Multi-Agency Niagara River Short Term Forecasting Model

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Abstract

The Niagara River is the natural outlet of Lake Erie and drains four of the five Great lakes. The river is used to move commerce and is home to both sport fishing and tourism industries. It also provides nearly 5 million kilowatts of hydropower for approximately 3.9 million homes. Due to a complex international treaty, and the necessity of balancing water needs for an extensive tourism industry, the power entities operating on the river require detailed and accurate short-term river flow forecasts to maximize power output. A new forecast system was implemented that took advantage of several previously independent components including the NOAA Lake Erie operational Forecast System (LEOFS), a previously developed HEC-RAS model and input from the New York Power Authority and Ontario Power Generation. The Corps of Engineers updated the HEC-RAS model of the upper Niagara River to use the output forcing from LEOFS and a planned Grass Island Pool elevation provided by the power entities. The entire system is integrated at the NOAA Northeast River Forecast Center; it is run multiple times per day. The new model helps improve discharge forecasts by better accounting for dynamic conditions on Lake Erie.

This work focuses on choosing appropriate boundary conditions given the complexities of the system and the sensitivities of overlapping, real-time energy markets.

Introduction

The Great Lakes and the channels which connect them, contain approximately 20-percent of the world's supply of fresh water and provide numerous recreational and economic opportunities such as: commercial navigation providing over $18-billion annually to the region (Lre.usace.army.mil, 2019), commercial and sport fishing which generates over $5-billion annually (glerl.noaa.gov/education/ourLakes/Economy). The Niagara River is the natural outlet of Lake Erie and drains four of the five Great lakes. The river is used to move commerce (on the upper Niagara) and is home world class sport fishing and tourism industries. It also provides nearly 5 million kilowatts of hydropower for approximately 3.9 million homes. Due to a complex international treaty, and the necessity of balancing water needs for an extensive tourism industry, the power entities operating on the river require detailed and accurate short-term river flow forecasts to maximize power output.

A new forecast system was implemented that took advantage of several previously independent components including the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) Lake Erie Operational Forecast System (LEOFS), a previously developed HEC-RAS model and input from the New York Power Authority and Ontario Power Generation. The U.S. Army Corps of Engineers (USACE) updated the HEC-RAS (Hec.usace.army.mil, 2019), model of the upper Niagara River to use the output forcing from LEOFS and a planned Grass Island Pool elevation provided by the power entities. The entire system is integrated at the NOAA Northeast River Forecast Center; it is run multiple times per day.

The new model helps improve discharge forecasts by better accounting for dynamic conditions on Lake Erie. LEOFS captures seiche events on the lake that are often several meters of displacement from still water level. These seiche events translate into flow spikes HEC-RAS routes downstream. Knowledge of the peak arrival time and flood wave attenuation parameters helps improve operational decisions at the Grass Island Pool.

Model Development

Hydraulic Model

The HEC-RAS model for this project was based on a previous HEC-RAS model constructed by the USACE Buffalo District. That model is a steady state model with 117 cross sections, (figure 1) and limited information about bridge crossings. The model was used to help answer questions pertaining to general planning studies and did not require forecasted boundary conditions. The updates to original model are described below.

There are three bridges currently included in the model. All three bridges have low chord deck elevations that are unlikely to impact the flow in the river at any discharge but they are all resting on piers that obstruct the flow in the river. So instead of modeling the bridges using the bridges option they were modeled simply using the blocked obstruction option at two cross sections, one on the upstream face of the bridge and one on the downstream face of the bridges. The three bridges modeled this way were the International Railroad Bridge, the I-90 Bridge and the Peace Bridge. The stations and dimensions of the piers for I-90 Bridge and the Peace Bridge were estimated using Google Earth while the International Railroad Bridge data was included in the original model.

The Manning's n values for the model were set as 0.03 for all cross sections and then the seasonal roughness calibration tool was used in HEC-RAS version 5.0 to adjust them. The calibration section of this report has additional information.

The bathymetry used for the updated model consisted of a number of different sets of data and were all obtained from the USACE Buffalo District Office except for the TVGA survey of the Grass Island Pool for the New York Power Authority. These datasets consist of various resolutions, projections, datums and collection methods.

Once all the datasets were projected as needed, they were combined to create a Triangulated Irregular Network (TIN) surface that best represents the upper Niagara River to use with HEC-GeoRAS to update the existing cross sections from the model provided by the Buffalo District and also to add new cross sections where necessary.

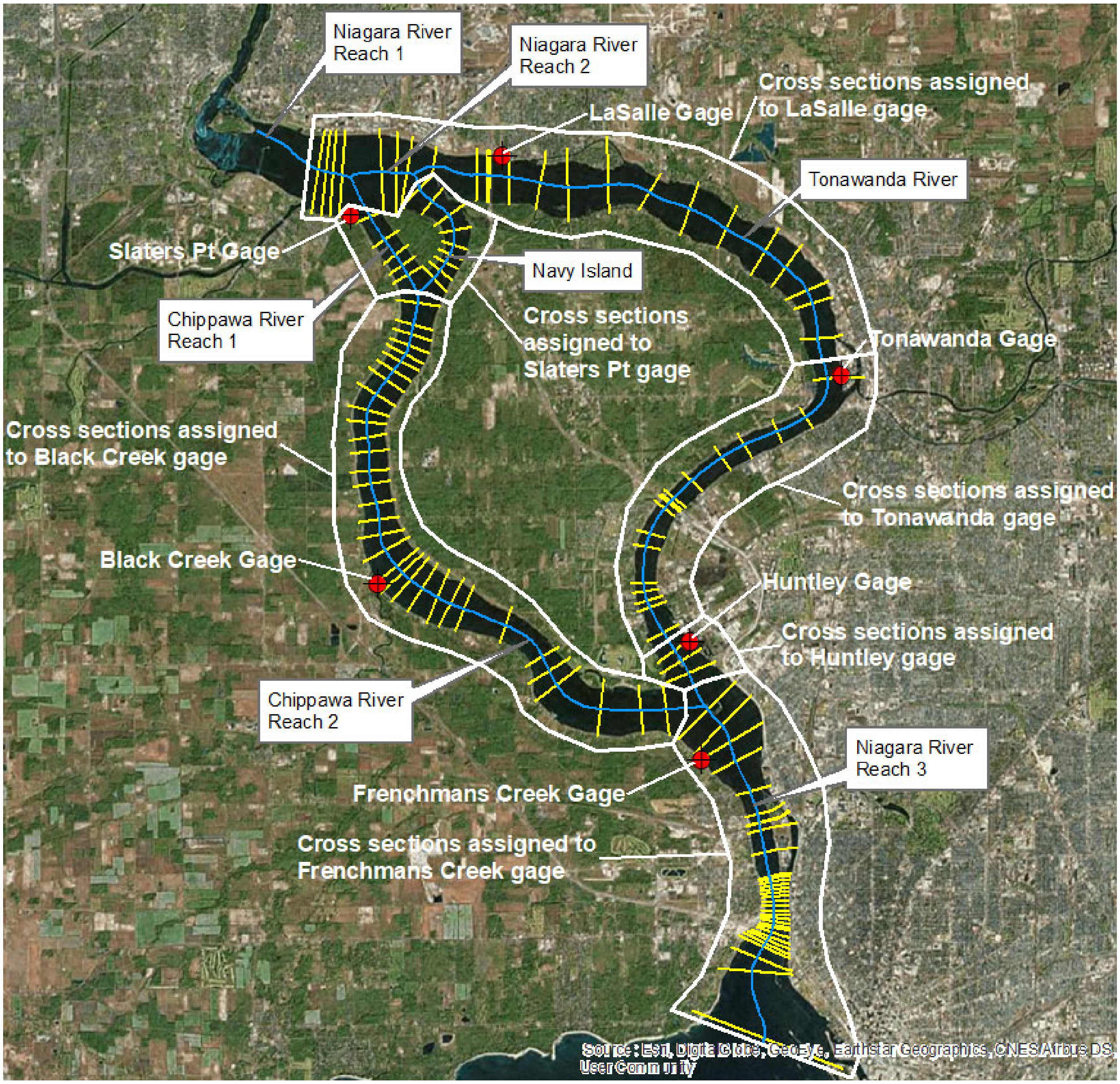

Figure 1. Map showing model layout, cross sections, gauge locations and automated calibration reach assignments

Calibration

Development of this model requires two sets of boundary conditions. One set for calibration, the other for operations. Both the upstream and downstream boundary conditions are straight forward for calibration. The boundary conditions for the operational forecast required more work.

Upstream Boundary Condition: The model currently extends from the outlet of Lake Erie downstream to the location of the Material Dock water level gage in the Grass Island Pool (GIP). During calibration, the upstream boundary condition is a flow time series based on the water level in Lake Erie. In order to calibrate the model the historic water level data at the

Buffalo water level gage was downloaded from the NOAA Tides and Currents website and converted to flow using the Buffalo rating equation shown below (U.S. Army Corps of Engineers, 2018).

$$Q = 643\ (Buffalo\ Water\ Level\ - 169.78)^{1.5}$$

For operational forecasting the upstream boundary condition is produced by LEOFS. LEOFS is a real-time, fully operational forecasting system built on the Finite Volume Community Ocean Model (FVCOM) (Chen, 2019) with roughly 6,000 nodes, 11,500 elements, 20 vertical layers, and grid sizes that vary in scale from 400m to 3.5km. Meteorological and hydrodynamic conditions are forecast every hour for each of these grids over a 120-hour forecast horizon with time increments of 60 minutes.

The authors evaluated water level simulations across a series of nodes near the outlet of Lake Erie, Figure 2, and isolated those that best represented what were believed to be actual water level fluctuations, using the nearby Buffalo, New York water level gaging station as a reference. Those nodes were then considered the best representation as the upstream boundary condition for the Niagara River HEC-RAS model in forecast mode.

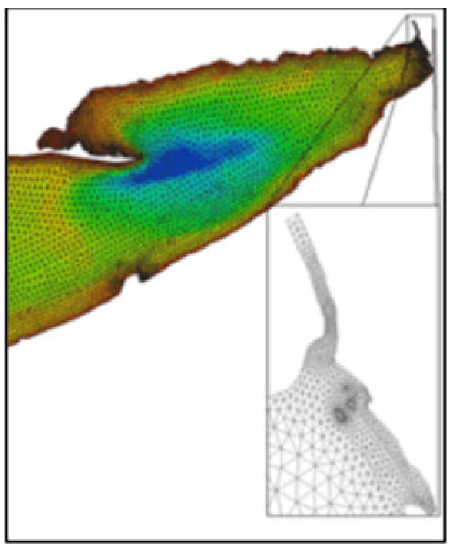

Figure 2. PLACEHOLDER GRAPHIC Detail of FVCOM grids within LEOFS in the eastern end of Lake Erie. Detailed insert shows grids in the transition between the Lake Erie outlet and the upstream section of the Niagara River

Downstream Boundary for Calibration:

The downstream boundary condition is a water level time series from the power entities' Material Dock water level gage for calibration. This gauge implicitly captures all of the operations affecting the water level in the GIP and makes it unnecessary to know the hourly operations affecting the pool.

The forecasting downstream boundary is complex and required extensive testing and sensitivity analysis to determine an appropriate amount of simplification. One of the complicating factors is the requirement for the boundary condition to be forecasted out several days. The following four boundary conditions were reviewed to determine accuracy and suitability.

1. The long term average monthly water level of the GIP
2. The estimated water level in the GIP computed by the Niagara River Control Center (NRCC) after all hydropower diversions and treaty regulated flows over Niagara Falls (referred to as the "Plan")
3. Normal depth
4. Using the Rules function in HEC-RAS to set the flow out of the model using information on the NRCC gated control structure, date, time of day and the amount of water withdrawn for hydropower usage

The ideal downstream boundary condition would be the fourth option which would extend the existing model past the GIP downstream to Niagara Falls. The Rules option would be coded to include frequent updates to flows through the River Control Structure gates and the combined flow diverted to the U.S. and Canadian hydropower plants. Due to the competing electrical markets, these forecasted operational flow data are sensitive and steps must be taken to ensure each hydropower entity's forecast is not made available to the other. Thus, this boundary condition was not considered for the real-time operational forecast model. However, for the purposes of calibration, the actual water level of the GIP were used as the boundary condition. This implicitly captures all of the complexity of the operations in the GIP.

There are six water level gages throughout the model domain that were used for calibration purposes. Figure 1 shows the locations of the gages. The Manning's n values were calibrated on a monthly basis using the automated roughness calibration tool now available in HEC-RAS version 5.0.1. All Manning's n values in the channel were set to a standard value of 0.03 in the geometry file and the seasonal roughness factors option was used to let HEC-RAS change the channel Manning's n value by month.

The automated roughness calibration tool works by assigning ranges of cross sections to an observed water level gage and then letting HEC-RAS vary the Manning's n value for the cross sections to match as close as possible the observed water level data at the gage. Figure 1 shows how the cross sections were assigned to the water level gages.

The model was run for each month and year in which gage data was available. Table 1 lists the available data by gage.

Table 1. Gage data available for calibration

Gage Name	Start Date	End Date
Frenchmans Creek	01 December 2003	18 June 2013
Huntley	12 February 2004	25 June 2012
Tonawanda	14 January 2004	23 June 2013
LaSalle	01 December 2003	19 June 2013
Black Creek	01 December 2003	18 June 2013
Slaters Point	01 December 2003	19 June 2013

The model was calibrated for the months of April to November. Although HEC-RAS has some ice modeling capabilities there are no relationships developed between ice cover/thickness and gage data for the Niagara River so the seasonal roughness values for December were set to be the same as November and the values for January to March were the averages between the November and April values.

Calibration Methodology

The model was run for the each month between April and November for the years of gage data available. Then the absolute differences between the model values and the gage values were calculated and averaged for each calibration month of each year. The results for each year were then reviewed against the following criteria:

1. The best calibration (lowest average departures between model and measured) for the Slaters Point and LaSalle gages since they are the closest gages to the GIP
2. The best overall calibration, defined by minimum average difference between model elevation and gage elevation, equation 1.

$$\min(average\ (modeled - measured)) \quad (1)$$

For example, Figure 3 shows the results for each April for the calibration years. As shown on the figure, the year 2004 had very low average errors for Slaters Point and LaSalle and also had the lowest difference between the six gages.

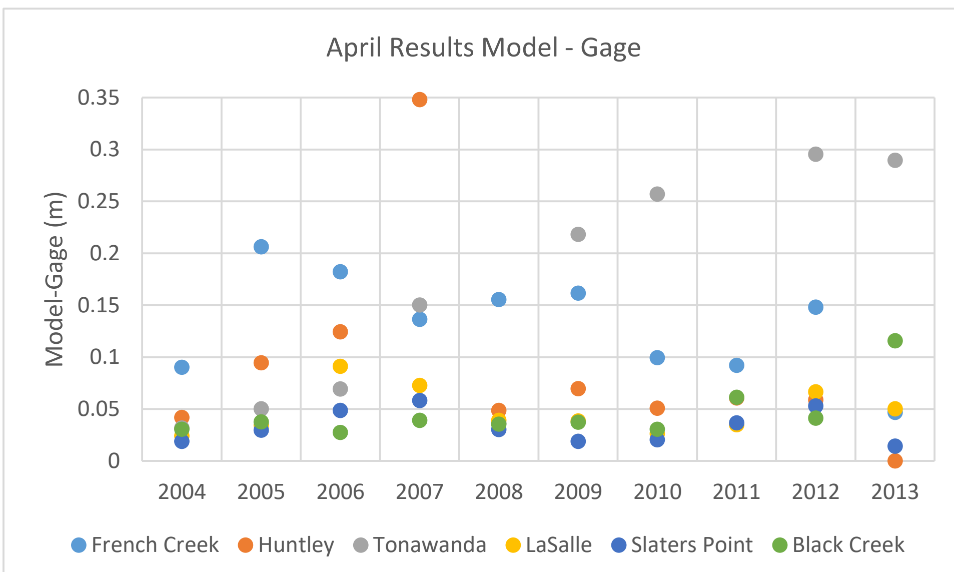

Figure 3. Calibration results for each April at all gauge locations

Based on the results above, the roughness factors calculated by HEC-RAS for April 2004 were set to be the seasonal roughness factor for April. Figures 4 through 9 show the results of using the April 2004 values at the six gages.

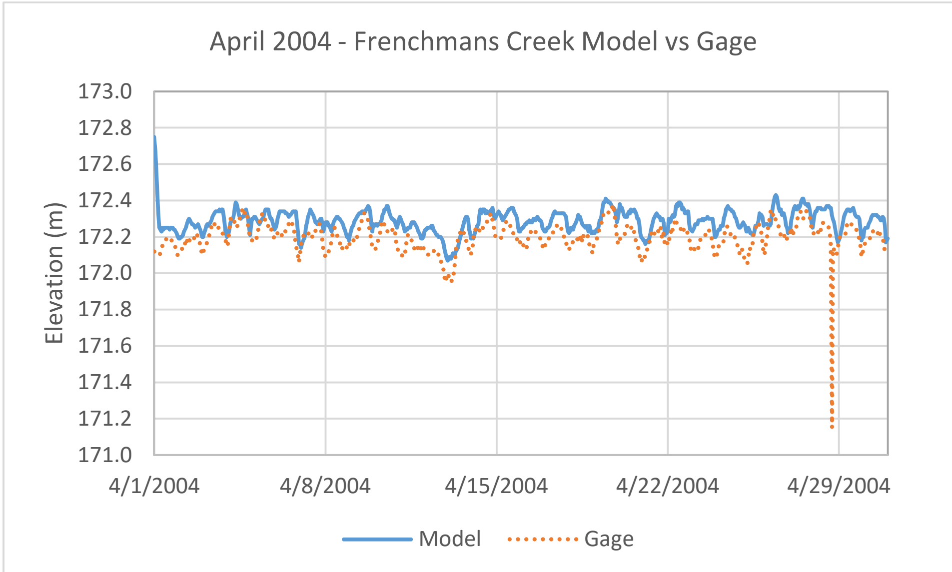

Figure 4. April 2004 Model Results vs Gage at the Frenchmans Creek Gage

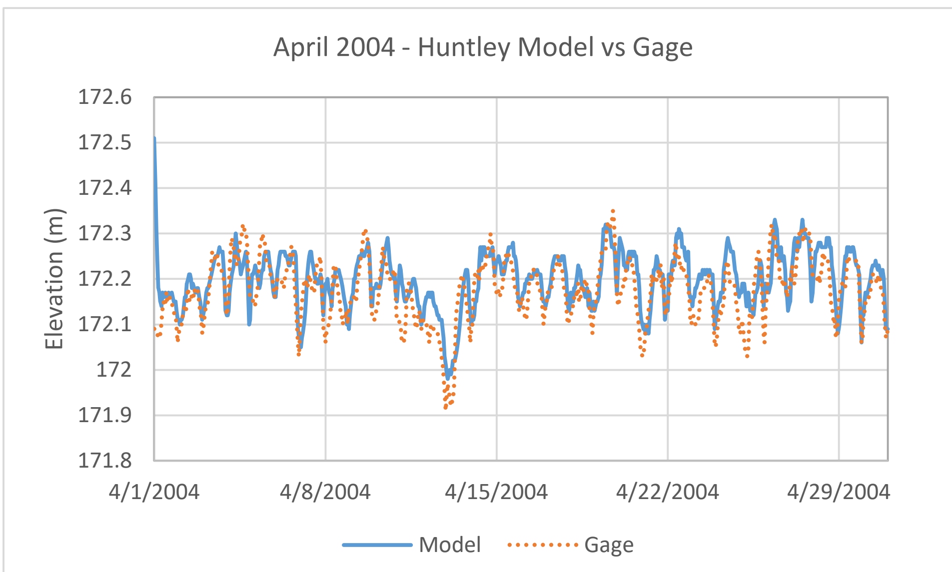

Figure 5. April 2004 Model Results vs Gage at the Huntley Gage

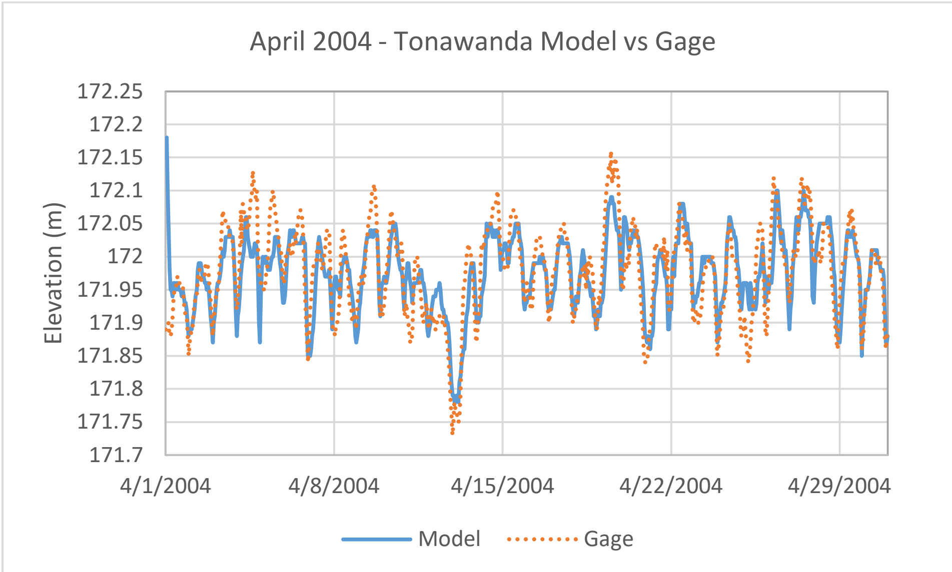

Figure 6. April 2004 Model Results vs Gage at the Tonawanda Gage

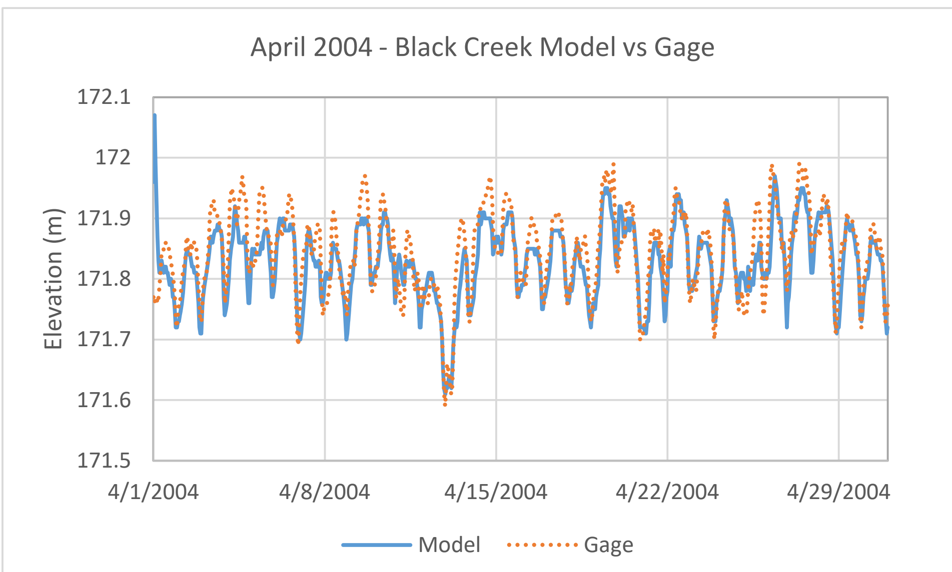

Figure 7. April 2004 Model Results vs Gage at the Black Creek Gage

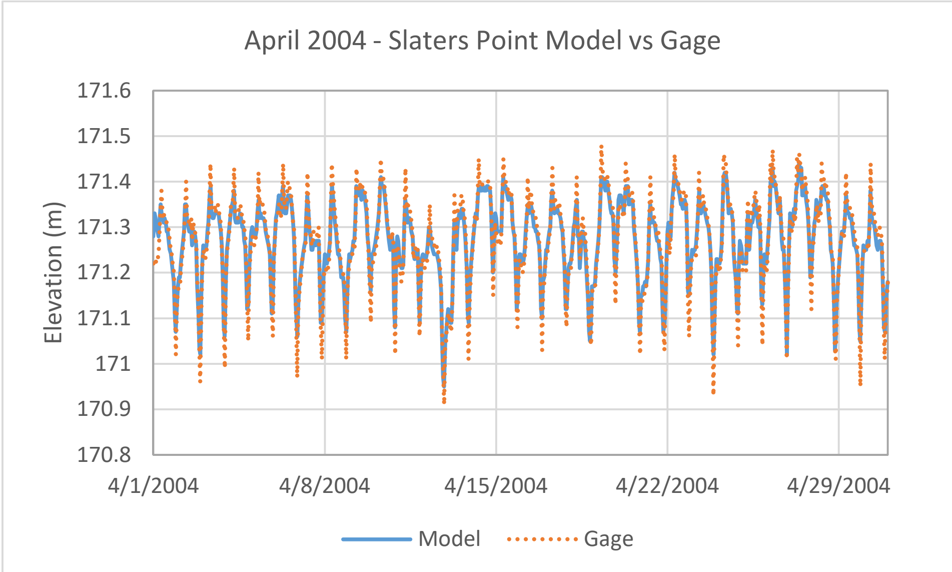

Figure 8. April 2004 Model Results vs Gage at the Slaters Point Gage

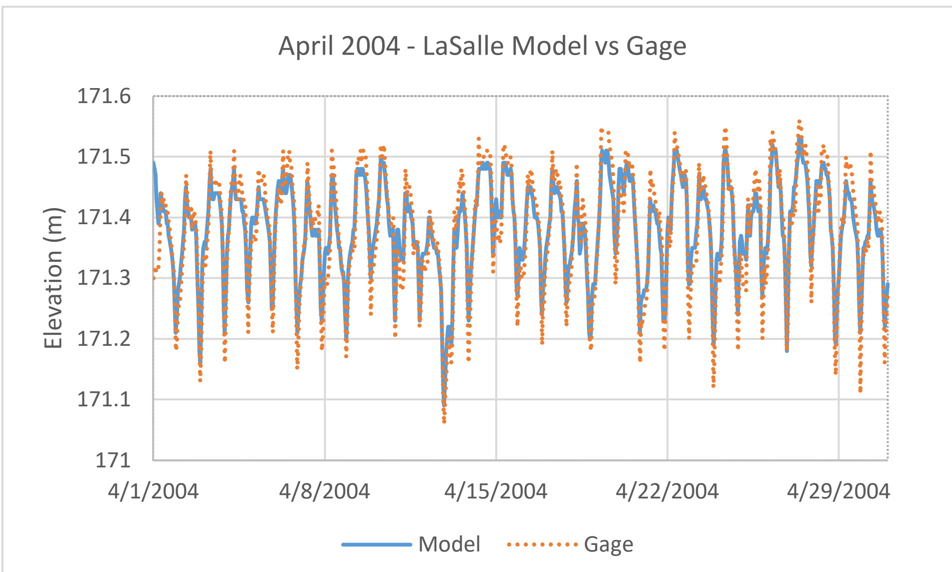

Figure 9. April 2004 Model Results vs Gage at the LaSalle Gage

The same methodology was used to determine the roughness factors for the months of May through November.

Forecasted Downstream Boundary

Long Term Average:

The long-term monthly average of the water level as reported at the Material Dock gage was considered as a static downstream boundary. While this boundary condition is easily forecastable it does not provide any temporal information about hydropower operations and is too simplistic for the purpose of forecasting discharge on the Niagara River.

The Plan:

The River Control Center develops estimates of GIP water levels at hourly resolution for an entire year. Each 24 hour period has the same cycle of water levels and the cycle changes each month. Using the GIP Plan as the downstream boundary condition has the advantage of a temporally varying boundary condition that can be reasonably well forecasted to coincide with the forecasted inflows at the upstream end of the model. Deviations are expected and at times are significant but the Plan has the advantage of informing the HEC-RAS model with a more likely, independent, temporally varying downstream boundary condition.

Normal Depth:

HEC-RAS can also use normal depth as a downstream boundary condition with a user specified slope. Normal depth occurs when the bottom slope of the river matches the slope of the water surface profile. While the normal depth boundary condition is best applied to sections with uniform flow, it is frequently applied to natural systems such as the Upper Niagara. Applying normal depth as the downstream boundary on the Niagara River does allow for a temporally varying boundary condition but only insofar as normal depth is a function of discharge and the discharge varies temporally. The probability of the water surface slope matching the bottom slope, especially during a flood wave associated with a seiche, is low. Normal depth also makes no attempt to capture the effects of independent, temporally varying hydropower operations.

Comparison of the Boundary Conditions:

The model was also run using the Material Dock water level gauge as the downstream boundary. For this modeling exercise, these flows were considered most representative of the actual flows entering the Grass Island Pool. Each of the three viable downstream boundary conditions for forecast operations were evaluated against model runs with Material Dock as the downstream boundary. Figures 10 through 12 show the model calculated flows at the upstream end of the GIP for April, July and November 2015.

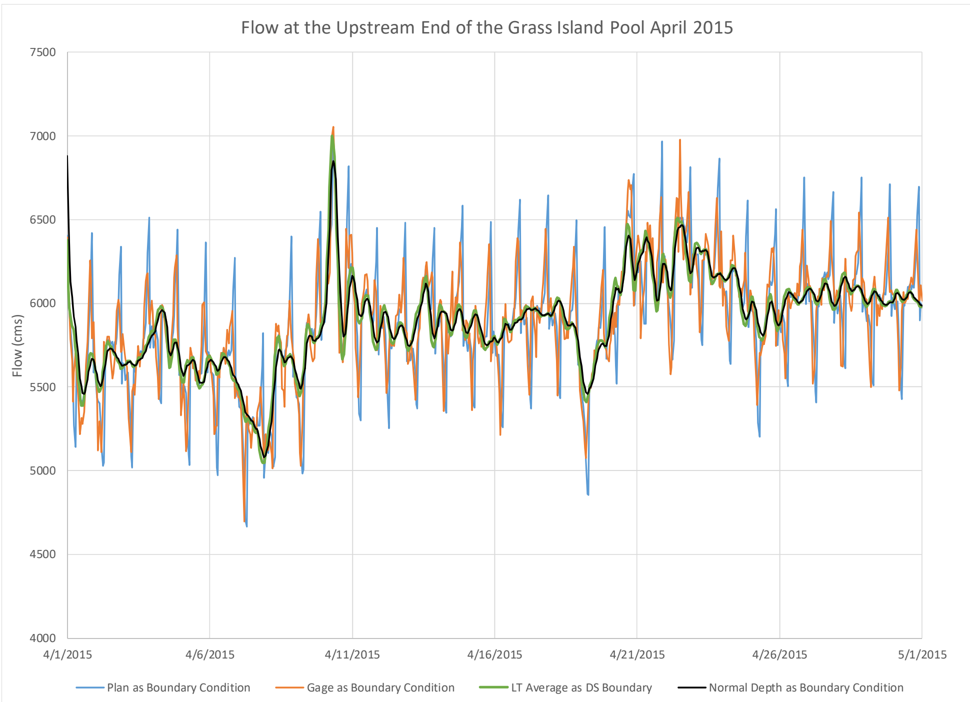

Figure 10. Modeled Flow at the Upstream End of the GIP April 2015 for 3 Boundary Conditions and the Material Dock Gage Data

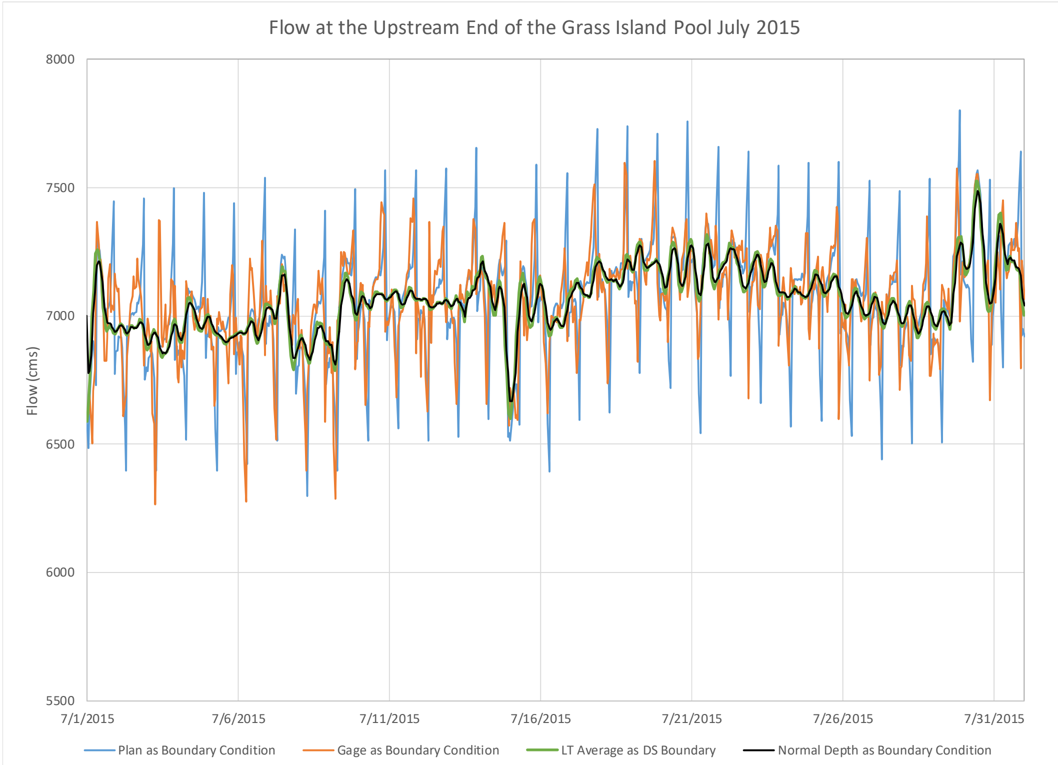

Figure 11. Modeled Flow at the Upstream End of the GIP July 2015 for 3 Boundary Conditions and the Material Dock Gage Data

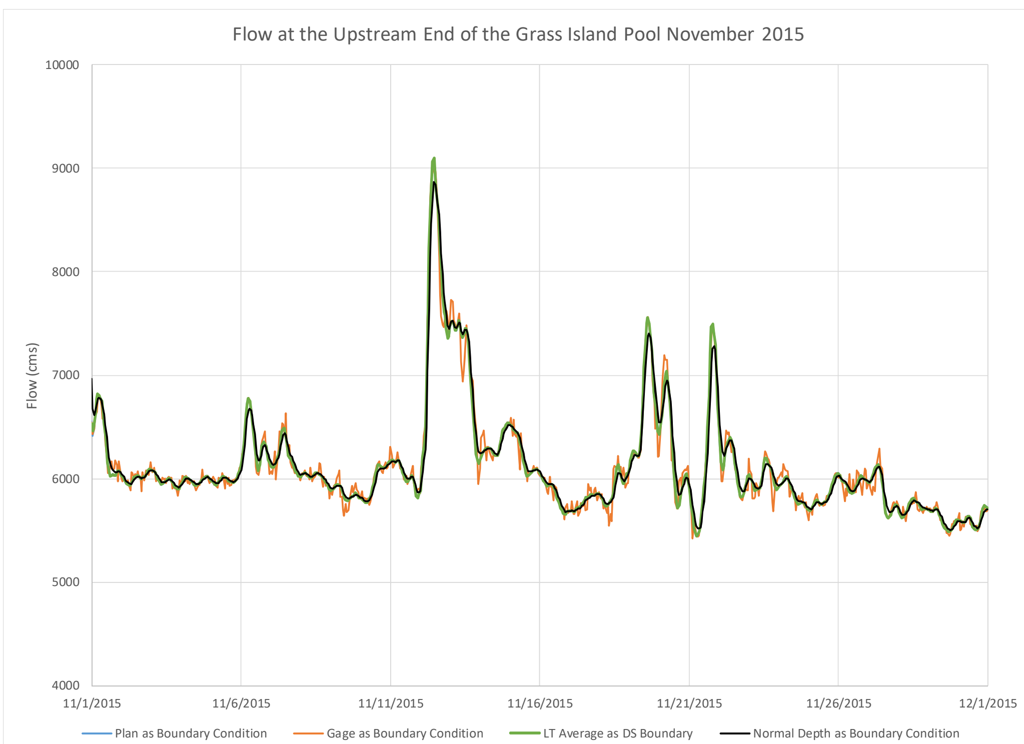

Figure 12. Modeled Flow at the Upstream End of the GIP November 2015 for 3 Boundary Conditions and the Material Dock Gage Data

The results for the two tourist season months (April and July) show that modeled discharges consistently underestimate peak flow and underestimates low flow when compared to modeled output using actual gauge data for the downstream boundary condition. The same is true when compared to modeled results with the long term average GIP as the downstream boundary condition. The results for the non-tourist season month (November) also show that modeled discharges underestimate peak flow for both the Plan and the long term average but to a lesser extent when compared to the tourist season. Using normal depth as the downstream boundary provides the smallest estimate of discharge into the GIP when compared to models with alternative downstream boundary conditions.

Recommendations

Based on the sensitivity analyses performed, it is the authors recommendation to use the Plan as the downstream boundary condition. Using the Plan adds a temporal variation component in the downstream boundary conditions. It enables the model to capture the cyclic nature of flow associated with regular hydropower operation, although it regularly under-predicts the high and low flow; it does, however, perform well under seiche events on Lake Erie, provided the LEOFS is forced with accurate meteorology.

The Niagara River HEC-RAS forecast model continues evaluation and improvement; the current version continues evaluation in operational mode at the National Weather Service, Northeast River Forecast Center. Forecasts are currently shared with the Niagara River Control Center and provide another tool to help regulate the water level in the Grass Island Pool at the head of Niagara Falls. Upon completion of model development, validation and implementation, results will be publically available.

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