congress, Albuquerque, NM, May 20-24, 2012.

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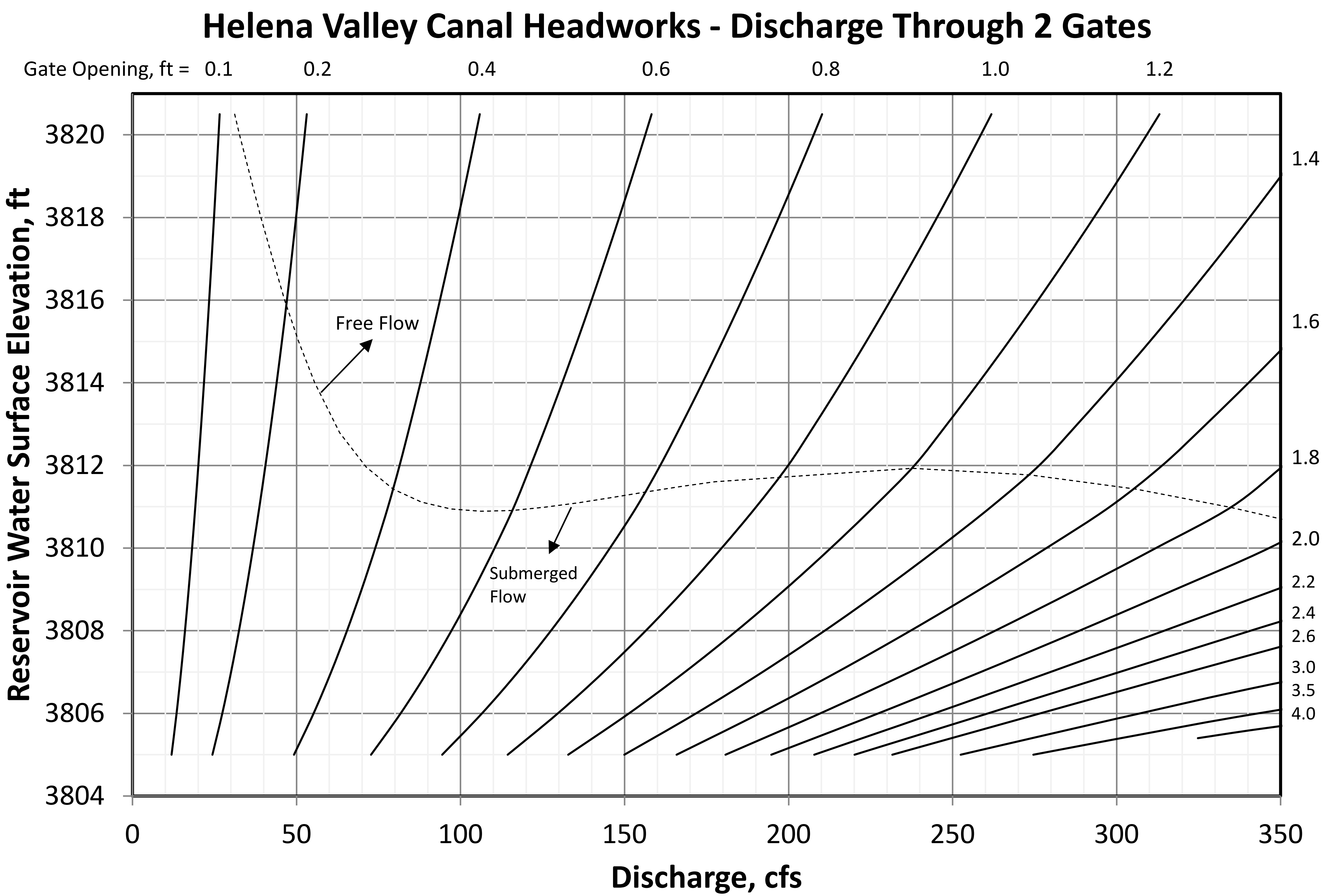


Figure 5. — Discharge curves for operation of two gates at the same setting. The dashed line indicates the approximate boundary between free and submerged flow operations.

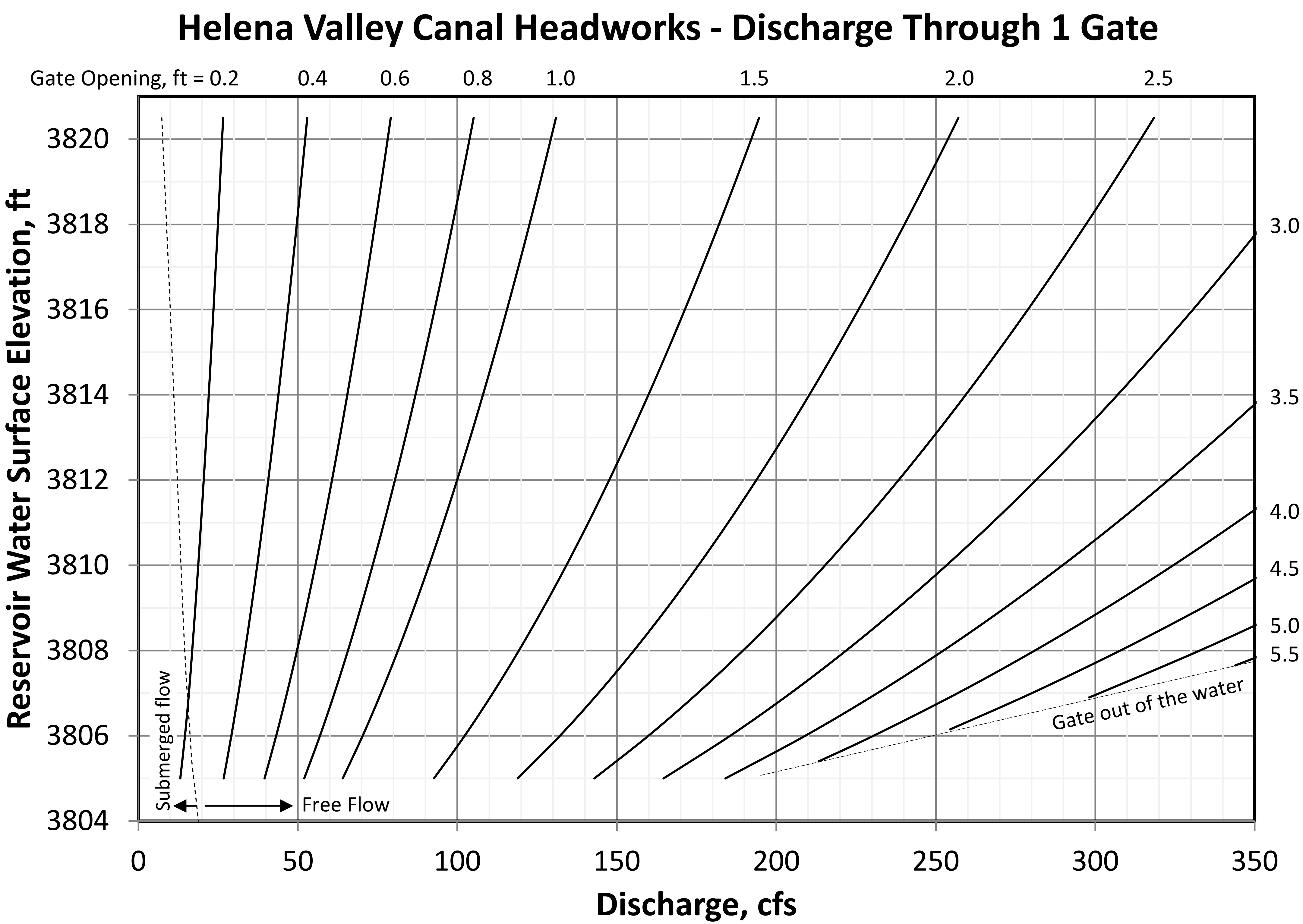


Figure 6. — Discharge curves for operation of only one gate (second gate fully closed). The dashed line indicates the approximate boundary between free and submerged flow operations.

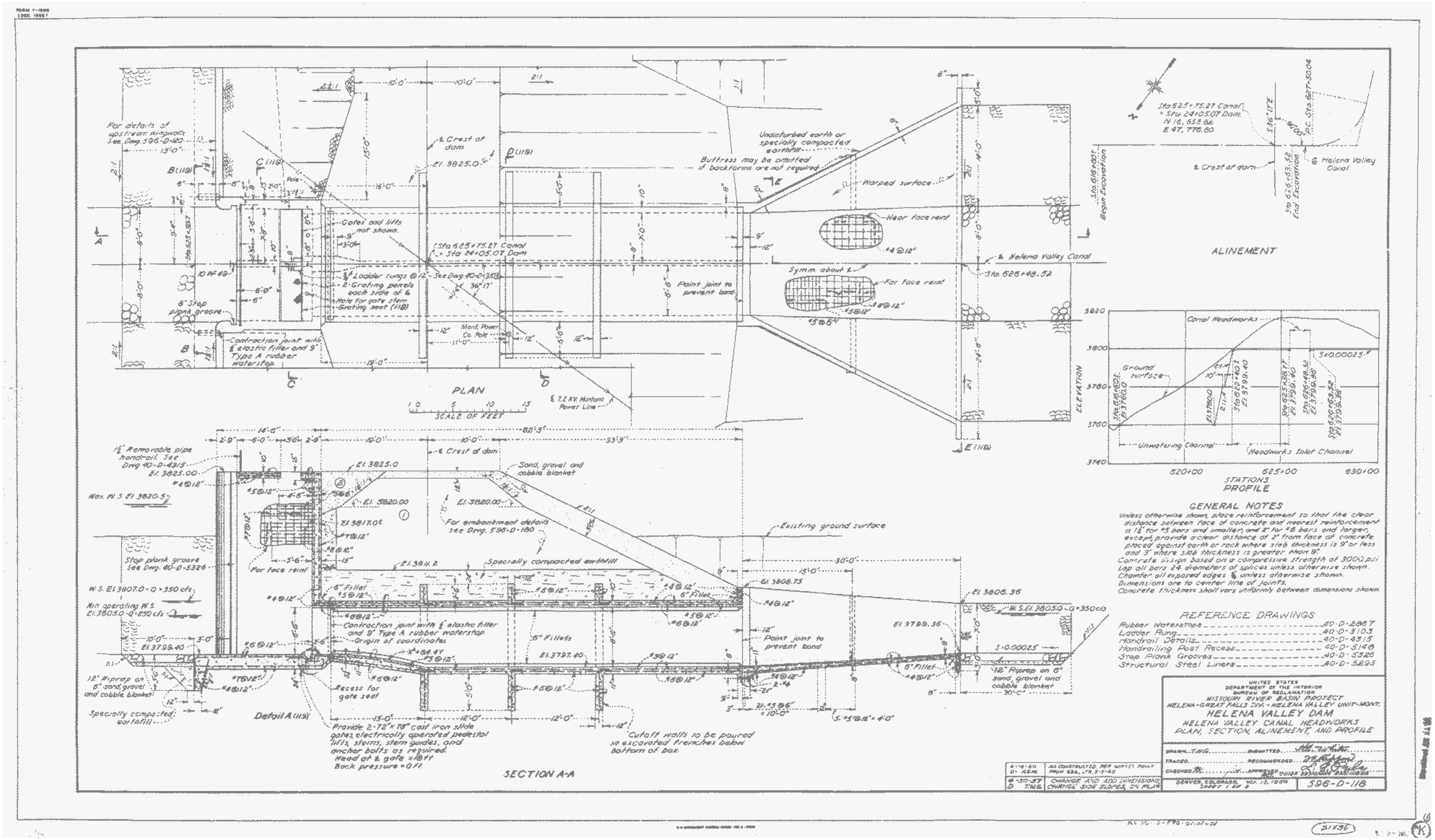


Figure 7. — Drawing 596-D-118.

# Appendix A – Direct Computation of Discharge

## Dual-Gate Operation

This procedure computes discharges matching the curves shown in Figure 5 for synchronized operation of the two gates in the Helena Valley Canal headworks. The method accurately reproduces the curves in Figure 5 for gate openings of 0.1 to 4.0 ft, reservoir heads from 3805.0 to 3820.5 ft, and total discharges of 12 to 350 ft$^3$/s. This procedure is not iterative (i.e., each step is performed only once to complete a flow calculation).

**<u>Input and Output Variables:</u>**

*RWSE* = reservoir water surface elevation, ft
*w* = vertical gate opening, ft
*g* = acceleration due to gravity, 32.2 ft/s$^2$
*Q* = total discharge through two gates, ft$^3$/s

**<u>Computational Procedure:</u>**

1. Compute free-flow discharge

   $$H_1 = RWSE - 3799.40$$

   $$C_{d,free} = -0.2258(w/H_1) + 0.6026$$

   $$Q_f = (2)C_{d,free}(6w)\sqrt{2gH_1}$$

2. Compute the threshold reservoir level for free flow

   $$R_{free} = 2.825 \times 10^{-13}(Q_f)^6 - 3.977 \times 10^{-10}(Q_f)^5 + 2.276 \times 10^{-7}(Q_f)^4 - 6.776 \times 10^{-5}(Q_f)^3 + 0.01098(Q_f)^2 - 0.9019(Q_f) + 3840$$

3. If $RWSE \geq R_{free}$, then the gates are operating in free flow. Total discharge $Q = Q_f$. STOP.

4. For submerged flow, choose coefficient values from Table 1 on the following page, then continue to step 5.

Table 1. — Coefficients for computing submerged flow discharge curve regression factors.

| Gate opening | Coefficient names and values | | | | |
|---|---|---|---|---|---|
| $w \leq 2.4$ ft | $A_4$ | $A_3$ | $A_2$ | $A_1$ | $A_0$ |
| | 13.827 | -24.431 | 12.727 | -87.255 | 1.9083 |
| | $B_4$ | $B_3$ | $B_2$ | $B_1$ | $B_0$ |
| | 2.3653 | -4.3871 | 7.3527 | -9.0305 | 0.5969 |
| | $C_4$ | $C_3$ | $C_2$ | $C_1$ | $C_0$ |
| | -11.168 | 20.322 | -31.036 | 115.6 | -2.9214 |
| $w > 2.4$ ft | $A_4$ | $A_3$ | $A_2$ | $A_1$ | $A_0$ |
| | 940.7 | -11592 | 53221 | -107450 | 80351 |
| | $B_4$ | $B_3$ | $B_2$ | $B_1$ | $B_0$ |
| | 147.13 | -1811.4 | 8319.6 | -16781 | 12551 |
| | $C_4$ | $C_3$ | $C_2$ | $C_1$ | $C_0$ |
| | -744.33 | 9168.5 | -42106 | 85009 | -63533 |

5. Use the coefficients selected in step 6 to compute the following regression factors needed for the discharge equation in step 6:

$$b = A_4(w)^4 + A_3(w)^3 + A_2(w)^2 + A_1(w) + A_0$$

$$m_1 = B_4(w)^4 + B_3(w)^3 + B_2(w)^2 + B_1(w) + B_0$$

$$m_2 = C_4(w)^4 + C_3(w)^3 + C_2(w)^2 + C_1(w) + C_0$$

6. Compute the total discharge for submerged flow:

$$Q = m_2\sqrt{H_1} + m_1 H_1 + b$$

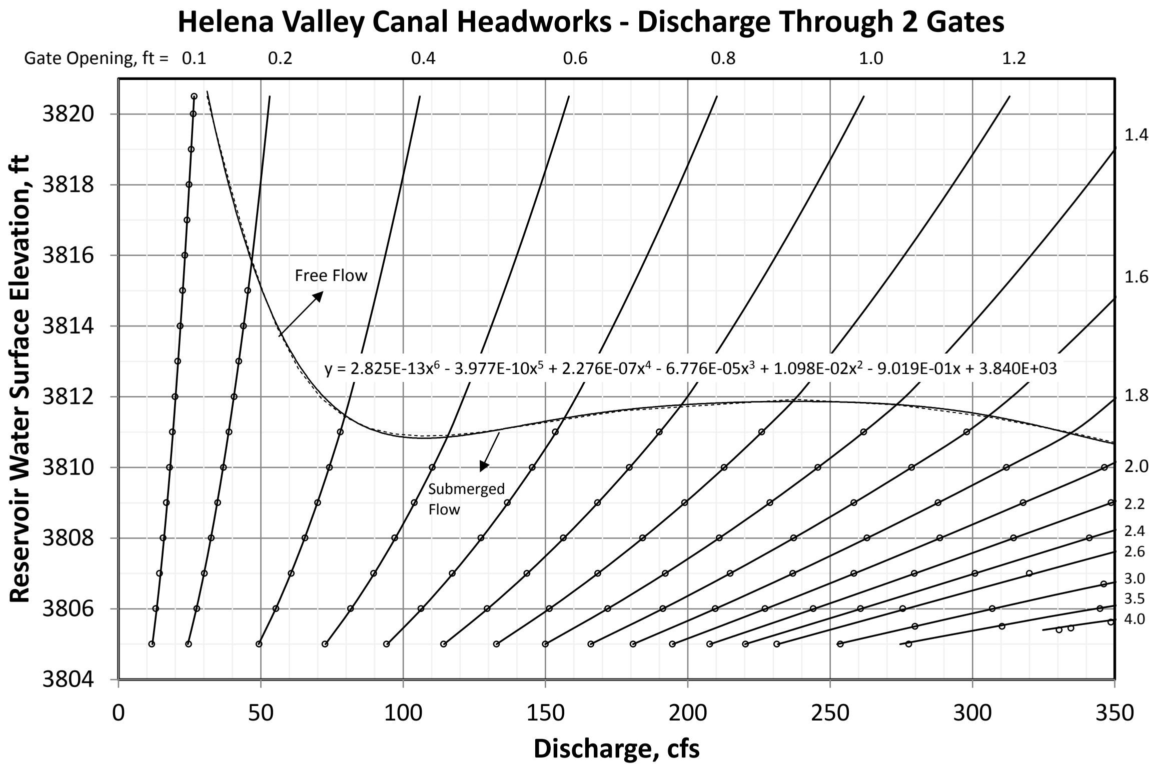


Figure 8. — Data points in the submerged flow region in this chart demonstrate that the computational procedure described above reproduces the discharge curves for dual-gate operation. The equation in the middle of the chart defines the line dividing free from submerged flow.

## Single-Gate Operation

This procedure computes discharges matching the curves shown in Figure 6 for flow through only one gate in the Helena Valley Canal headworks (second gate fully closed). The method accurately reproduces the curves in Figure 6 for gate openings of 0.2 to 5.5 ft, reservoir heads from 3805.0 to 3820.5 ft, and total discharges of 13 to 350 $ft^3/s$. The method will not be accurate for very large gate openings and low reservoir levels at which the gate leaf is out of the water (i.e., below the bottom end of the curves shown in Figure 6).

This method uses only the free-flow discharge equation, since the zone of submerged flow is very limited and within that zone the discharge reduction due to submergence is extremely slight for single-gate operation. This procedure is not iterative (i.e., each step is performed only once to complete a flow calculation).

**<u>Input and Output Variables:</u>**

$RWSE$ = reservoir water surface elevation, ft
$w$ = vertical gate opening, ft
$g$ = acceleration due to gravity, 32.2 $ft/s^2$
$Q_{free}$ = discharge through one gate, $ft^3/s$ (free flow assumed for all conditions)

**<u>Computational Procedure:</u>**

1. $H_1 = RWSE - 3799.40$
2. $C_{d,free} = -0.2258(w/H_1) + 0.6026$
3. $Q_{free} = C_{d,free}(6w)\sqrt{2gH_1}$