Background and Introduction

Historical estimates and projections of the Great Lakes water budget are an integral component of regional water resources management decisions, including those based on short- and long-term water level dynamics. The water budget of each of the Great Lakes is based primarily on precipitation inputs, over lake evaporation, and inflows and outflows through diversions and the rivers that connect the lakes (commonly referred to as “connecting channels”). Of those connecting channels, the St. Marys River (Figure 1) (the channel connecting Lake Superior to Lake Huron) is somewhat unique as it involves a complex combination of flow pathways at Sault Ste. Marie (Figure 2) which currently include three hydroelectric facilities, five navigation locks, three domestic water supply intakes, and a gated dam at the head of the St. Marys Rapids known as the Compensating Works. The Compensating Works are comprised of 186 steel sluice gates at the head of the St. Marys Rapids (Figures 3-4), with gates 1-8 located in Canada and gates 9-14 located in the United States. The gate structure provides control of flow to the St. Marys Rapids immediately downstream, and, therefore, in combination with other control flow pathways in the St. Marys River, moderates regulation of Lake Superior water levels (Clites, Quinn 2003).

Importantly, flows through the Compensating Works constitute a significant and often highly variable component of the overall flow through the St. Marys River. Therefore, understanding the relationships between water levels and flows is critical to the operation of the Compensating Works and to the determination and regulation of the total flow through the St. Marys River and water levels of Lake Superior and Lake Michigan-Huron.

There are a variety of different gate opening arrangements that can be utilized within the Compensating Works in order to adjust flow rates. Due to these various settings as well as uncertainty relating to methods used to measure flow through the gates, we decided to explore alternative approaches to calculating flow with partially open gate settings. Our ultimate goal is to propose recommendations for future operational water budget and hydraulic modeling protocols for the federal agencies responsible for regulating flows through the St. Marys River and, ultimately, the water levels of Lake Superior.

Methods

Table 1. Measured flows, gate heights, and water elevations taken by the International Lake Superior Board of Control:

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Flow Rate</th>
<th>Gate Height</th>
<th>Water Level</th>
</tr>
</thead>
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<td>420 ADCP</td>
<td>0.2794</td>
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<td>0.254</td>
<td>0.2</td>
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</table>

Data

Rapid discharge measurements and surface water elevation immediately upstream of the Compensating Works (Figure 5) have been simulated by the International Lake Superior Board of Control. The sample depth is calculated as the difference between the surface water elevation at NOAA’s Southwest Pier gage, and the elevation of the submerged gate sill (Figure 6). The water surface elevation at the Southwest Pier is used as an accurate representation of water levels upstream of all gates. However, there is still some uncertainty in water level measurements due to the ice-out and ice-up steps between the SPM and the Compensating Works.

Flow measurements have also been collected periodically (Table 1) and have been used to either verify or calibrate parameterizations of gate flows, as described in the next section. Additional in-measurement protocol survey periods, including differing locations (Table 1, column 4) and different equipment (Table 1, column 2) contribute to uncertainties in historical relationships between gate settings and flow rates.

Figure 1. Site location map of the Great Lakes and the St. Marys River. Figure 2. Side view of the Compensating Works gates. Figure 3. Cross-section of the Compensating Works at Sault Ste. Marie. Figure 4. Aerial view of the St. Marys River in the area.

Model

Estimates of flow through the Compensating Works at partially open gate settings can be computed by applying the following well-known equation (Chow, 1960):

\[ Q = C \cdot A \cdot \sqrt{2guy} \]

where:
- \( Q \) = Daily average flow rate through single gate [m³/s]
- \( C \) = Discharge coefficient [-]
- \( A \) = Wet width [m], equals 0.85 to 0.95 in all cases
- \( y \) = Gate height [m]
- \( u \) = Upstream depth [m]

Historically, the Superior Board has applied equation (1) to estimate Compensating Works flows using a value of \( C = 0.62 \) when the flow at an open gate [m³/s] is known. A more fundamental and complete basis for this equation is shown below. The discharge coefficient can be calculated using the following expression:

\[ C = \frac{C_1 \cdot C_2 \cdot C_3}{C_4} \]

where:
- \( C_1 \) = Discharge coefficient [-]
- \( C_2 \) = Contraction coefficient [-]
- \( C_3 \) = Gate opening height \( h \), and a contraction coefficient \( C \)

\[ C_2 = \frac{C_1}{h} \]

\[ C_3 = \frac{C_1}{2guy} \]

and equation (1) then is modified as follows:

\[ Q = \frac{2guy}{C} \left( \frac{C_1}{h} \right) \left( \frac{C_1}{2guy} \right) \]

with:
- \( C_1 \) = Contraction coefficient [-]
- \( C_2 \) = Gate opening height \( h \)
- \( C_3 \) = Wet width [m]
- \( C_4 \) = Upstream depth [m]

We applied equation (1) to estimate Compensating Works flows using a value of \( C = 0.62 \) when the flow at an open gate [m³/s] is known. A more fundamental and complete basis for this equation is shown below. The discharge coefficient can be calculated using the following expression:

\[ C = \frac{C_1 \cdot C_2 \cdot C_3}{C_4} \]

where:
- \( C_1 \) = Discharge coefficient [-]
- \( C_2 \) = Contraction coefficient [-]
- \( C_3 \) = Gate opening height \( h \)
- \( C_4 \) = Wet width [m]
- \( C_5 \) = Upstream depth [m]

\[ C_2 = \frac{C_1}{h} \]

\[ C_3 = \frac{C_1}{2guy} \]

and equation (1) then is modified as follows:

\[ Q = \frac{2guy}{C} \left( \frac{C_1}{h} \right) \left( \frac{C_1}{2guy} \right) \]

with:
- \( C_1 \) = Contraction coefficient [-]
- \( C_2 \) = Gate opening height \( h \)
- \( C_3 \) = Wet width [m]
- \( C_4 \) = Upstream depth [m]

Model Parameter Estimation (Calibration)

We explored a range of values for the contracted flow resulting from contracted flow values and measured flow values. For this, we used the same well-known equation (1) shown above, but we allowed the contraction coefficient to vary (within the range of flow rates for our given data). This occurs as we move from the steeper to a more rigorous model parameter estimation procedure. Once a range of contraction coefficients were determined, we explored the contract flow coefficients and estimated the simulated flow coefficients. We then used a very broad range of contraction coefficient values, based on what might be needed to explain nearly all of the observed flow variability, to reproduce historical flows from May through November of 2014. We applied the maximum and minimum values of the contraction coefficient, given those along with the estimated flows that were used during the calibration process. Since the range for contraction coefficients is in steps, it captures all of the estimated flows for the time period and for each gate setting. There is a large range of potential solutions that could be occurring through the corresponding ranges.

Conclusions and Next Steps

We have determined that using the contraction coefficient reflects simulated values of flow in comparison to the discharge coefficient, but the “fit” setting is not well suited using this model. Also, the contraction coefficient used in our analysis can be a significant change in flow with varying coefficients. We recommend more data measurements for higher flow regimes in order to get more conclusive results regarding a correct contraction coefficient when using the “multiple partial gates” setting.

References


Acknowledgments

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