Quantifying Uncertainty in St. Marys River Flow Estimates

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Background and Introduction

Historical estimates and projections of the Great Lakes water budget are an integral component of regional water resource 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 these 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 16 steel sluice gates at the head of the St. Marys Rapids (Figures 3-4), with gates 1-8 located in Canada and gates 9-16 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 controlled 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 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.

Figure 1. Site location map of the Great Lakes with detailed photo inset of the St. Marys River.

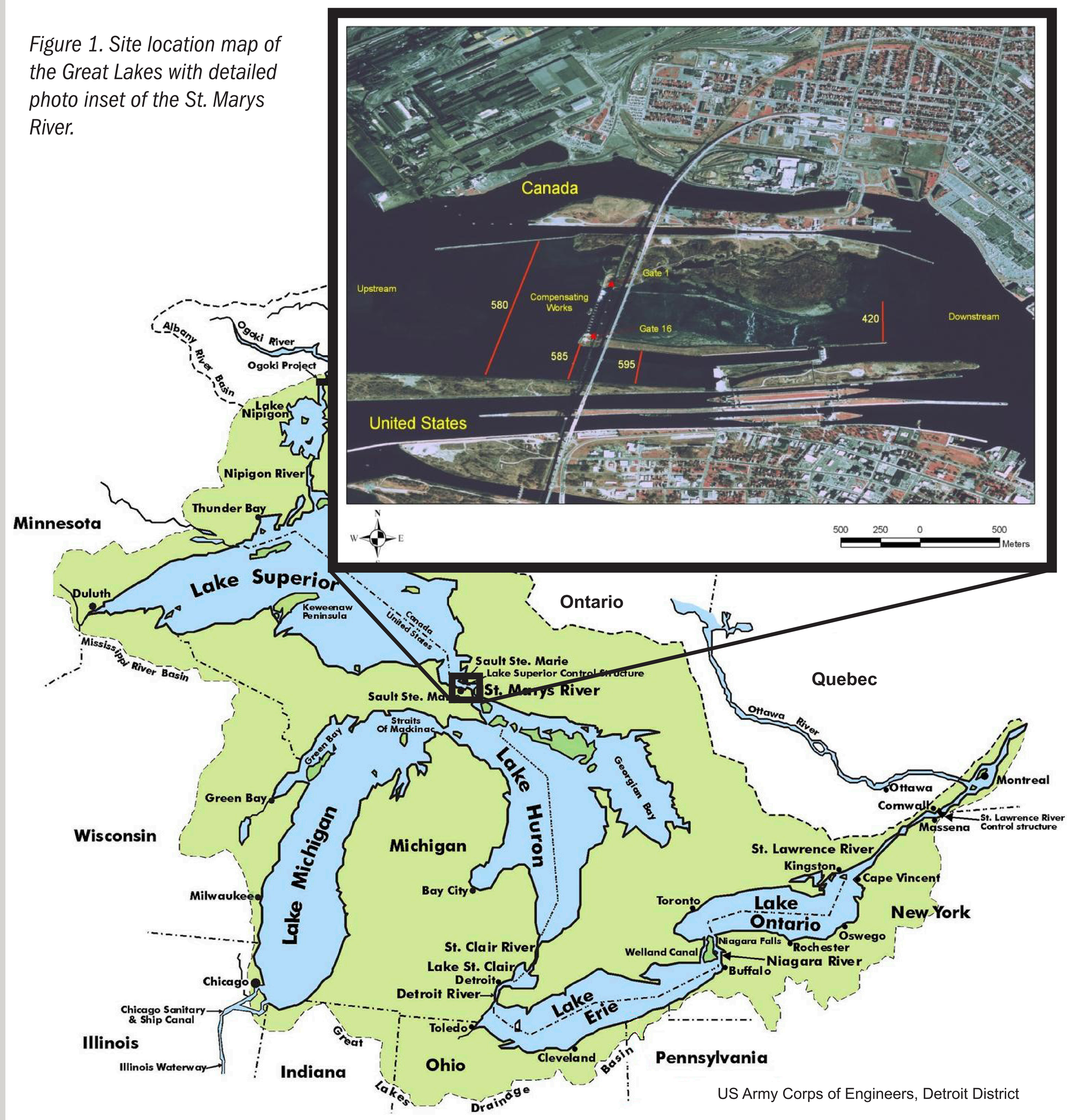

Figure 2. St. Marys River site layout with labeled flow pathways.

Figure 3. Side view of the Compensating Works gates.

Figure 4. Aerial view of the St. Marys River in the winter.

Table 1. Measured flows, gate heights, and water elevations taken by the International Lake Superior Board of Control: Dark blue represents 1/2 gate setting (gate 9 open to roughly 1 m). Green represents 1/2 gate equivalent setting (four gates open to low flow setting collectively replicating flow at 1/2 gate setting). Light blue represents multiple partial gates (multiple gates open to some less-than maximum height to spread flow across the span of the river).

Flow measurement conditions					Gate opening (m)															
Date	Location	Equipment	Flow (m^3/s)	Upstream wse (m)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
10/15/1987	Upper Gate and US Power Cana	Conventional	338	183.3	0.2	0	0	0	0	0	0	0	1.0922	0	0	0	0	0	0	0
7/27/1989	Lower Rapids	Moving Boat	135	183.385	0.2	0	0	0	0	0	0	0	1.0922	0	0	0	0	0	0	0
7/27/1989	Lower Rapids	Conventional	147	183.373	0.2	0	0	0	0	0	0	0	1.0922	0	0	0	0	0	0	0
7/27/1989	Lower Rapids	Conventional	170	183.377	0.2	0	0	0	0	0	0	0	1.0922	0	0	0	0	0	0	0
9/11/1990	Lower Rapids	Moving Boat	98	183.141	0.2	0	0	0	0	0	0	0	1.0922	0	0	0	0	0	0	0
8/5/1999	580 & 585	ADCP	120	183.336	0.2	0.254	0.254	0.254	0.254	0	0	0	0	0	0	0	0	0	0	0
8/5/1999	580 & 585	ADCP	126	183.32	0.2	0.254	0.254	0.254	0.254	0	0	0	0	0	0	0	0	0	0	0
8/5/1999	420	ADCP	105	183.273	0.2	0.254	0.254	0.254	0.254	0	0	0	0	0	0	0	0	0	0	0
8/7/1999	580 & 585	ADCP	108	183.247	0.2	0	0	0	0	0	0	0	1.0922	0	0	0	0	0	0	0
8/7/1999	580 & 585	ADCP	128	183.266	0.2	0	0	0	0	0	0	0	1.0922	0	0	0	0	0	0	0
8/7/1999	420	ADCP	131	183.215	0.2	0	0	0	0	0	0	0	1.0922	0	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
8/11/2005	420	ADCP	103	183.22	0.2	0	0	0	0	0	0	0	1.0922	0	0	0	0	0	0	0
8/12/2005	420	ADCP	103	183.192	0.2	0	0	0	0	0	0.3048	0.2413	0.254	0.254	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
6/8/2006	420	ADCP	94	183.185	0.2	0	0	0	0	0	0.2032	0.2032	0.2032	0.2032	0	0	0	0	0	0
6/9/2006	420	ADCP	115	183.184	0.2	0	0	0	0	0	0.2794	0.2794	0.2794	0.2794	0	0	0	0	0	0
6/9/2006	420	ADCP	105	183.168	0.2	0	0	0	0	0	0.2794	0.2794	0.2794	0.2794	0	0	0	0	0	0
6/9/2006	420	ADCP	125	183.163	0.2	0	0	0	0	0	0.2794	0.2794	0.2794	0.2794	0	0	0	0	0	0
6/9/2006	420	ADCP	91	183.279	0.2	0	0	0	0	0	0	0	1.0922	0	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
8/24/2012	u/s 420	ADCP	101	183.012	0.2	0	0	0	0	0	0	0	1.0922	0	0	0	0	0	0	0
6/3/2014	580 & 585	Conventional	754	183.38	0.2	0.686	0.686	0.686	0.686	0.686	0.686	0.686	0.686	0.686	0.686	0.686	0.686	0.686	0.686	0
7/15/2014	580 & 585	Moving Boat	918	183.58	0.2	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.05
10/7/2014	580 & 585	Conventional	836	183.62	0.2	0	0.8	0.8	0.8	0.8	0.8	0.8	0.787	0.787	0.787	0.787	0.787	0.787	0.787	0

Methods

Data

Rapids discharge measurements and surface water elevations immediately upstream of the Compensating Works (Figure 5) have been collected by the International Lake Superior Board of Control. The upstream 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 5). The water surface elevation at the Southwest Pier is used as an accurate representation of water levels upstream of all the gates; however there is some inaccuracy in upstream water level estimates due to the distance and slope between the SWP and the Compensating Works.

Flow measurements have also been collected periodically (Table 1) and have been used to either verify or calibrate parameters of gate flow models (as described in the next section). Variations in measurement protocol over this period, including different locations (Table 1, column 2) and different equipment (Table 1, column 3) contribute to uncertainties in historical relationships between gate settings and actual flow rates.

Model

Flow through the Compensating Works at partially open gate settings can be determined by applying the following weir equation (Chow, 1964):

$$Q = Clh\sqrt{2gy} \tag{1}$$

where:

Q	=	Daily average flow rate through single gate [m^3/s]
C	=	Discharge coefficient [-]
l	=	Weir width [m], equal to 15.91 m for all gates
h	=	Weir height [m]
g	=	Gravitational constant [m/s^2]
y	=	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 ½ gate and ½ gate equivalent settings were used based on past calculations. However, recent flow measurements at multiple partially open gate settings under higher flows indicate that this discharge coefficient is too large. This creates a greater predicted flow through the Compensating Works than is actually occurring, and therefore inaccurate measurements of flow through the St Marys River.

Here, we propose an alternative formulation of equation (1) that expresses C as a function of upstream channel depth y, gate opening height h, and a contraction coefficient C_c. This approach accommodates theoretical relationships between the C_c, y, and h (Figure 6). The equation is shown as follows:

$$C = \frac{C_c}{\sqrt{1 + \frac{C_c}{y/h}}} \tag{2}$$

where:

C	=	Discharge coefficient [-]
C_c	=	Contraction coefficient [-]
y	=	Upstream depth [m]
h	=	Weir height [m]

and equation (1) can then be modified as follows:

$$Q = lC_c y\sqrt{\frac{2g}{y + hC_c}} \tag{3}$$

Model Parameter Estimation (Calibration)

We explored a range of contraction coefficients and constrained the range based on a comparison between calculated flow values and measured flow values. Then, for both the use of equations (1) and (3), we compared measured flow vs. simulated flow determine if using the contraction coefficient refines the simulated flow values for our given data. This analysis sets the stage for a more rigorous model parameter estimation procedure. Once a range of contraction coefficients was determined, we decided to see how using these coefficients would change the estimated flow through the Compensating Works in 2014 during May through November.

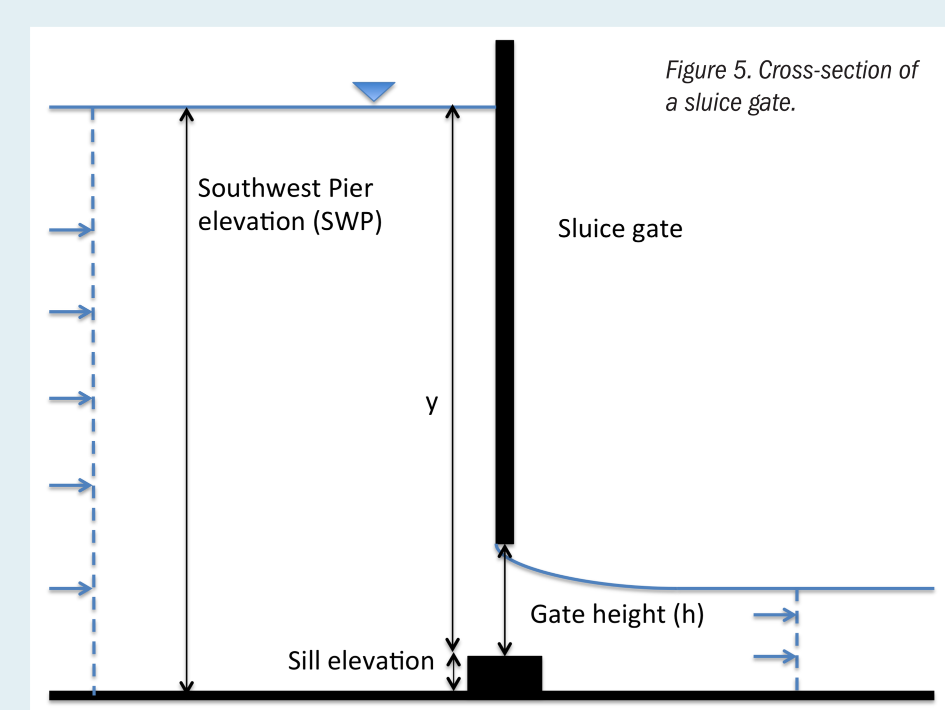

Figure 5. Cross-section of a sluice gate.

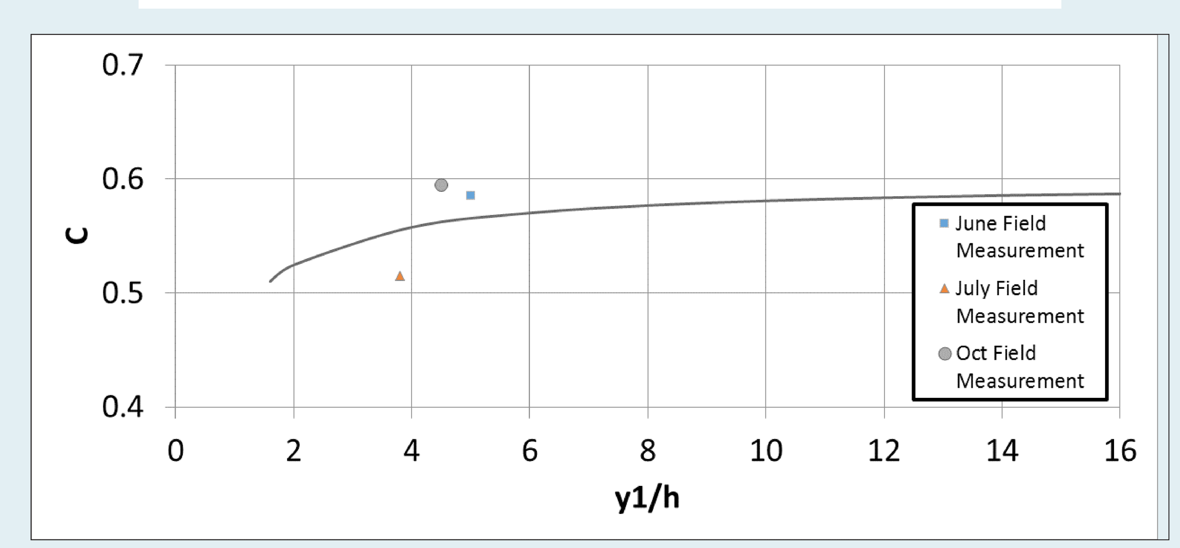

Figure 6. Discharge coefficient vs. y/h.

Results

In general, we find that using a contraction coefficient instead of the constant discharge coefficient improved the accuracy of modelled flow estimates for most of the points on the graph (Figure 7). The improvement varies between data points due to the combination of y/h values. However, in general we find it provides a better result for most of the data points. We have also concluded that the model does not provide accurate results for the "½ gate setting". This is most likely due to the fact that since the model simply relies on fixed values for both y and h, the flow will not change.

In lieu of a calibration we explored potential values of the contraction coefficient (Figure 7). First, using the proposed contraction coefficient model with a contraction coefficient range of 0.598-0.611, we find that the value does not fully encompass all of the variability in the observed data. We then used a broader, and higher range for the contraction coefficient of 0.64-0.74 based on a preliminary Bayesian statistical analysis. However, this range of values still did not provide a full explanation of the observed flow measurement variability.

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 resimulate historical flows for May through November of 2014. We applied the maximum and minimum values of the contraction coefficient range, graphing those along with the estimated flows that were used during the time period (Figure 8). Since the range for contraction coefficients is so large, it captures all of the estimated flows during the time period and for each gate setting, there is a large range of potential outflows that could be occurring through the compensating works.

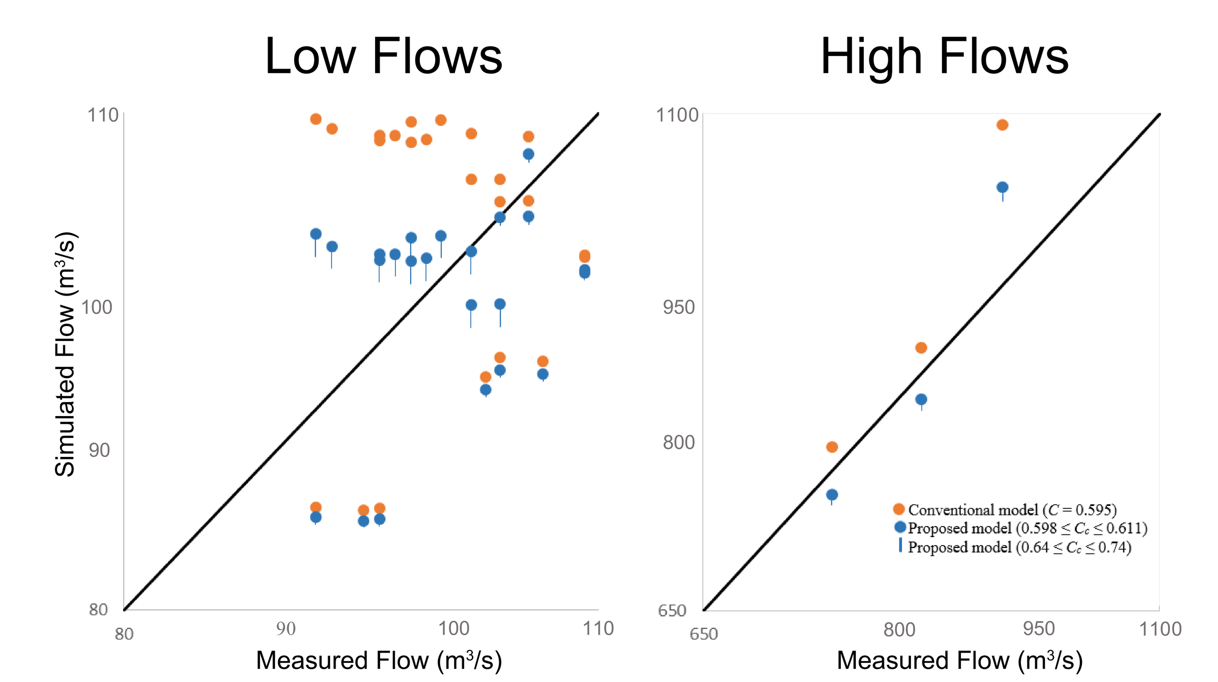

Figure 7. Measured flows vs. simulated flows using various discharge coefficients and contraction coefficients.

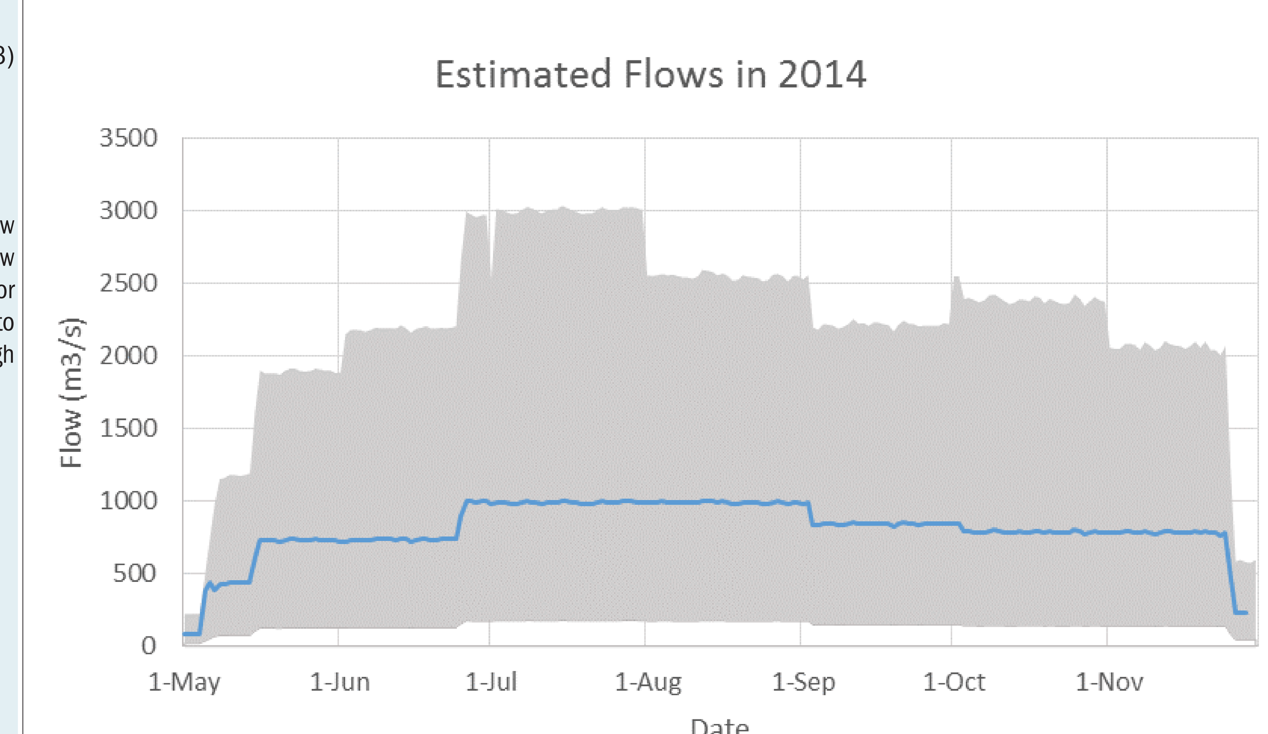

Figure 8. Maximum and minimum estimates for historical flows compared to the historical flow calculation.

Conclusions and Next Steps

We have determined that using the contraction coefficient refines simulated values of flow in comparison to the discharge coefficient, but the "½ gate" setting is not well simulated using this model. Also, the contraction coefficient and outflow vary linearly, creating 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

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