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Rainy River 2D Hydrodynamic Modelling Study – Phase II

Controlled Technical Report

CHC-CTR-127

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Executive Summary

The National Research Council – Canadian Hydraulics Centre (NRC-CHC) has prepared this report for the International Joint Commission (IJC) as part of the ongoing study examining Rainy Lake and the upper Rainy River, including the assessment of conveyance of the river reach from Rainy Lake to the dam structures at Fort Frances / International Falls, and is a continuation of the study conducted by NRC-CHC in 2009/2010 (Phase I). Phase I involved the development of a series of hydrodynamic models to examine the conveyance of the upper Rainy River and Rainy Lake, perform dynamic simulations of several flood years and to examine the state of nature condition of the upper Rainy River. Review of the Phase I findings identified a number of questions relating to the model and the upper Rainy River that required further investigation primarily relating to variable powerhouse performance, sensitivity of the hydrodynamic model, and simulations of the 1950 flood event. This report constitutes the results of those investigations.

The first area of investigation was to examine the effects of different gate configurations on the water levels in the lake in order to determine if past flooding could have been mitigated if some gates had been opened earlier. The results showed that at moderate to high flow rates, the increase in outflow associated with additional gate opening is limited by the lake level. Opening most or all of the gates only results in additional outflow when the lake level is relatively high.

The next investigation looked at the ability of the model to represent past flood events to determine if the model could accurately represent dynamic inflows and gate operations. Four historic flood events were simulated: the largest flood event on record which occurred in 1950, as well as three more recent events occurring in 2002, 2005 and 2008. The model performed reasonably well, slightly underestimating peak lake levels in all four cases, with a maximum error in peak levels of 0.04 m.

The potential influence of variable powerhouse performance on the conveyance curves developed in the previous study was examined. Historical operational data showed a reduction in performance of the two powerhouses of approximately 15% from lower total outflows ($400 \text{ m}^3/\text{s}$) to the highest total flows ($1200 \text{ m}^3/\text{s}$). The first approach taken to quantify was to determine the relationship between headwater and powerhouse performance, but the relationship was not as strong as anticipated. A second approach was examined modeling powerhouse performance as a function of total lake outflow. The relationship based on total outflow more closely matched observed results and provided a more

conservative set of conveyance curves, but it failed to provide a physical cause for the reduced powerhouse performance.

The influence of changes to bathymetry at key locations in the upper Rainy River on lake levels was examined in order to determine the effects a dredging or similar effort could have on conveyance within the system. It was determined that bathymetric adjustments at Ranier Rapids would show the greatest benefit, with a lake level drop of approximately 0.18 m with a 1 m reduction in local bathymetry.

The final section of the report was conducted to determine the sensitivity of the State of Nature model. First, the roughness sensitivity was determined by systematically adjusting the roughness in the model up and down by 10% of the prescribed values. The results showed that the state of nature rating curve is not very sensitive to changes in the roughness. Finally, the sensitivity of the state of nature model to changes in local bathymetry was analyzed by adjusting the bathymetry at three key locations along the river up and down by 1 m. It was determined that Koochiching falls shows the highest sensitivity to changes in bathymetry for the state of nature model.

A number of recommendations are provided, including a further investigation into powerhouse performance prediction and the potential benefits of increased powerhouse performance on power generation and lake levels. Additionally questions were raised about the much higher conveyance observed in 1950 period, which could potentially be answered with further investigations into the data and operations for that period.

Acknowledgements

The authors would like to acknowledge the assistance of Rick Cousins and Matt DeWolfe of Environment Canada (EC) / Lake of the Woods Control Board (LWCB) who provided valuable background information on Rainy Lake, state of nature data and information on powerhouse and sluice gate operations. Also the assistance of Martin Serrer, Stephanie Piche and Nicolas Sgro in data and model preparation and analysis was greatly appreciated. The members of the IJC International Rainy Lake and Rainy River boards were also very helpful in their feedback, particularly as the work bridged from Phase I to Phase II, and their contributions positively influenced this second phase of investigation.

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List of Acronyms

CGVD28	Canadian Geodetic Vertical Datum 28
CHS	Canadian Hydrometric Service
DFO	Department of Fisheries and Oceans, Canada
EC	Environment Canada
EDC	Elevation Duration Curve
FDC	Flow Duration Curve
GPS	Global Positioning System
HEC-RAS	Hydrologic Engineering Center - River Analysis System
IF/FF	International Falls / Fort Frances
IJC	International Joint Commission
IRLBC	International Rainy Lake Board of Control
IRRWPB	International Rain River Water Pollution Board
LWCB	Lake of the Woods Control Board
NRC-CHC	National Research Council – Canadian Hydraulics Centre
QA/QC	Quality Assurance / Quality Control
SL	Surface Level
USACE	United States Army Corps of Engineers
USC&GS 1912	United States Coast and Geodetic Survey 1912
USGS	United States Geological Survey
UTM	Universal Transverse Mercator

1 Introduction

The National Research Council (NRC-CHC) has prepared this report for the International Joint Commission (IJC) as part of the ongoing study examining Rainy Lake and the upper Rainy River, including the assessment of conveyance of the river reach from Rainy Lake to the dam structures at Fort Frances / International Falls.

This phase of the investigation is a continuation of an ongoing study that was commenced by NRC-CHC in 2009/2010 (Phase I) [10]. In the first phase of this study a series of two-dimensional hydrodynamic models were developed for the Rainy Lake / Rainy River system upstream of the dam at International Fall / Fort Frances. These models were calibrated and validated to sets of observed near steady-state flow conditions, and then applied to a series of steady-state and dynamic flooding scenarios. The first phase of the study also examined the state of nature condition of the upper Rainy River employing bathymetric data obtained from previous studies conducted in association with the IJC [11]. The state of nature model was employed to generate a lake level-discharge rating curve. Compared to previous estimates of the same curve [11], the modeled curve was similar at low flows but estimated lower lake levels at high flows. This extension of the study, Phase II, examines in more detail some further issues identified by IJC and the Rainy Boards including questions relating to turbine performance, communication with stakeholders, model sensitivity and the simulation of the 1950 flood event.

1.1 Background

The Rainy River Basin is a watershed upstream of Lake of the Woods which straddles the border between Canada (Ontario) and the United States (Minnesota). A map of the location of the study site is shown in Figure 1.

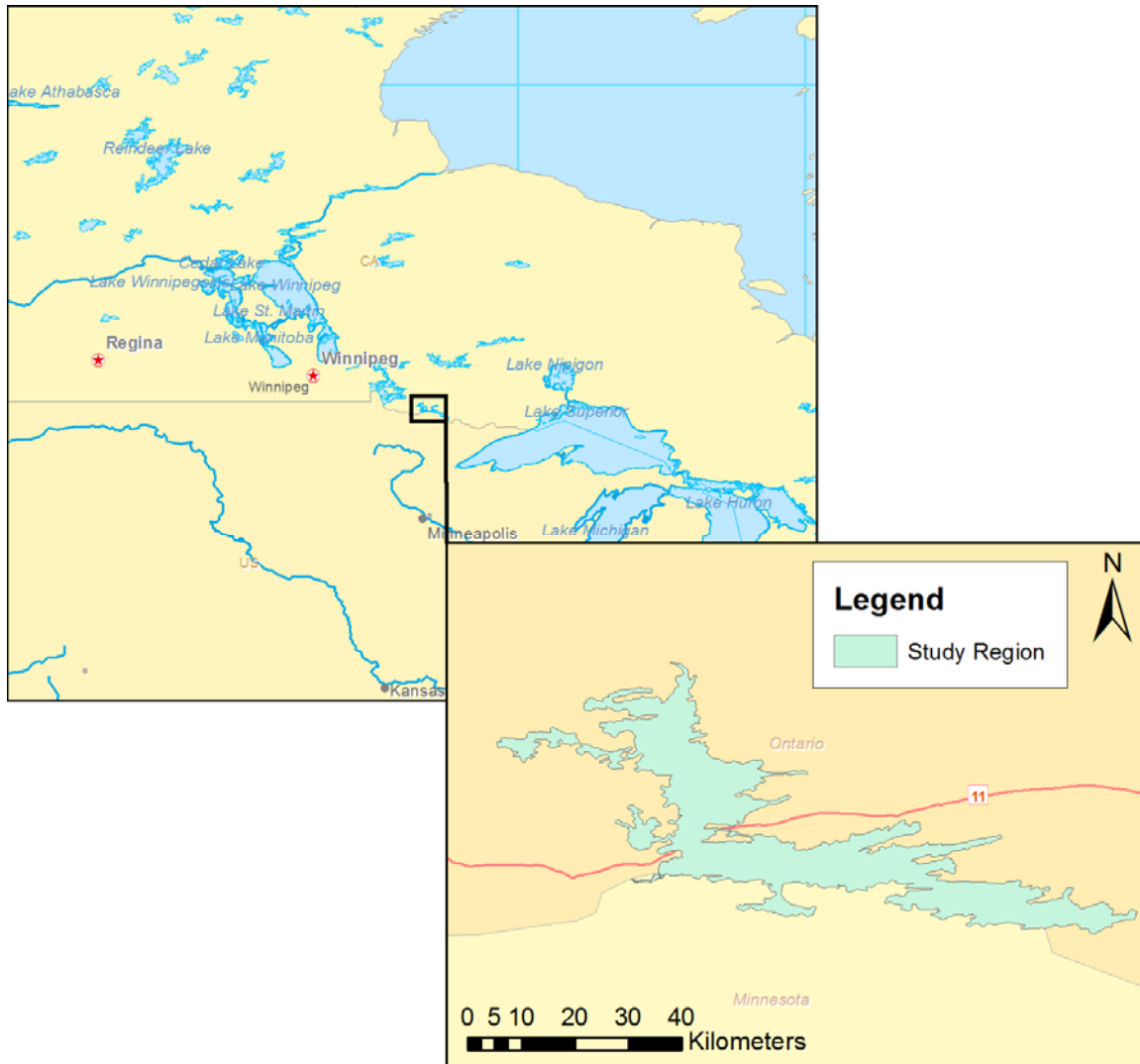


Figure 1 - Study Site Location - Rainy Lake

The Rainy River Basin is a shared resource between these jurisdictions and the Native Peoples for hydropower generation, water supply, navigation, recreation and tourism [6]. Of particular interest are the hydropower generation stations located at International Falls/Fort Frances (IF/FF) downstream of Rainy Lake which have an impact on lake water levels and downstream flow rates, both of interest to local stakeholders. The IJC established two boards, the International Rainy River Water Pollution Board (IRRWPB) and the International Rainy Lake Board of Control (IRLBC) with the responsibilities of supervising water quality in the Rainy River and supervising water levels in Rainy Lake, respectively.

The Rainy Lake elevation has been regulated since 1909 when the dam construction was finished at IF/FF. Rainy Lake has a surface area of approximately 92 000 ha, a mean depth of 9.9 m, a maximum

depth of 49.1 m and 42% of the lake area is littoral, or less than approximately 15 ft (4.6 m) deep [2]. Since lake level records began in 1911 the lake has had a mean elevation of approximately 337.3 m and tends to vary annually by 1.2 m on average from a mean low of 336.7 m to a mean high of 337.9 m. The highest recorded water height was 339.2 m in the summer of 1950, the year with the highest recorded flow volume from Rainy River, and the historical low level was in the spring of 1923 at 335.7 m. High lake levels have been recorded again recently with higher than average water levels recorded in 2001 (338.2 m) and 2002 (338.6 m) [3]. The average precipitation in the Rainy River district is approximately 700 mm/year; however from 1990 to 2004 most years (73%) received in excess of this amount. During calendar year 2001 areas in the Rainy Lake region received over 1000 mm of precipitation, the highest precipitations on record at some weather stations [4]. 2002 was also a wet year with 930 mm falling, but of particular interest was an intense multi-day storm in June in which over 300 mm of precipitation was recorded (Mine Centre weather station) [4] causing the very high levels in Rainy Lake mentioned above [7].

Water levels in Rainy Lake are also artificially influenced by the upstream reservoir control at Namakan Lake. Namakan Lake is located to the south east of Rainy Lake and has an area of 10 000 ha, but a number of other connected lakes increase the total lake area to approximately 26 000 ha. These connected lakes are referred to as the “Namakan Chain” of Lakes.

1.2 Phase I Study and Findings

The results of the Phase I findings were presented in the NRC-CHC report CHC-CTR-112 and presented to the Rainy River Boards and the IJC in 2010 [10]. This first phase of examination of the conveyance of the Rainy River involved the development of a series of hydrodynamic computer models to simulate the upper Rainy River from the dam near Koochiching Falls (Fort Frances, ON and International Falls, MN) upstream to include the Rainy Lake. The models were designed to simulate steady-state conditions, dynamic conditions including the whole of Rainy Lake, and steady-state conditions considering a state-of-nature bathymetry.

Historical water level data were available for the Rainy Lake as well as the powerhouse forebay levels, or the water levels just upstream of the powerhouse intakes. The numerical models were calibrated to existing lake and powerhouse forebay level measurements and then validated against independent period in both steady-state and dynamic flow situations. The model also represented flow through the two powerhouses at the dam as well as the 15 gates used to bypass flow. The models

showed a good capability to match lake levels in both dynamic and steady-state simulations, and also showed the flexibility to dynamically change gate configurations to match historical operational history.

The conveyance analysis conducted in Phase I indicated that there are three areas of flow constriction in the upper Rainy River: at the Rainer Rapids beneath the rail bridge, at the second narrows at Pithers Point and at the historical rapids at Koochiching Falls near the international bridge upstream of the dam. These locations along with the gate and powerhouse positions are presented in Figure 2.

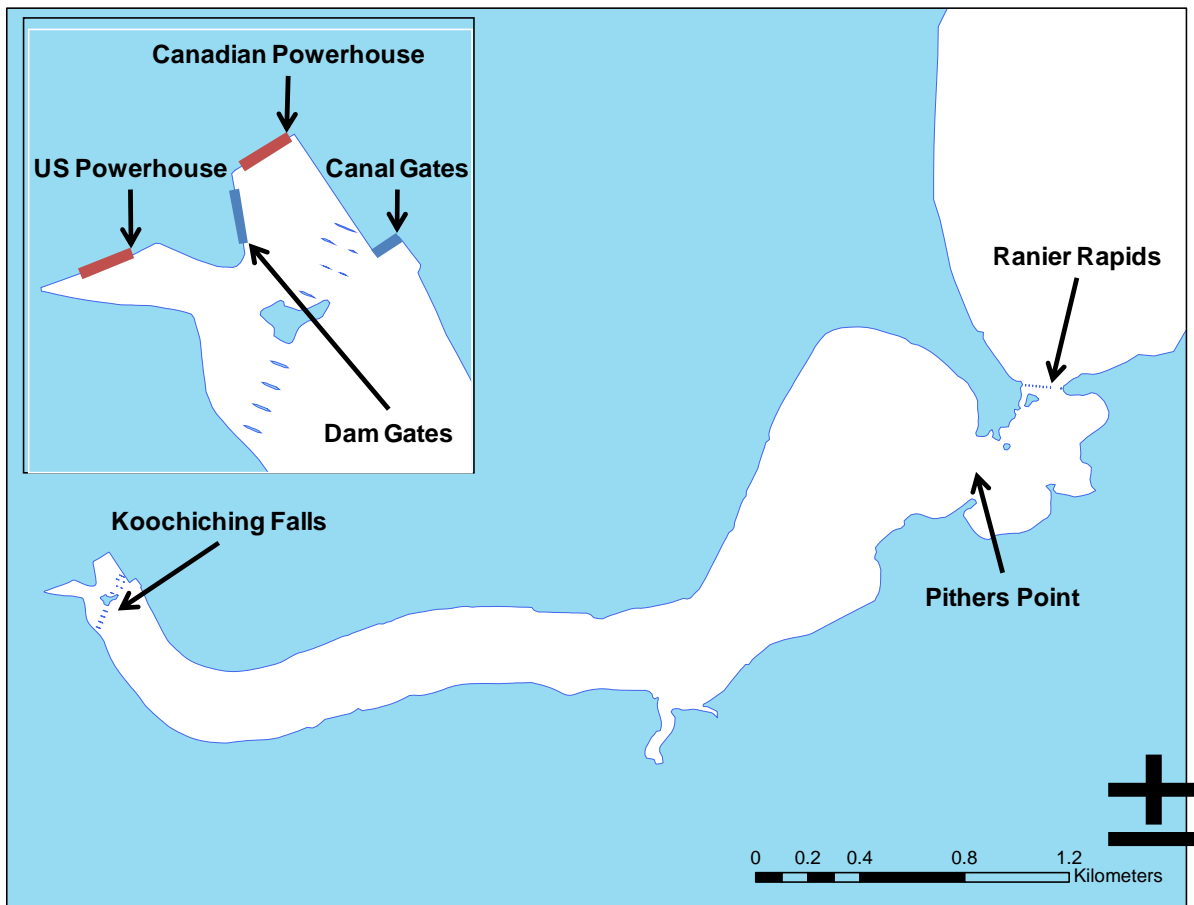


Figure 2 - Map of Key Locations in Upper Rainy River

It was observed during flow simulations that under certain flow conditions hydraulic performance could not be improved by opening gates beyond a certain number, because of the hydraulic controls observed upstream. Indeed, in the simulations opening all gates tended to lower water levels

substantially in the Canadian forebay often with little improvement in overall conveyance, a phenomenon that has been observed in reality.

The state of nature model was developed primarily to reproduce or evaluate historical rating curves relating flow to lake levels under natural conditions. The state of nature model produced similar results previous rating curves at lower flows, but suggested lower lake levels at higher flows than previously predicted. The modelled state of nature conveyance was compared with the modelled current rating curve with the dam in place. It was found that the changes in bathymetry and the addition of the canal bypass in the current state provide substantially higher conveyance over the state of nature condition.

1.3 Phase II Scope and Objectives

Review of the Phase I findings identified a number of questions relating to the hydrodynamic model and the upper Rainy River that required further investigation. Primarily, issues were raised with the overall sensitivity of the models to changes in input data, the performance of the turbines under different flow conditions, and a means by which the Phase I conveyance findings could be elaborated and the results communicated clearly to stakeholders. Phase II of the Rainy River modeling study was comprised of 6 specific investigations that addressed these issues, which are described below:

1. Gate Operation Scenarios

This investigation examined the operation of the hydrodynamic model with different dam operation configurations during historical high flow conditions. The objective of this investigation was to provide a response to queries of residents whether the dam gates should have been opened earlier during some previous events and if that would have mitigated flooding. Initially five scenarios were anticipated but many more than this were run to perform the analysis. The results of this investigation are outlined in Section 2.

2. Gate Operation Scenarios – Graphical Animation / Visualization

To facilitate communications with residents and stakeholders, a graphical animation or visualization product was requested to illustrate the gate operation scenarios presented in the first investigation. Section 3 outlines the development of this communication product.

3. Simulation of 1950 Flood

The 1950 flood event represents the largest flood of Rainy Lake on record. This investigation included enhancements to the hydrodynamic model and additional simulation setup to replicate the 1950 flood event. This required the collection and interpretation of data available at the time of the event, changes to the model boundary conditions, bathymetry, powerhouse turbine operation and additional simulations to attempt to match the observed flow and level conditions during that event. The results of this investigation are described in Section 4.

4. Powerhouse Performance Impacts

Variable powerhouse performance was not considered in Phase I of this study, although it was suspected that under certain flow conditions the two powerhouses would carry flows below their capacity – particularly with low headwater levels. This investigation examined the potential impacts of degraded turbine performance on the conveyance curves developed in the previous study. The existing turbine operational history was examined along with forebay and tail water (water levels downstream of the dam structure) elevation data to devise performance relationships. Additionally, a number of simulations were re-run at key flows to examine the impact reduced turbine performance would have on total conveyance. Section 5 outlines the results of this investigation.

5. Bathymetric Sensitivity

This section of the study investigated the hydrodynamic model's sensitivity to local changes in bathymetry at the key control at Ranier Rapids. This investigation was originally prescribed to include the adjustment to the bathymetry of the calibrated model in and around the hydraulic control near Ranier Rapids, but was expanded to look at the influences of bathymetric changes at Pithers Point and the Koochiching Falls as well. The general purpose of this investigation was to examine the effects dredging or similar efforts could have on conveyance within the system. The results of this investigation are presented in Section 6.

6. Sensitivity in State of Nature Rating Curve

This investigation was initiated to determine the sensitivity of the State of Nature model to changes in bathymetry and to roughness in the model. For this investigation the state of nature model was modified with perturbations in the model roughness and local bathymetric changes at the three key

hydraulically significant locations: Rainier Rapids, Pithers Point and the Koochiching Falls. The results of this investigation are presented in Section 7.

2 Gate Operation Scenarios

Phase I of this study involved the development of a 2D hydrodynamic model that represented the Rainy River upstream of the International Falls dam, including a complete representation of the two powerhouses, the gate operation and the complex flow environments around the narrows at Rainer Rapids and the Koochiching Falls. This model was successfully constructed and validated in that study, both using steady-state and dynamic scenarios. The extension of that analysis for this phase of the investigation included a complete characterization of the flow-lake level relationships, for each of the gate operation scenarios.

This complete characterization involved running the calibrated model over a complete range of possible flow and gate operation scenarios and developing performance curves for each executed scenario. The model employed in this study was the current condition upper Rainy River model. That is, it included bathymetry from the 2009 bathymetric survey conducted by environment Canada and included only a small portion of Rainy Lake approximately 4 km upstream of the Rainer Rapids. For these model runs the flows at the powerhouses were set at their prescribed maximum (250 m³/s for the US powerhouse and 150 m³/s for the Canadian Powerhouse) and the balance of flow was carried through the canal and dam gates as prescribed by the individual rating curves. In Phase I, flow rates for these analyses ranged from 400 m³/s to 1500 m³/s prescribed as an upstream boundary condition distributed over the lake boundary and were executed until a steady-state condition was reached.

Figure 3 shows the TELEMAC domain employed in the gate operation scenarios. Table 1 summarizes the results of the approximately 120 simulations conducted to generate the performance curves. Figure 4 shows the final performance curves, presenting the relationship between the steady-state outflow from the model and the corresponding lake-level elevation for a number of gate configurations. The gate configurations are represented in Figure 4 as “[canal gates open]-[dam gates open]”. For instance, “5-2” would represent 5 canal gates open and 2 dam gates open. The gates were opened in sequence with the gates closest to the centre of the channel opened first. More details on the model steady-state and boundary condition configuration can be found in the Phase I report [10].

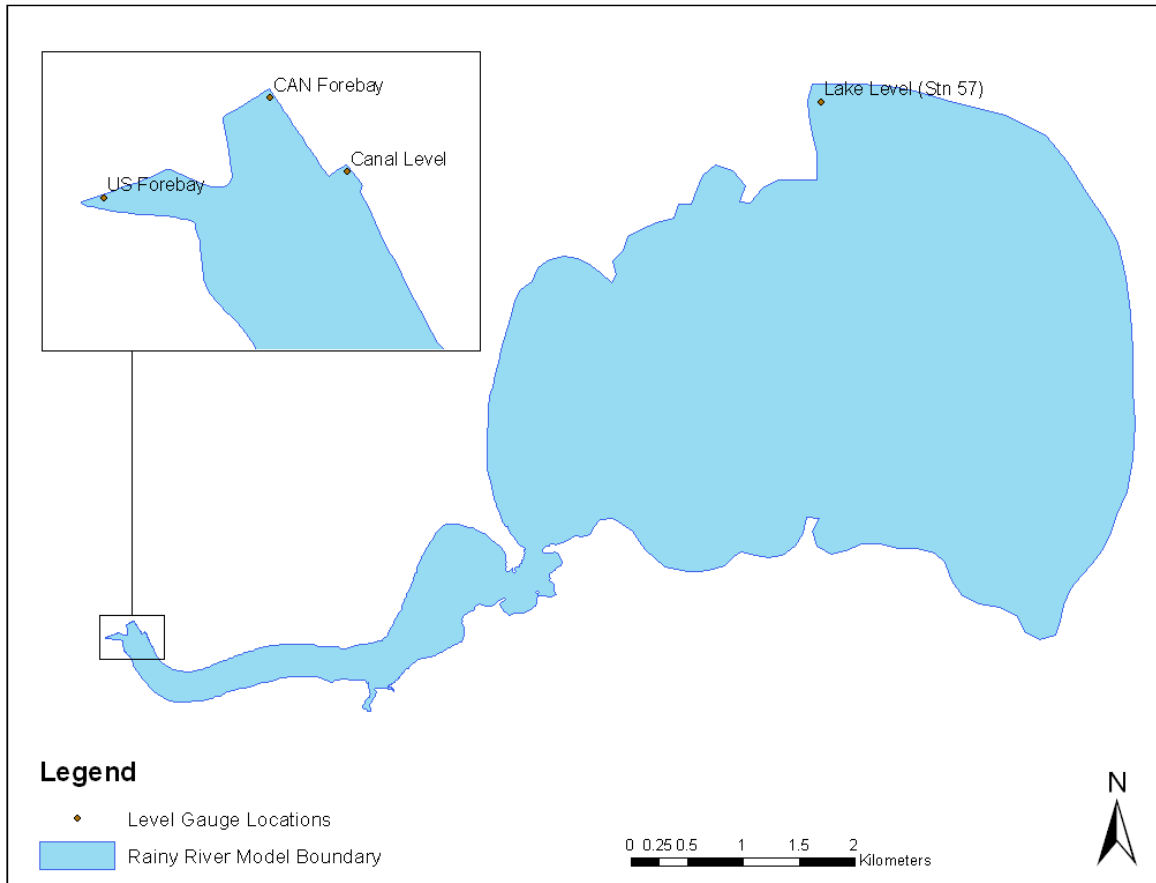


Figure 3 - TELEMAC-2D Upper Rainy River Model Domain and Level Gauge Locations

Table 1 - Gate Operational Scenarios – Lake Elevations

Flow (m ³ /s)	Steady-state Lake Elevation (m)										
	Gate Configurations										
	5-0	5-1	5-2	5-3	5-4	5-5	5-6	5-7	5-8	5-9	5-10
400	336.38	336.38	336.38	336.38	336.38	336.38	336.38	336.38	336.38	336.38	336.38
500	336.72	336.72	336.71	336.71	336.71	336.71	336.71	336.71	336.71	336.71	336.71
600	337.10	337.03	337.01	337.01	337.01	337.01	337.01	337.01	337.01	337.01	337.01
700	338.40	337.61	337.36	337.29	337.28	337.28	337.27	337.27	337.27	337.27	337.27
800	341.08	339.28	338.23	337.76	337.60	337.55	337.53	337.53	337.53	337.52	337.52
900	344.36	341.94	340.00	338.82	338.23	337.94	337.83	337.79	337.78	337.77	337.77
1000	347.88	344.16	342.37	340.52	339.36	338.70	338.32	338.12	338.05	338.02	338.02
1100	352.26	345.89	344.10	342.64	341.08	339.90	339.15	338.69	338.45	338.33	338.27
1200			345.74	345.13	343.09	341.46	340.32	339.57	339.08	338.78	338.61
1300							341.74	340.73	339.96	339.45	339.11
1400								342.10	341.08	340.33	339.79
1500										341.39	340.66

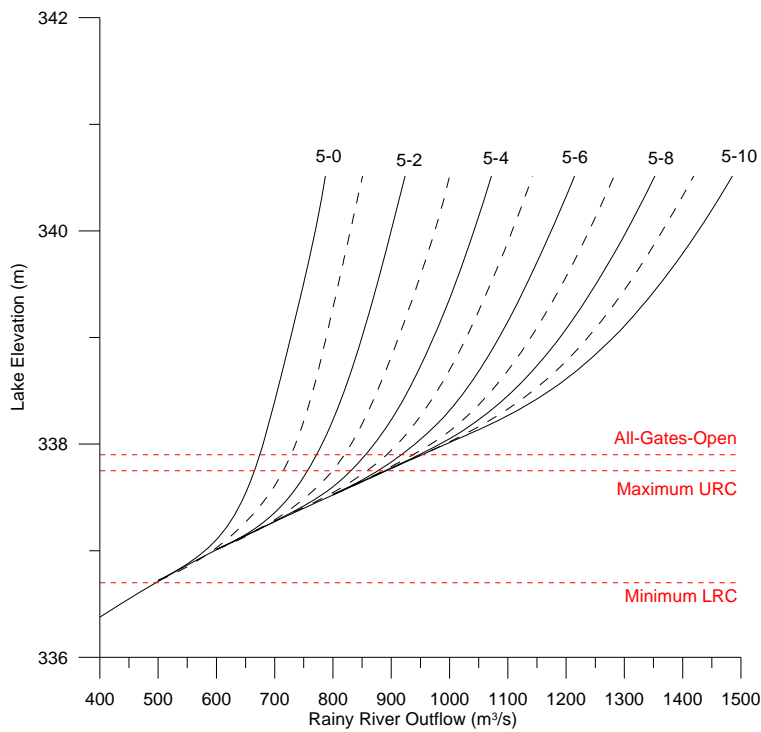


Figure 4 - Gate Operational Scenario Curves and Key Operating Rule Levels

The results of the gate operations scenario runs presented in Table 2 and Figure 4 indicate that the benefits in the increased flow associated with opening a certain number of gates depends substantially on the level of the lake. Based on the simulation results, at the "All Gates Open" lake elevation maximum outflow is obtained by having 5 canal gates and 7 dam gates open. The opening of further gates does not increase outflow and has the negative effect of lowering the river level in front of the dam. Based on observed historical lake levels, the frequency of events requiring all gates to be opened should be rare. Only lake levels in excess of 338.3 m would necessitate the opening of all gates, which has occurred on 6 occasions in the last 96 years (1912 – 2009) [5]. As described above, these results do not account for variability in powerhouse performance due to lower forebay levels and other factors. Section 5 presents this analysis.

As a validation of the above operational scenarios, the measured or estimated daily elevations and outflows were plotted alongside the gate operational curves (data period: August 1999 to January 2009). Although the measured data do not represent steady-state conditions and the gate configurations change regularly at high flows, it is expected that the observed flow-level measurement points should not lie below the maximum conveyance line "5-10". Figure 5 shows the results and

demonstrates general compliance of the data to fall within the limit imposed by the 5-10 curve with a slight underperformance is observed for a section of the higher flow period (1050 m³/s to 1150 m³/s approximately), when all gates were reported open. This appears to be due to powerhouse performance reductions at those levels (see Section 5).

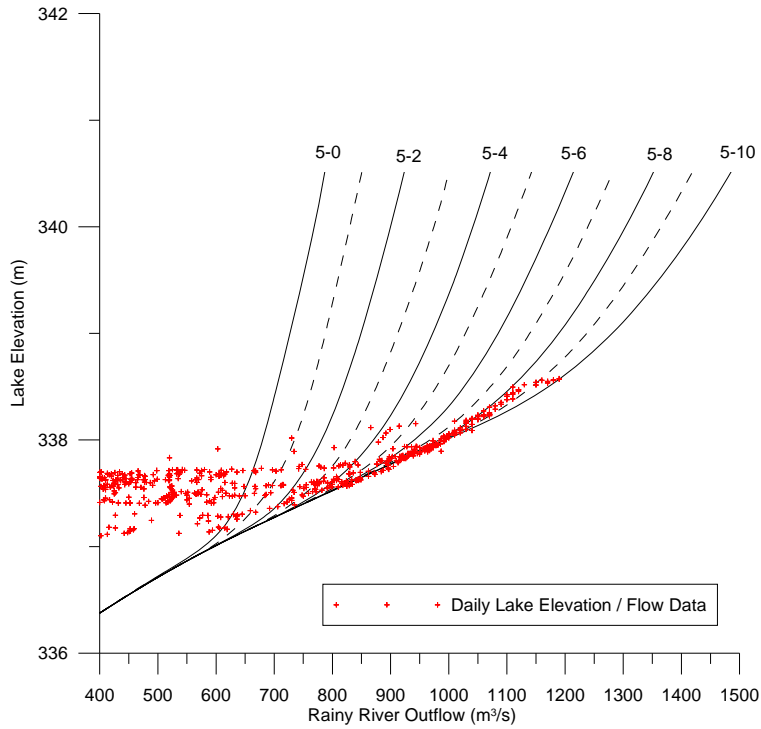


Figure 5 - Gate Operational Scenario Curves and Measured Elevation / Flow Data (Aug 1999 - Jan 2009)

3 Gate Operation Scenarios – Visualization Component

The results of Phase I of this study and the results presented in Section 2 of this document illustrate the complexity of the flow through the upper Rainy River. The multiple potential hydraulic controls identified include the dam itself, the Koochiching falls and the Ranier Rapids, each potentially controlling lake levels depending on the flow-rate through the system and operational conditions. The IJC required a communication product for stakeholders to clearly explain the relationship between the dam operations (i.e the number of gates open) and the river and lake levels. The primary concept requiring clear elucidation was that, depending on the conditions, opening more gates may not increase flow or reduce the lake levels more quickly. As part of this exercise a communication deliverable was devised based on consultation with members of the Rainy River boards and the IJC.

Two visualization products were delivered to the IJC and the Rainy Boards. The first was a somewhat sophisticated animation that illustrated the above phenomenon using multi-dimensional animation of the model results. The animation was developed using the NRC-CHC Blue Kenue software package [9] and a frame of this animation is illustrated in Figure 6. This animation shows the time series of a dynamic model simulation including the complex 2D flow near the dam, the changes in elevation along the channel and differences between the lake and the forebay levels.

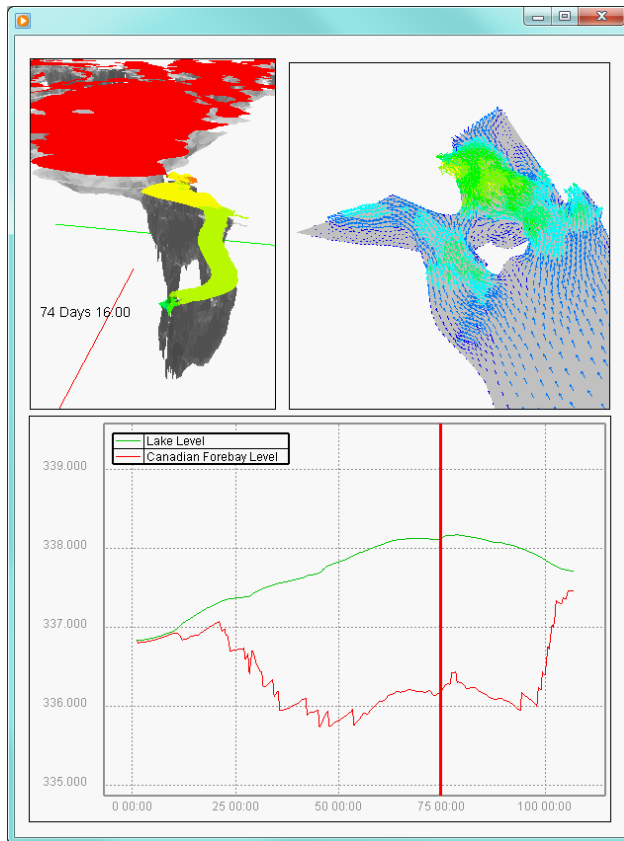


Figure 6 - Visualization Alternatives using Blue Kenue – Synchronized 1-D, 2-D and 3-D Animations

Although illustrative, the above animation was considered complex for general interpretation and a simpler communication product was devised to illustrate the effects the dam operation has on lake levels. The solution was to present the upper Rainy River as an interactive Adobe Flash animation as shown in Figure 6. This product represents the flow conditions at a near “all gates open condition” (lake elevation of 337.8 m) and allows users to adjust the number of dam gates that can be opened, showing the change in the water surface profile and the total flow passing the dam. The animation illustrates the point that after opening 10 gates the flow does not increase but the forebay levels drop substantially.

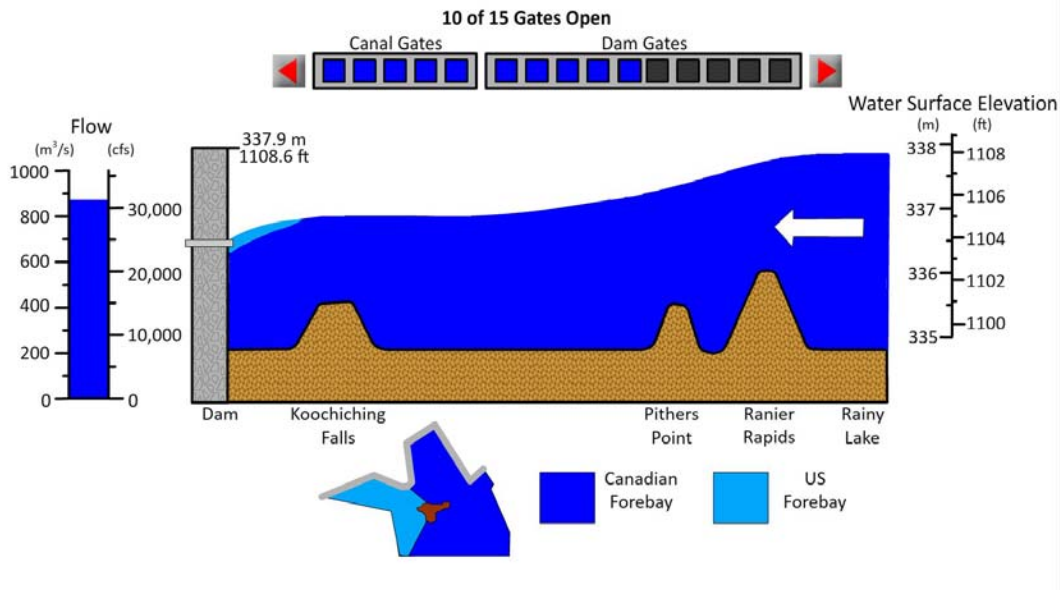


Figure 7 - Interactive Adobe Flash Visualization Schematic of Upper Rainy River

To create the visualisation, flow profiles were created for each gate configuration using steady-state results at a flow that would give a lake elevation of 337.8 m. Flow profiles were created by obtaining water levels from the simulations at key locations and fitting a curve to those points. A simplified representation of the river bathymetry and dam were added to the animation along with the flow values needed for each gate configuration to obtain the lake levels shown. The communication products are to be made available on the IJC Rainy Lake board website.

4 *Dynamic Simulations*

The 1950 flood event represents the largest flood of Rainy Lake on record [5], and efforts were made in this investigation to modify the TELEMAC Rainy Lake model to accommodate the particular conditions observed in 1950. As part of the Phase II investigations, improvements were made to the model to better represent dynamic runs, which would benefit not only the 1950 dynamic simulations but the other periods as well. These improvements were accomplished by examining the mesh and comparing to detailed CHS charts [1] to more accurately represent the true lake area and bathymetry. Part of the improvements involved increasing the Rainy Lake areal extent. The original area of the model was 904.0 km² which was modified to be 957.7 km² as illustrated in Figure 11. The new area more closely matches the assumed area employed by Environment Canada in calculating lake inflows, data which were employed in this modeling study.

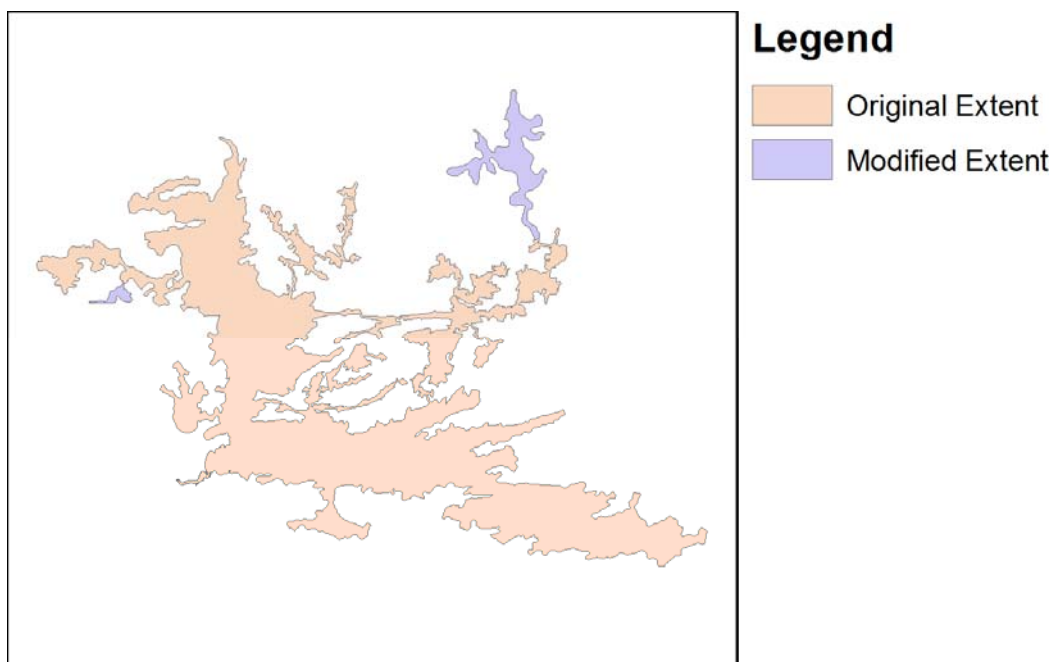


Figure 8 – Modification of model extent for Phase II simulations.

To examine the effects of these domain changes the 2002 (DS1) and 2005 (DS2) simulations from Phase I were re-run, and two new dynamic simulation periods, 1950 (DS3) and 2008 (DS4), were also simulated. Table 2 outlines the characteristics of all four simulations. The details of the updated simulations are detailed in the sections below.

Table 2 - Dynamic Simulations, Dates and Characteristics

Characteristic	Simulation			
	DS1	DS2	DS3	DS4
Start Date	8 June 2002	1 April 2005	1 April 1950	15 April 2008
End Date	13 August 2002	27 July 2005	31 August 1950	31 July 2008
Duration (days)	66	117	153	108
Maximum Rainy Lake Outflow (m ³ /s)	1195	982	1357	1019
Maximum Lake Level (m)	338.58	337.96	339.23	338.10
Minimum Lake Level (m)	337.47	336.85	336.73	336.83
Minimum Canadian Forebay Level (m)	335.44	335.39	336.35	335.48
Starting Canadian Forebay Level (m)	337.45	336.64	336.56	336.76
Starting Lake Level (m)	337.49	336.85	336.9	336.83

4.1 1950 Flood Event (DS3)

The 1950 flood event differed from the other dynamic simulations in that it was the event with the highest observed lake elevation and it was the only event where the dam was overtopped. The 1950 period also showed distinctly different conveyance data from the other periods. Figure 9 presents the conveyance plots developed in Section 2 with the current flow and lake level data (1999-2009) plotted along with similar data from 1950. It shows a conveyance in 1950 that is higher than the modeled all gates open scenario and more than any observed conveyance in the other more recent flow data. This extra conveyance cannot be explained simply by the overflow because there is extra conveyance present before the dam overflows, as seen in Figure 10.

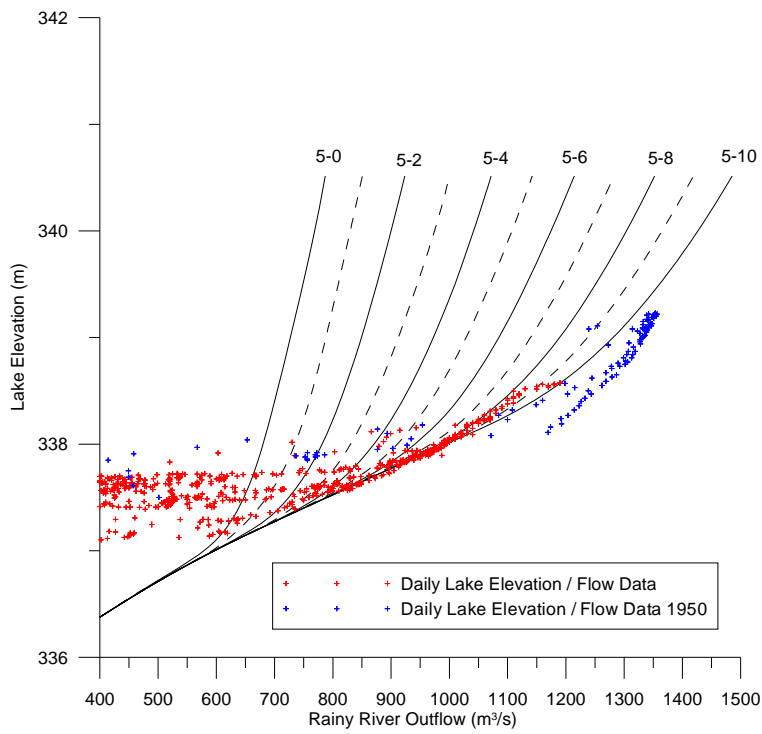


Figure 9 - 1950 and Current Conveyance Data

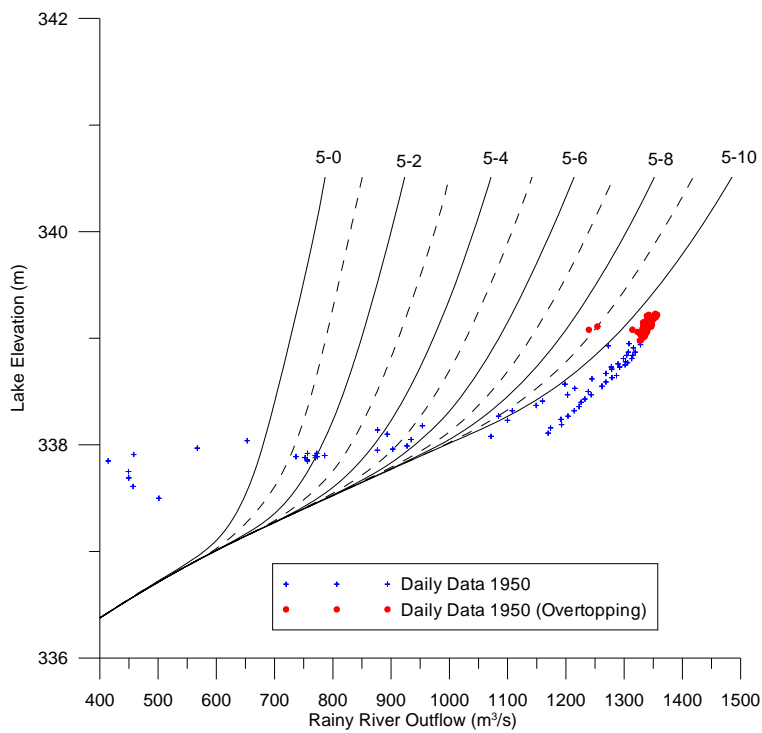


Figure 10 - 1950 Conveyance with Overtopping Period

The 1950 data record also posed other challenges in that estimates of flow were provided but with no records as to how the flow estimates were made; namely, flow over the dam during the high water levels or through the dam and canal gates with apparently only one forebay measurement.

In spite of the challenges, modelling was attempted with the existing model with the only change being the addition of an additional boundary condition to simulate the overtopping of the dam simulated as a broad-crested weir. The location of the overflow is shown in Figure 11. The total length of the spillway was divided into 24 nodes, and the discharge was calculated separately for each node using the following broad-crested weir equation

$$Q = C \frac{2}{3} L \sqrt{2g} (h_1^{3/2})$$

where Q is the discharge (ft^3/s); C is the discharge coefficient (0.6); L is the length of the spillway (367.45 ft); g is acceleration due to gravity (32.2 ft/s^2); and h_1 is the total upstream head measured above the spillway including the velocity head (ft).

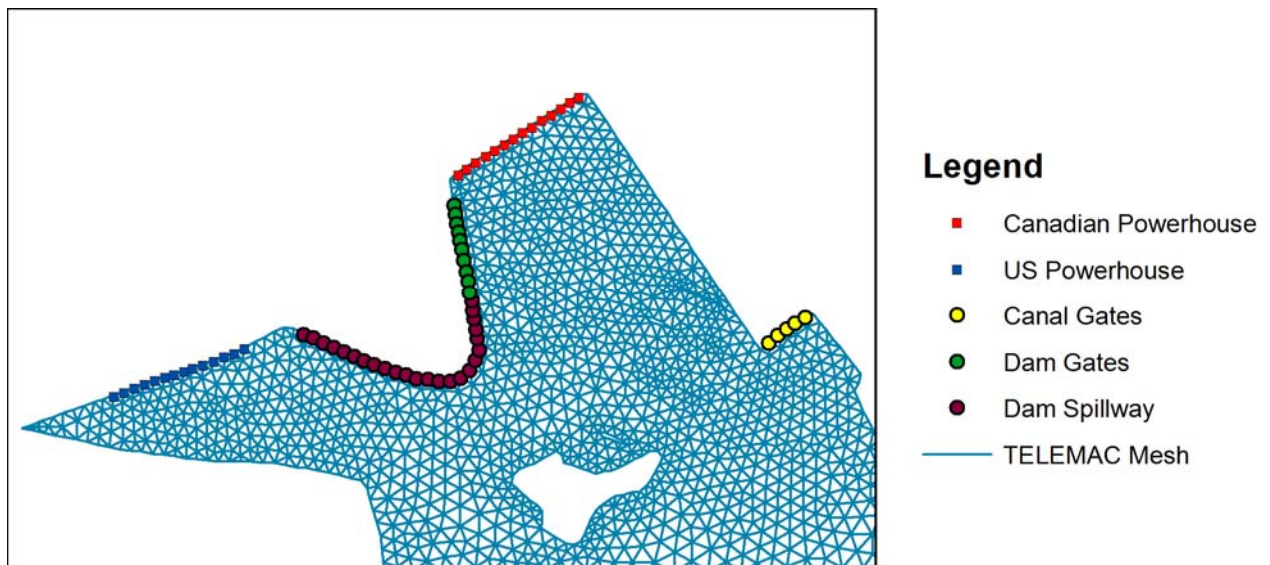


Figure 11 - Model Downstream Boundary Conditions

The results of the 1950 simulations are shown below. In these simulations the same number of gates were employed as with the model for the current condition, with the addition of the spillway over the dam. The operational history was adapted from historical records of the operation during 1950 as were estimated lake inflows and flow passing the dam. Although the estimates of flow passing the dam

included powerhouse and gate were provided, no explicit estimates were provided for the flow overtopping the dam or the means by which that was calculated. Forebay levels were also available from the 1950 period but it was unclear where exactly within the forebay measurements were taken, including whether the measurement location was on the Canadian or US side of the dam. The boundary conditions were set such that the inflow to the lake was prescribed, as were the flow rates through the two powerhouses. The dam gates and the dam overflow were both controlled by their physical equations and driven by model state variables including the hydraulic head taken approximately 10 m upstream from each point of discharge. Further details on the model boundary conditions are available in the Phase I report. The performance of the 1950 simulations is shown below in the model’s ability to simulate forebay levels (Figure 12), lake levels (Figure 13) and flow through the wastegates (Figure 14).

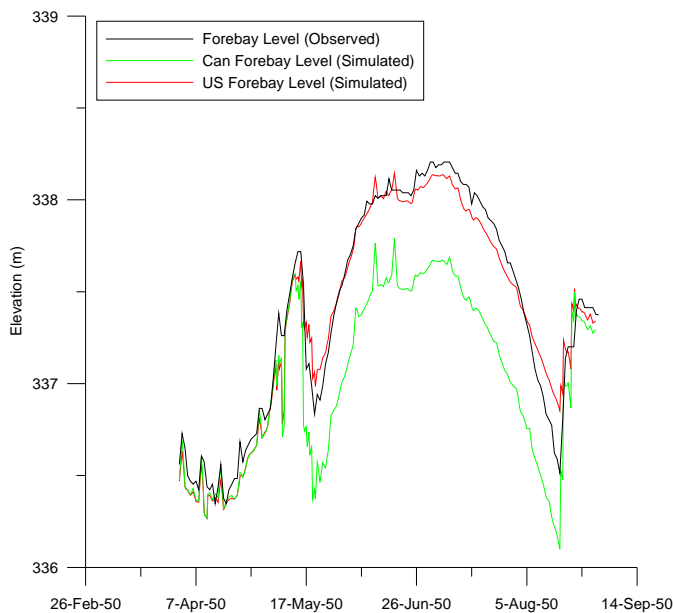


Figure 12 - Forebay Levels 1950 (DS3)

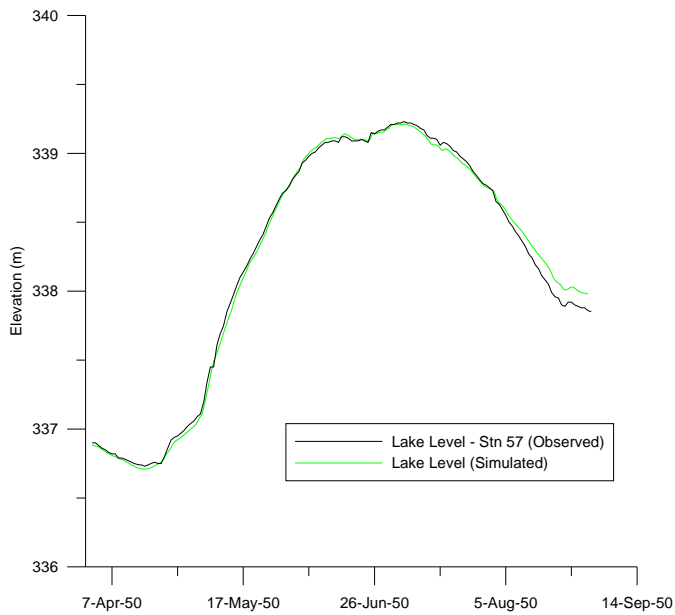


Figure 13 - Lake Levels 1950 (DS3)

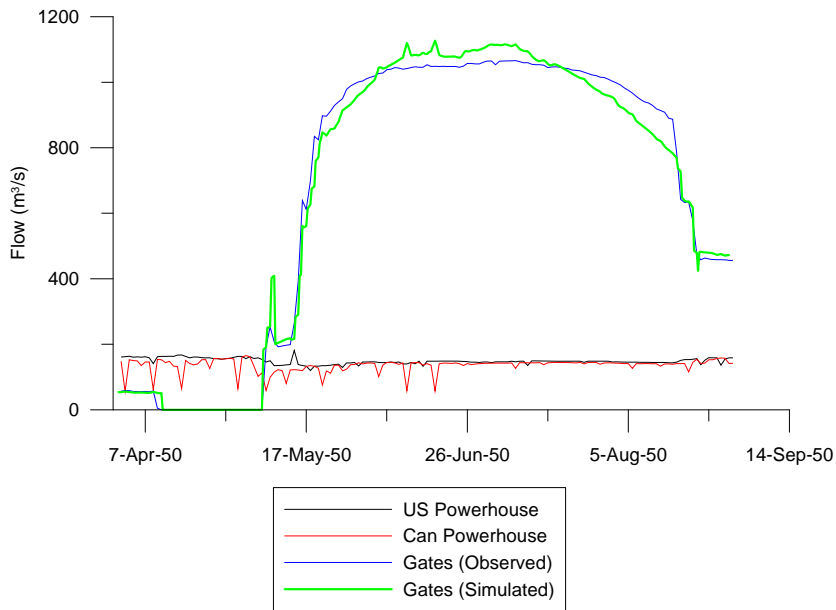


Figure 14 - Flow Estimates 1950 (DS3)

In spite of the differences in overall observed conveyance the 1950 events are reasonably well simulated. The observed forebay levels were likely taken from the US forebay as the observed measurements match closely simulated US forebay levels (see Figure 12). The error at the forebay level

peak is 0.06 m. Lake levels are well matched as illustrated in Figure 13, with the simulated peak level being 339.21 m compared to the observed peak level being 339.23 m. Simulated flow estimates through the dam gates varied from the observed flow estimates as illustrated in Figure 14. Although the simulation appears to underestimate the gate flows at the start and end of the simulation, the flows are overestimated during the middle period. This pattern also matches the lake level error with an overestimation of lake levels during the rising limb and slight underestimation during the peak itself and then overestimation again during the falling limb. Table 3, presented at the end of this section, compares results of this simulation with the other three dynamic simulations.

4.2 Dynamic Simulation Improvements – 2002 (DS1) and 2005 (DS2)

As describe above, changes made to the TELEMAC model form Phase I to Phase II involving primarily the adjustment of the lake delineation. Further details were obtained from CHS nautical charts and to include areas of the lake that were previously not included. Additionally, more bathymetric points were obtained from the CHS maps to improve the representation of the overall bathymetry. Results from the 2002 run are presented in Figure 15 (forebay levels), Figure 16 (lake levels), and Figure 17 (flow). Results from the 2005 run are presented in Figure 18 (forebay levels), Figure 19 (lake levels), and Figure 20 (flow). The 2002 observations are accurately simulated with the exception of the peak lake level which shows a 0.04 m underestimation. However, gate flows are well matched resulting in a very close matching water balance throughout the simulation. The 2005 simulations show a closer matching of observed peaks, however an underestimation of flows during the highest flows in the simulation period compromised the water balance and resulted in higher lake levels at the end of the simulation than observed.

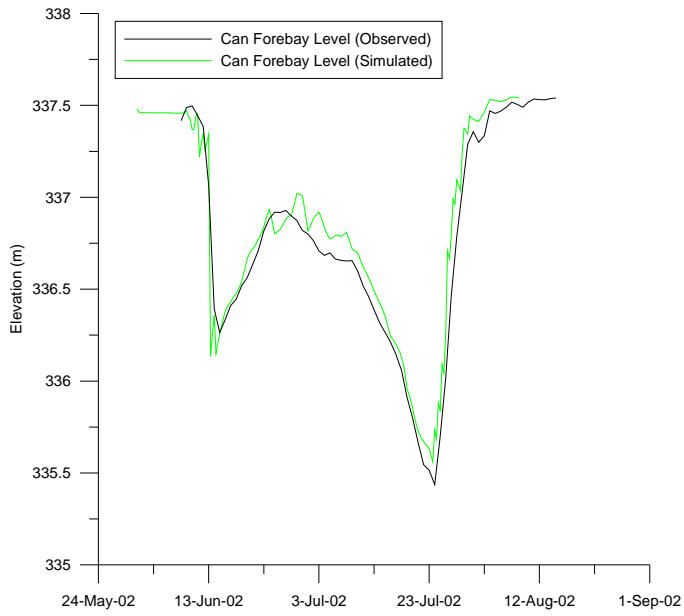


Figure 15 - Dynamic Run 2002, Forebay Levels

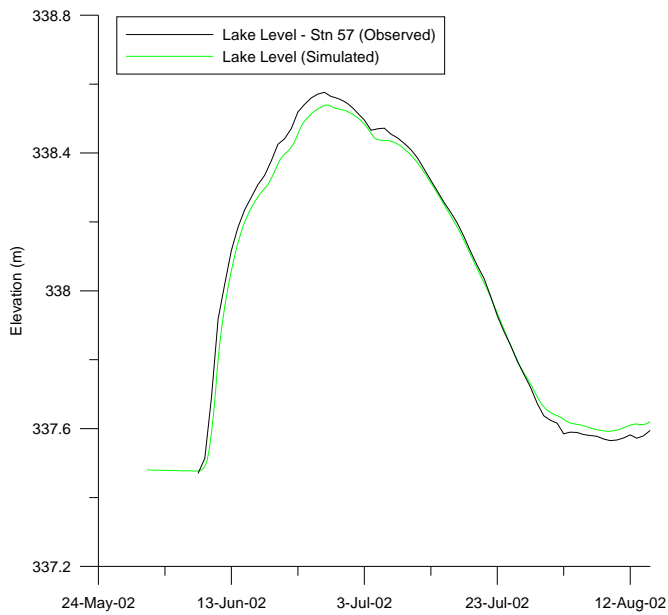


Figure 16 - Dynamic Run 2002, Lake Levels

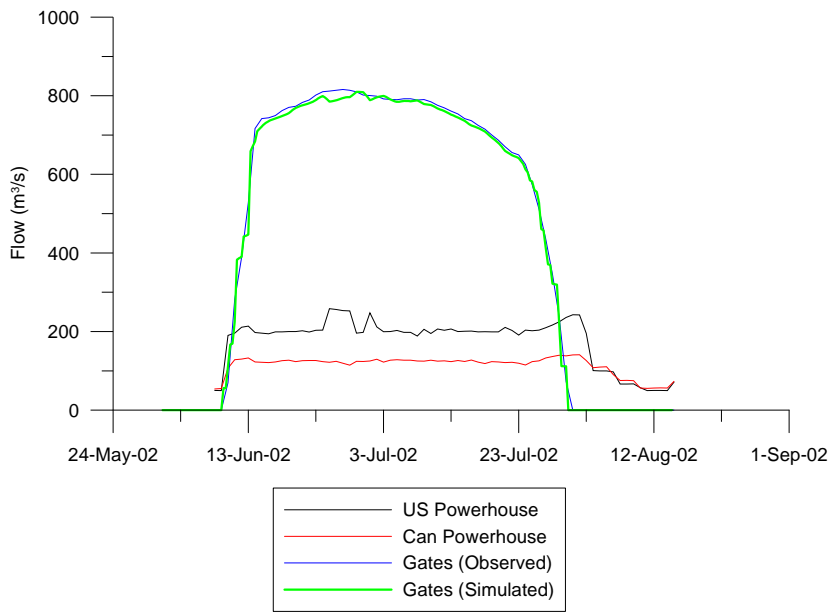


Figure 17 - Dynamic Run 2002, Flows

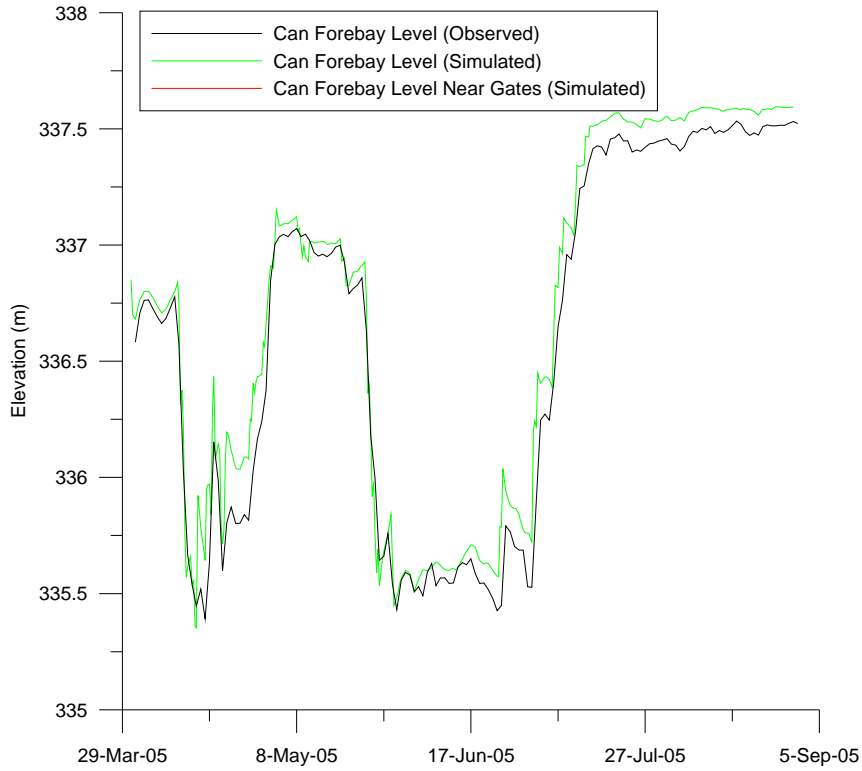


Figure 18 - Dynamic Run 2005, Forebay Levels

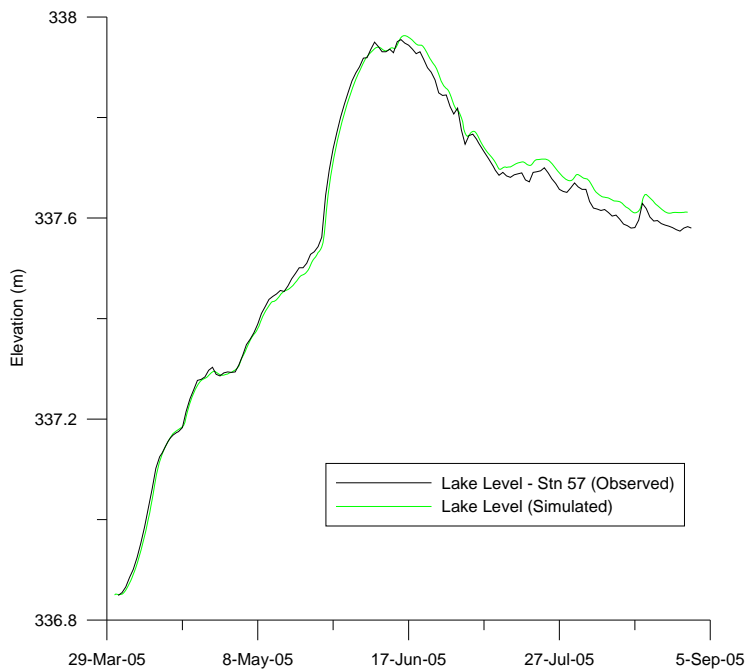


Figure 19 - Dynamic Run 2005, Lake Levels

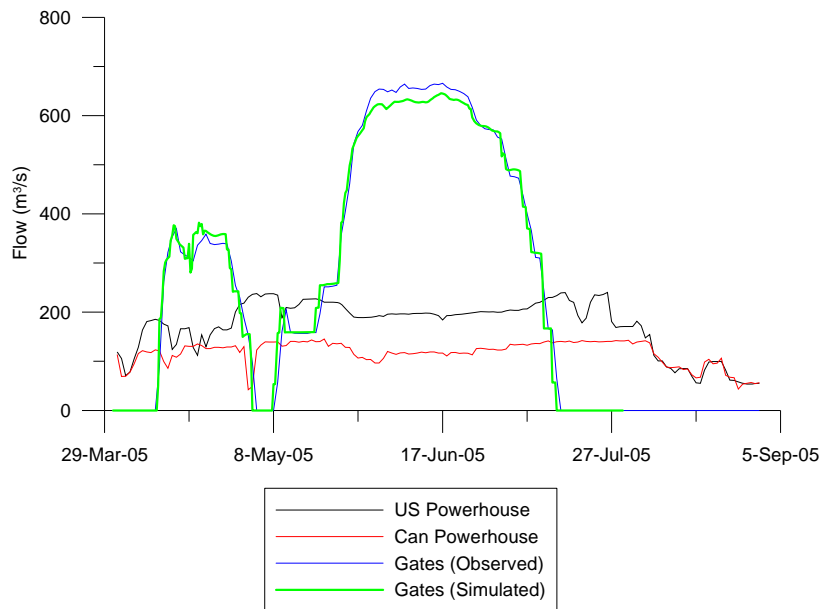


Figure 20 - Dynamic Runs 2005, Flows

The observed forebay levels patterns are well matched by both simulations with the 2005 simulations slightly overestimating the levels. Lake levels are well matched with the peak in 2002 underestimated by 0.04 m and the 2005 peak underestimated by 0.01 m. Simulated flow estimates through the dam gates varied from the observed flow estimates early for the main peak of 2005 but matched the pattern very closely in 2002. The Table 3, presented at the end of this section, compares results of these two simulations with the remaining two dynamic simulations.

4.3 Dynamic Simulations – 2008 Flood Event (DS4)

An additional dynamic run for 2008 was added to the simulations to potentially provide a fourth profile the represented the most recent flooding event. The 2008 flood event was originally constructed with the intention of adjusting the gate operation sequence to examine the influence on lake levels. However, the ultimate utility of these types of simulations was questioned, in light of the clear results obtained in steady-state analysis and at the recommendation of the Rainy Boards they were de-scoped. The 2008 simulations were still included as a fourth dynamic validation of the TELEMAC model. The results of the simulation are presented in Figure 21 (forebay levels), Figure 22 (lake levels), and Figure 23 (flows).

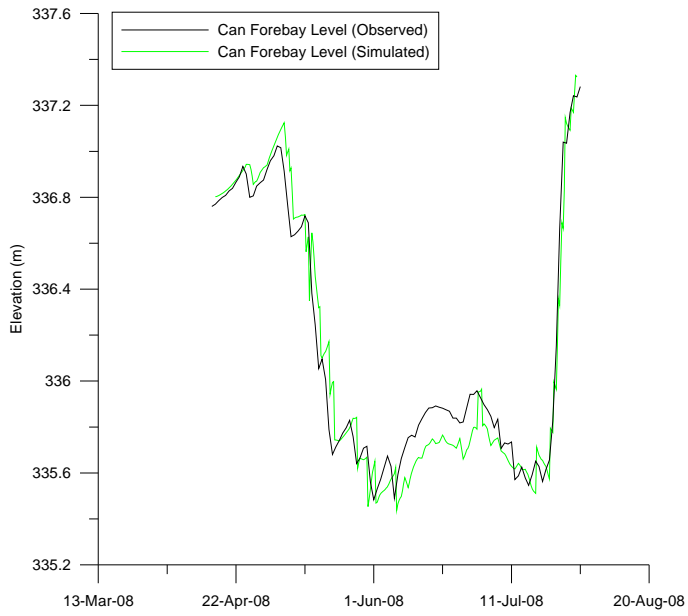


Figure 21 - Dynamic Run 2008, Forebay Levels

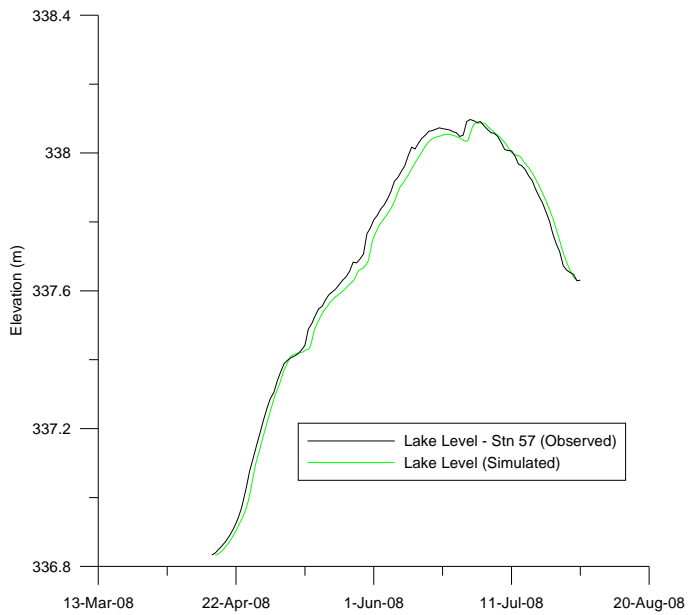


Figure 22 - Dynamic Run 2008, Lake Levels

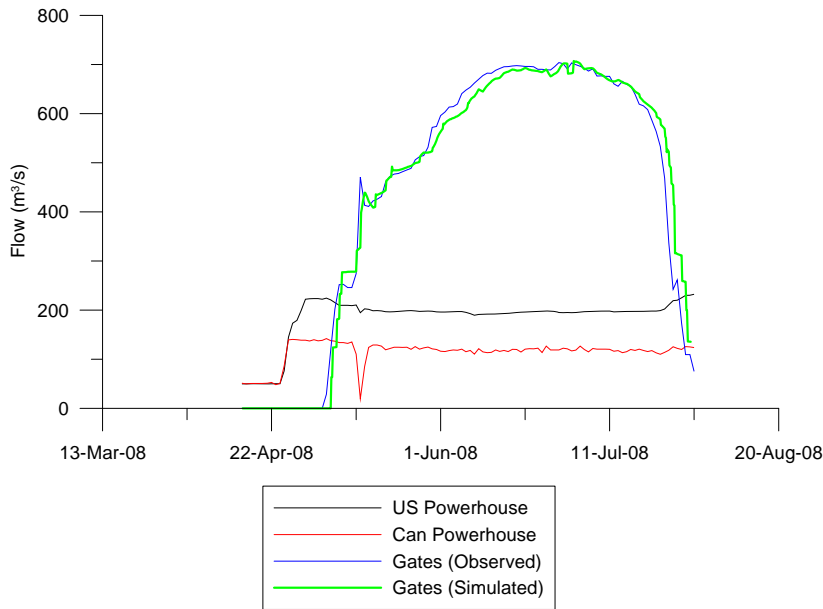


Figure 23 - Dynamic Runs 2008, Flows

For the 2008 simulation the forebay levels are matched quite closely, although underestimated near the peak flows, which matches an underestimation of flow at approximately the same time in the simulation. The peak lake levels are matched well with a peak level error of 0.01 m.

4.4 Dynamic Runs Summary Performance

The primary performance concern is the ability of the model to simulate observed lake levels. The table below shows the results of the ability of the model to match the peak level and timing of each simulation period.

Table 3- Peak Lake Level Prediction Performance

	Lake Level - Peak Elevation (m)			Date of Peak		
	Observed	Simulated	Error	Observed	Simulated	Error (days)
DS1 – 2002	338.58	338.54	-0.04	27/06/2002	27/06/2002	0
DS2 – 2005	337.95	337.94	-0.01	15/06/2005	15/06/2005	0
DS3 – 1950	339.23	339.21	-0.02	05/07/1950	05/07/1950	0
DS4 – 2008	338.10	338.09	-0.01	29/06/2008	29/06/2008	0

5 Powerhouse Performance Impacts

During the Phase I study the powerhouse performance was assumed static under all flow conditions and the flow through each of the two powerhouses was selected to be the approximate maximum total conveyance. For the US powerhouse a flow of 250 m³/s was assumed and for the Canadian powerhouse a flow of 150 m³/s was assumed. The operational history shows that the powerhouse performance can vary substantially from the maximum under different conditions. Figure 5-1 shows the relationship between the flow through the powerhouses and total outflow of the river. The turbine operational history shows the drop in performance of the US and Canadian powerhouses as the total outflows increase. In the US side an apparent drop from approximately 240 m³/s to 200 m³/s was observed and the Canadian powerhouses showed a drop from approximately 140 m³/s to 120 m³/s. Both cases represent nearly 15% reduction in maximum capacity on average but in some cases the performance can be substantially lower, especially with the Canadian power house.

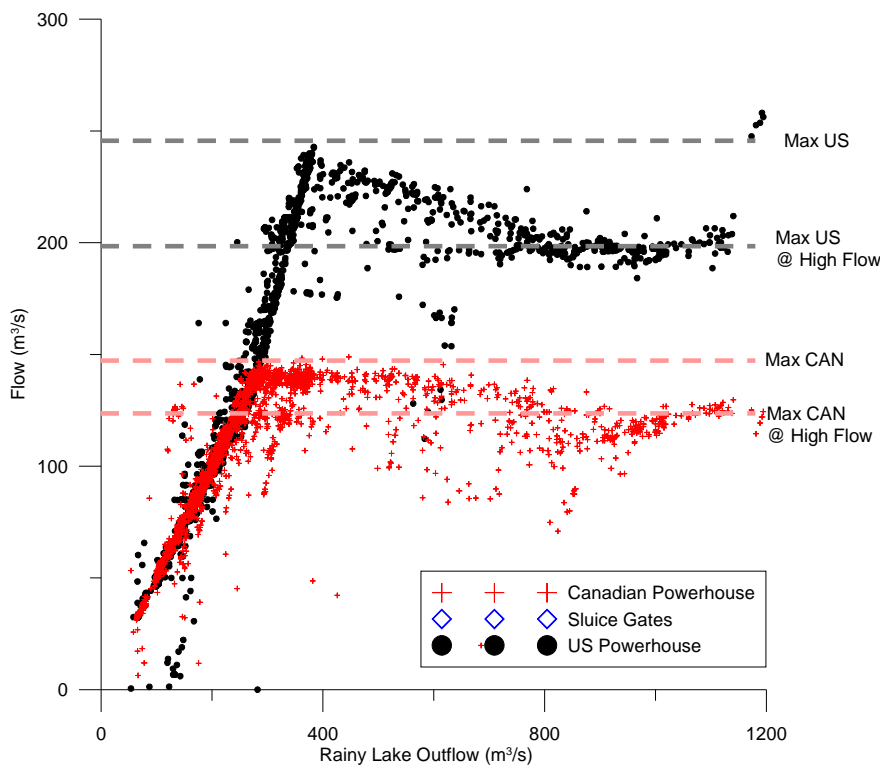


Figure 24 - Flow through the Power Houses as a Function of Total Outflow

It was originally presumed that the headwater levels were contributing to the reduced powerhouse performance. Figure 25 shows the change in measured headwater for each powerhouse levels as a

function of total lake outflow. A reduction in headwater levels is observed as flow increases from 400 m³/s with significant scatter likely due to the dynamic gate configurations at the lower flows (less than about 800 m³/s). The Canadian headwater levels drop much more substantially than the US headwater levels, as is expected considering the location of the dam gates. Above about 1000 m³/s an all gates open situation is required so the gate configurations are generally static above this value, and as flows increase the so do the headwater levels.

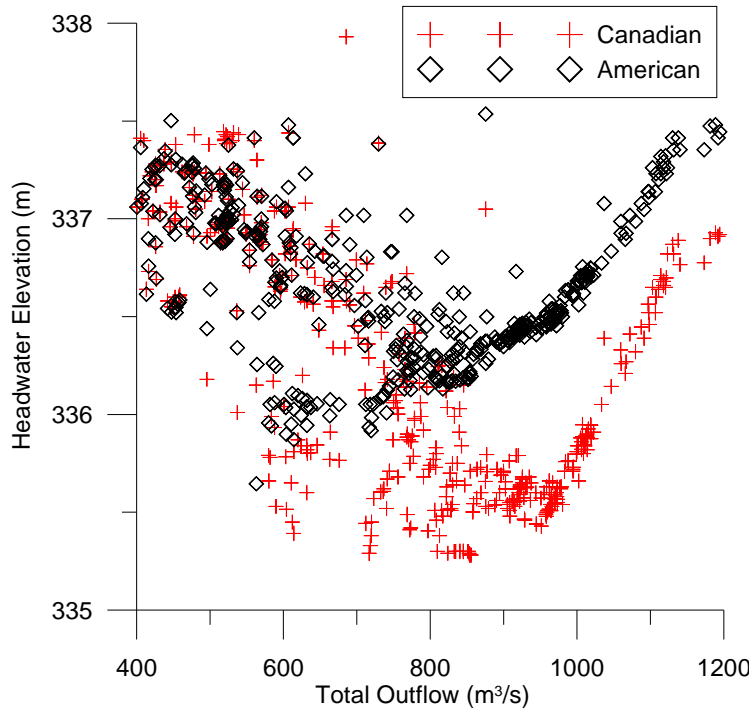


Figure 25 - Headwater Levels as a Function of Total Outflow

The relationship between the flow through the each powerhouses and the associated headwater level were examined with an interest in developing a predictive powerhouse performance relationship. The results are shown graphically in Figure 26 and Figure 27 for the Canadian and US powerhouses respectively. The plots do show a reduction in flow with a reduction in headwater level but the relationships are not entirely straightforward and evidence pointed to two separate populations within the datasets, especially the data for the US powerhouse. With the populations split between low and high flow it becomes clear that as the headwaters recover at very high flow conditions the flow through the powerhouse does not fully recover.

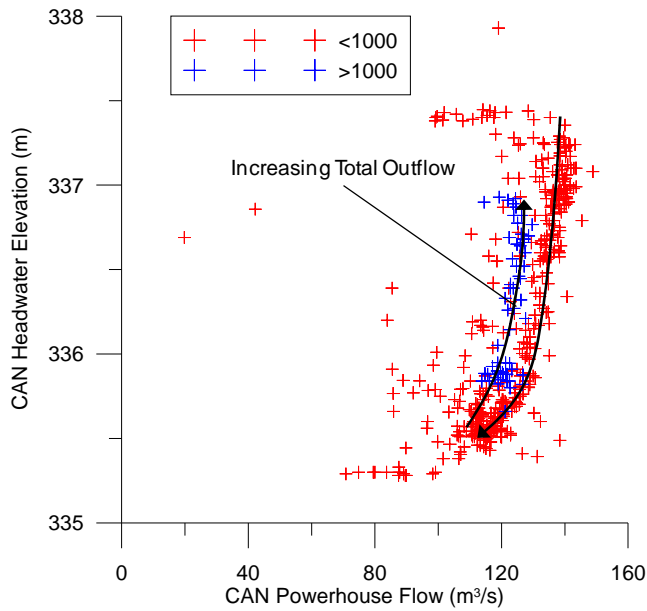


Figure 26 - Canadian Powerhouse, Flow Headwater Relationships

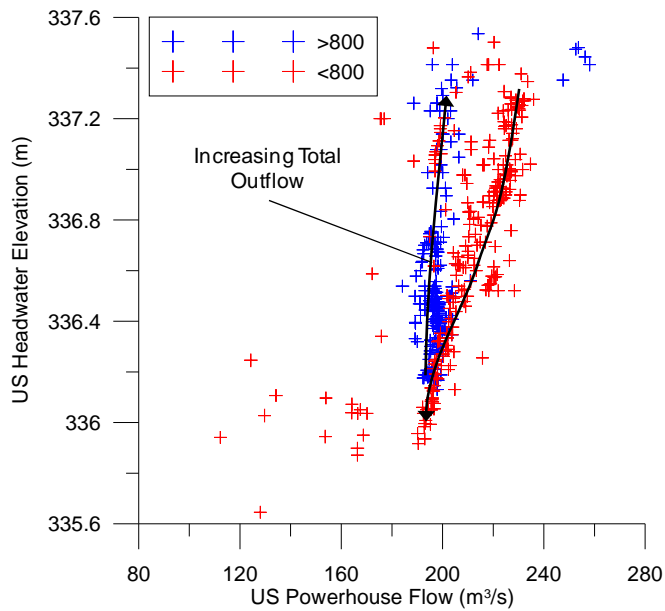


Figure 27 – US Powerhouse, Flow Headwater Relationships

Discussions with members of the Rainy Boards suggested that a number of operational factors could be in play when the flows are very high. Anecdotal evidence suggested that at higher flows increased

vibration could be observed in the powerhouses in which case a turbine may be shut off. The details and rationale of these sorts of operations were not available. In lieu of some operational rule two approaches to estimating the influence of the variable powerhouse performance were considered: a performance “envelope” based on headwater levels and a performance curve based on the total simulated outflow from Rainy Lake. These two approaches are described below.

5.1 Headwater Powerhouse Performance

The first approach taken to model the decreased performance was to develop a performance envelope representing the observed relationship between powerhouse flow and headwater elevations for low total flow. Separate envelope curves were created for each powerhouse, and flows were calculated based on levels directly upstream of each powerhouse. The envelopes were selected to represent the maximum flow for each of the populations, considering the high degree of scatter at the lower flows. The performance envelopes used may be seen in Figure 28 and Figure 29. The comparison of the variable powerhouse performance model to the previous model with maximum turbine performance can be seen in Figure 30, which shows the performance curves for the 5-0, 5-4 and 5-10 gate scenarios (A), and the differences between the two curves (B). This performance curve shows overall very small changes in conveyance with maximum differences near 0.4 m for the 5-0 curve and 0.1 m for the 5-10 curve.

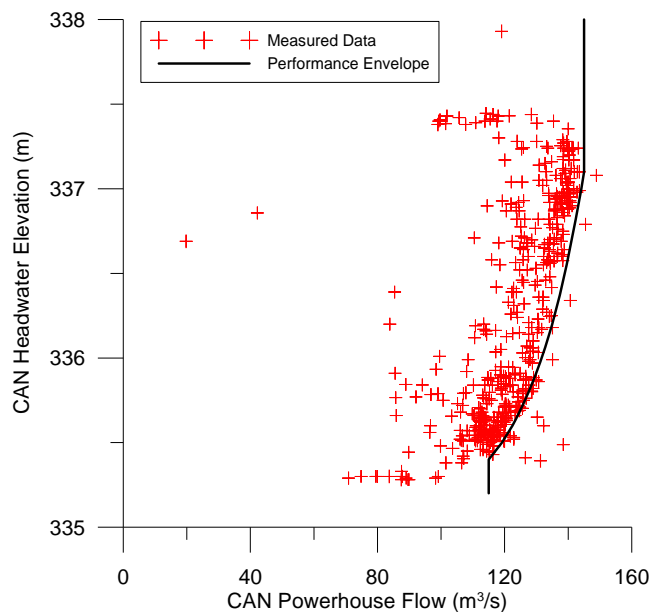


Figure 28 - Canadian Powerhouse Performance Curve as function of Canadian Headwater

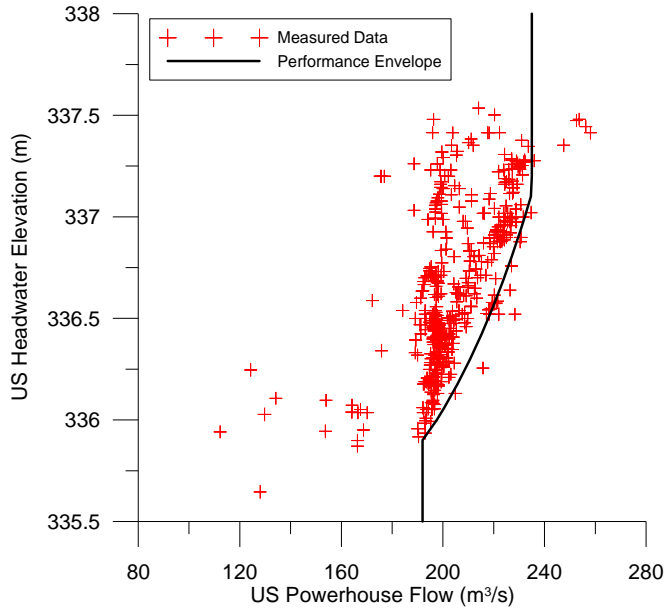


Figure 29 - US Powerhouse Performance Curve as function of US Headwater

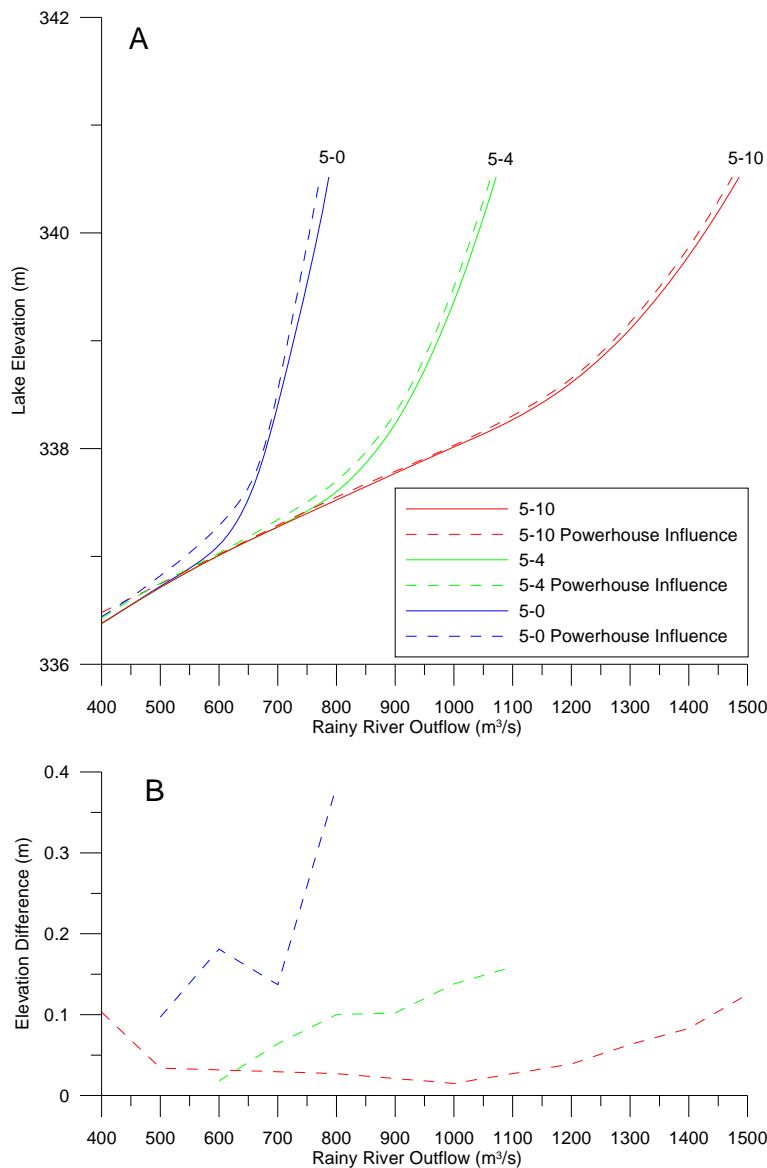


Figure 30 – Powerhouse Performance Influence on Steady-state Curves – Headwater Performance Curves

5.2 Outflow Powerhouse Performance Curves

The second approach taken was to model directly the relationship between total lake outflow and powerhouse performance. This approach was philosophically less appealing than the headwater relationships above as the total outflow is not a state variable that could provide a physical explanation of the drop in powerhouse performance. However, this approach did reproduce historical performance so in that way would provide a measure of historical conveyance. These curves used to estimate flow through the two powerhouses can be seen in Figure 31. The comparison of the variable powerhouse

performance model to the previous model with maximum turbine performance can be seen in Figure 32, which shows the performance curves for the 5-0, 5-4 and 5-10 gate scenarios (A), and the differences between the two curves (B). This performance curve shows much greater differences than the previously defined curves based on headwater levels with maximum differences greater than 2 m for the 5-0 curve and 0.5 m for the 5-10 curve.

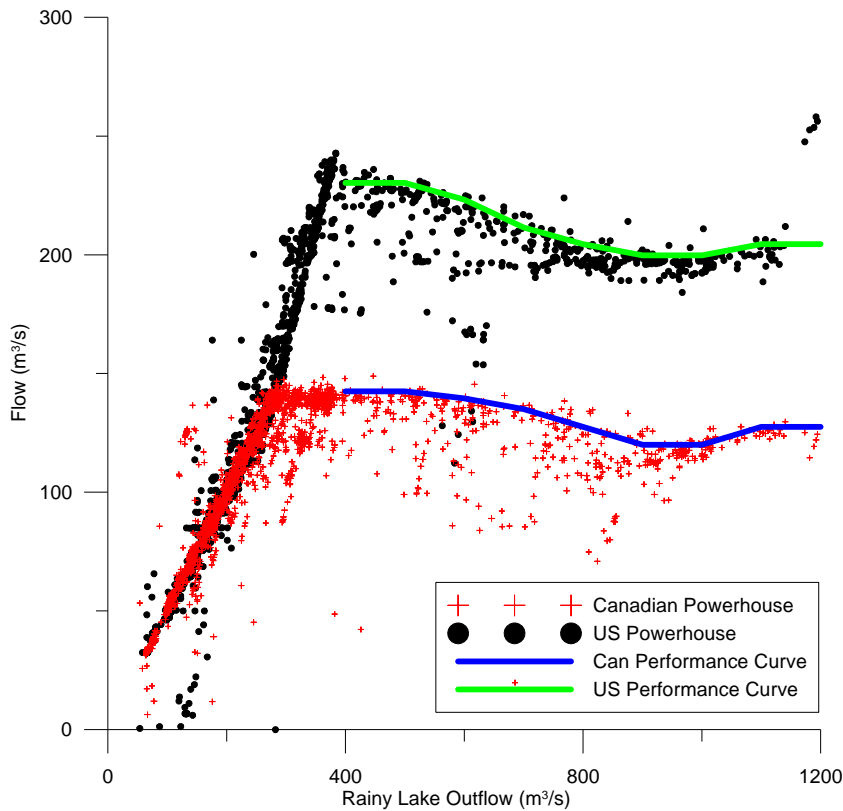


Figure 31 - Powerhouse Performance Curves as function of Total Outflow

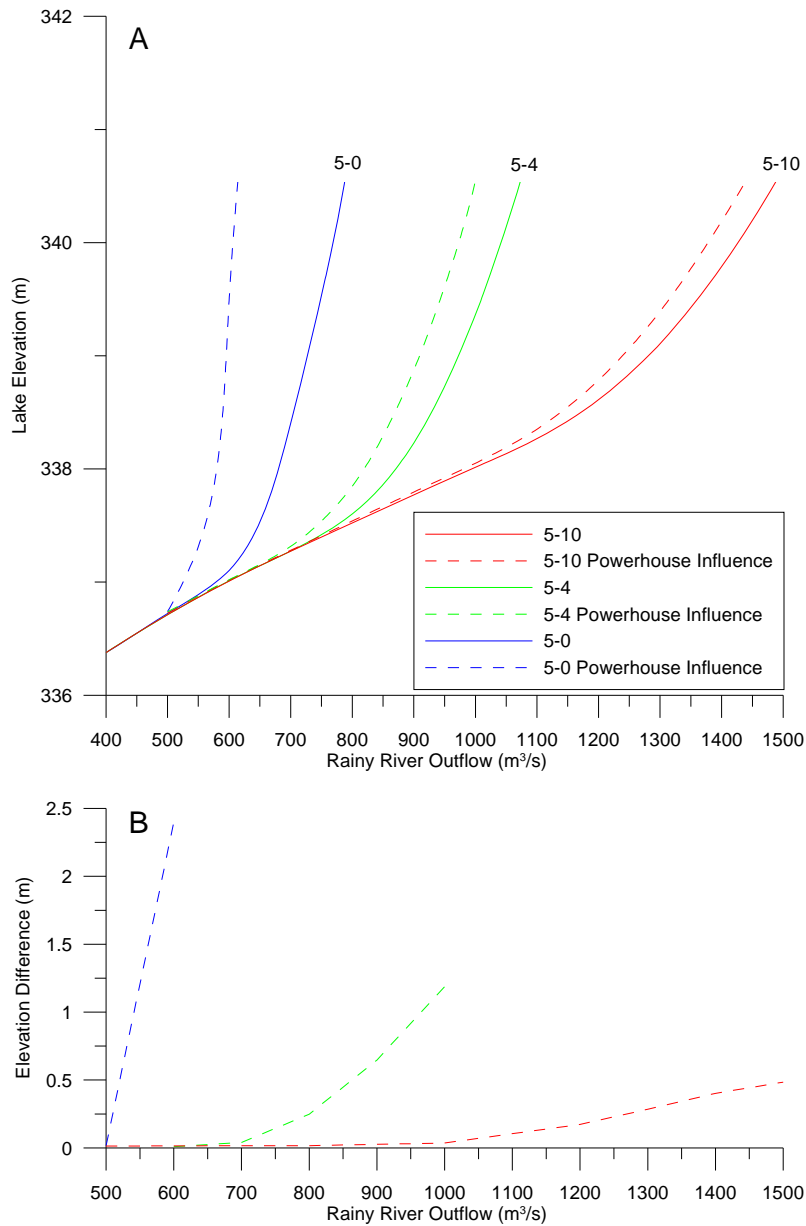


Figure 32 - Powerhouse Performance Influence on Steady-state Curves – Outflow Performance Curves

The outflow powerhouse performance curves are more conservative than the headwater powerhouse performance curves in that they predict a lower overall conveyance. As such this approach was selected as the best option to produce a performance curve similar to that developed in Section 2 but with the variable performance of the powerhouses considered. The results of this analysis are shown in Figure 33 and tabulated in Table 4.

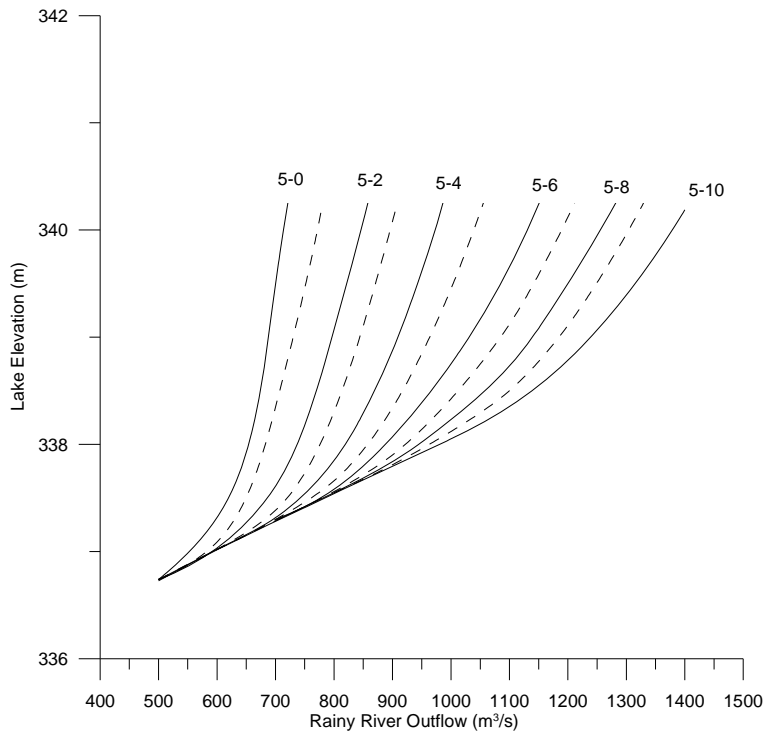


Figure 33 - Conveyance Curves - Outflow Powerhouse Performance Curve

Table 4 - Gate Operational Scenarios – Lake Elevations, with Outflow Powerhouse Performance Curves

Flow (m ³ /s)	Steady-state Lake Elevation (m)										
	Gate Configurations										
	5-0	5-1	5-2	5-3	5-4	5-5	5-6	5-7	5-8	5-9	5-10
500	336.74	336.74	336.74	336.74	336.74	336.74	336.74	336.74	336.74	336.73	336.73
600	337.32	337.09	337.03	337.02	337.02	337.02	337.02	337.02	337.02	337.02	337.02
700	339.50	338.35	337.61	337.39	337.32	337.30	337.30	337.29	337.29	337.29	337.28
800	343.04	341.06	339.07	338.30	337.85	337.66	337.58	337.56	337.55	337.55	337.54
900			341.29	340.08	338.88	338.34	338.07	337.90	337.84	337.81	337.80
1000				342.21	340.55	339.45	338.75	338.42	338.23	338.12	338.05
1100					342.50	341.01	339.65	339.12	338.73	338.50	338.35
1200						342.94	340.97	340.12	339.50	339.11	338.78
1300							342.48	341.37	340.44	339.96	339.39
1400									341.80	341.03	340.19
1500											341.14

The modified conveyance curves were compared with the observed flow data for the 1999-2009 periods. The results are shown graphically in Figure 34, and illustrate that the match between observed and simulated data (5-10) in the 1000 m³/s and 1100 m³/s range is much closer than without the variable turbine performance. The extra conveyance observed above 1100 m³/s is now outside the limiting curve, but these data represent an apparently anomalous period where very high flow through the US powerhouse is observed, well outside the general operational pattern.

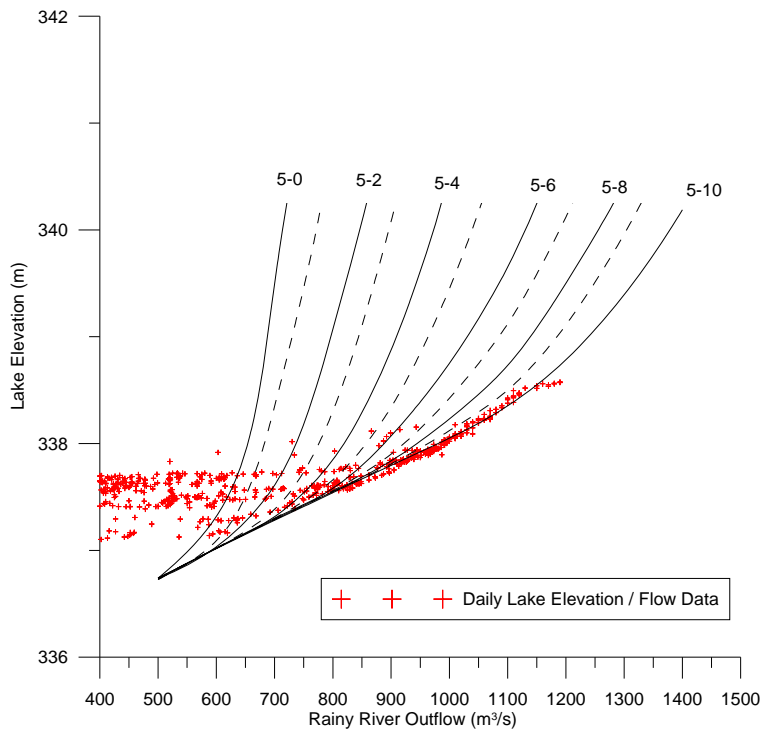


Figure 34 - Conveyance Curve - Outflow Powerhouse Performance Curve with Flow / Elevation Data (1999-2009)

6 Bathymetric Sensitivity

This investigation was conducted to examine the sensitivity of the model to adjustments in bathymetry, particularly around the Ranier Rapids section of the model. The scope was expanded to include areas at the Pithers Point and Koochiching Falls as well. The sensitivity was conducted by delineating an area over the region and then adjusting the local bathymetry by 1 m up and down and examining the impacts on lake levels. In each case the areas were chosen to maximize the local conveyance. The areas are shown in Figure 35.

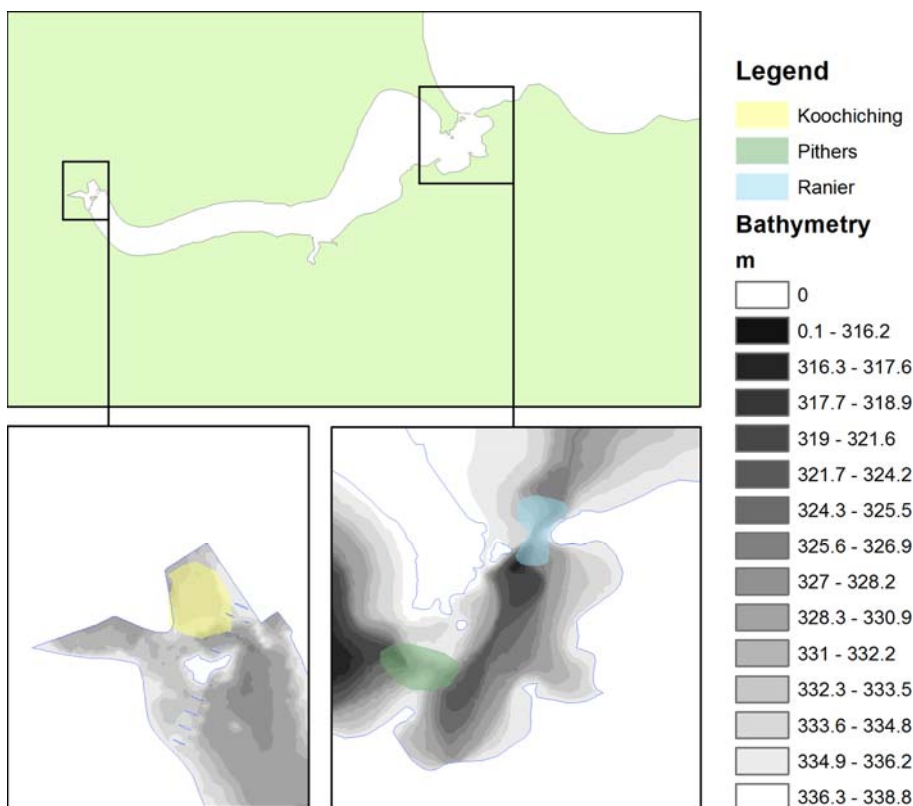


Figure 35 - Bathymetric Sensitivity - Selected Adjustment Areas

The models with the adjusted bathymetry were then subjected to a high flow 1000 m³/s to see the effects in lake levels. The results are shown in Figure 36, and indicate that the Ranier Rapids region shows the most sensitivity and the most potential benefit to lake levels through bathymetric adjustment, with a lake level drop of approximately 0.18 m with a 1 m reduction in local bathymetry. An equivalent increase in local bathymetry shows an increase of 0.15 m. Pithers Point shows a similar

increase with a 1 m increase in local bathymetry but a much smaller lake level reduction (0.07 m). Koochiching falls show a relatively small sensitivity (± 0.05 m).

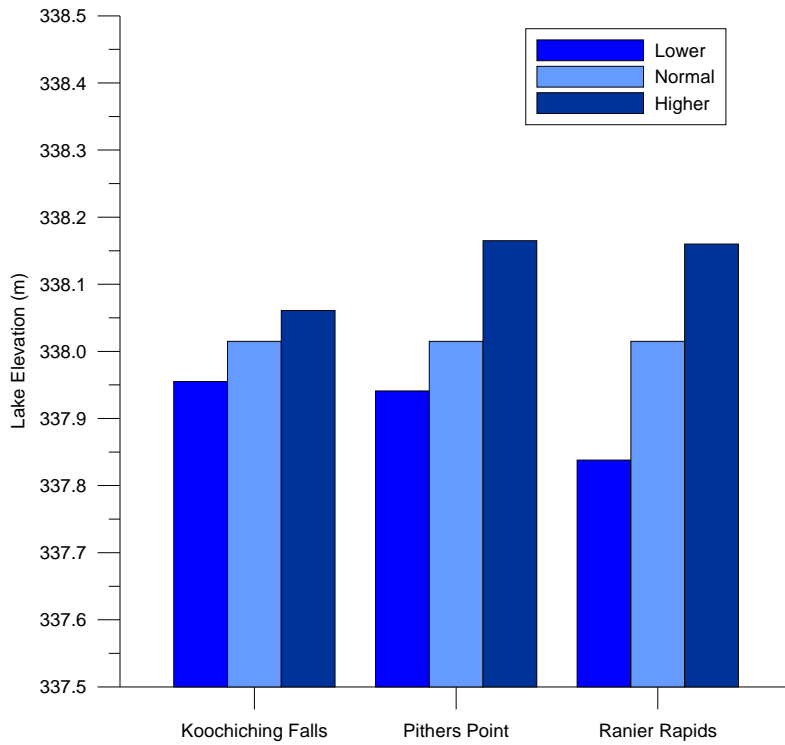


Figure 36 - Lake Level Sensitivity to 1 m Bathymetric Adjustments ($Q = 1000 \text{ m}^3/\text{s}$)

These results indicate that at higher flows through the Rainy River an adjustment to bathymetry at the Ranier Rapids would provide the greatest increase in conveyance had the greatest benefit to lake levels.

7 Sensitivity in State of Nature Rating Curve

As part of the Phase I study, a state of nature model was developed which included the best estimates of original bathymetry and no anthropogenic contributions, such as dams, bridges or piers. A state of nature rating curve was generated relating lake levels to steady-state flow rates and was presented in the Phase I report, and is reproduced here in Figure 37.

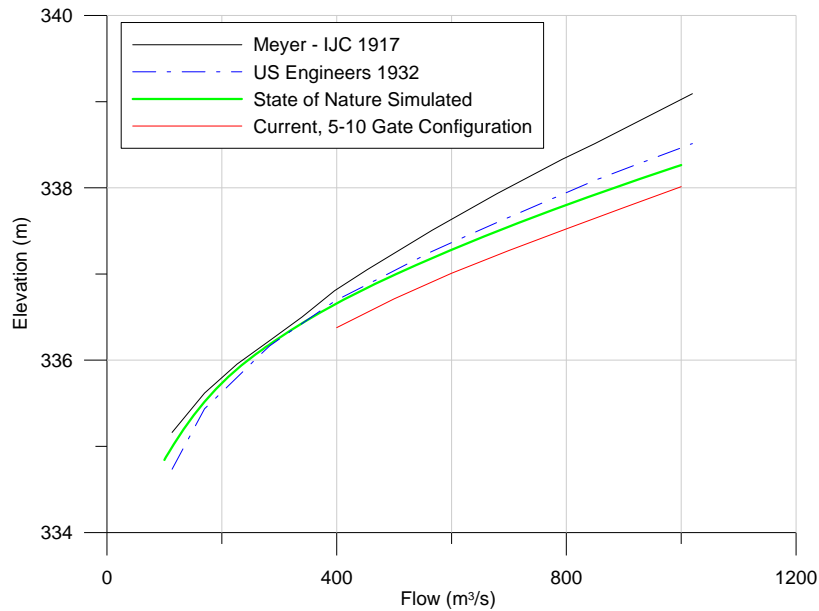


Figure 37 - Rating Curve Comparison for Rainy Lake Levels in a State of Nature

Figure 37 shows the simulated state of Nature rating curve, and two other curves suggested by US Engineers and Meyer [8]. Also plotted on Figure 37 is the maximum conveyance curve for the current configuration, representing an all-gates-open (or 5-10) and maximum powerhouse flow through scenario.

As one of the requirements of the Phase II investigation the sensitivity of the simulated rating curve to adjustments to roughness and bathymetry were investigated. The roughness sensitivity was performed by systematically adjusting the roughness in the model up and down by 10% of the prescribed values. The model was then run over a range of flow simulations from 100 to 1000 m³/s. The results are presented in Figure 38.

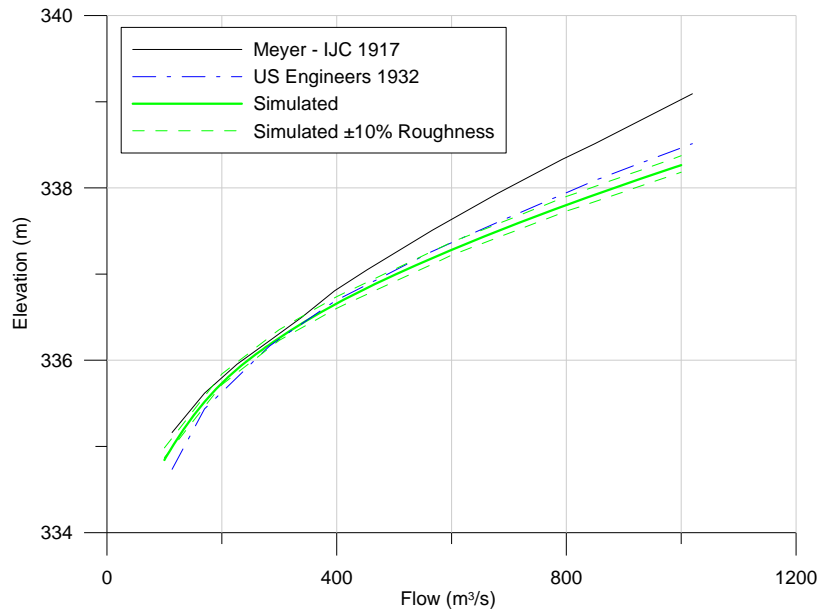


Figure 38 - State of Nature Rating Curve - Roughness Sensitivity

The rating curve is not very sensitive to fairly significant changes in roughness. At the lower flows ($100 \text{ m}^3/\text{s}$) the difference is approximately 0.03 to 0.07 m in lake level estimation. At the higher flows ($1000 \text{ m}^3/\text{s}$) the difference is 0.09 to 0.12 m. The range of elevations provided by the sensitivity analysis does not bring the rating curve in line with either the US or Meyer curve at the higher flows.

The sensitivity of the state of nature rating curve to changes in bathymetry was also examined. In order to perform this analysis a number of sections of restricted conveyance were identified within the model. The bathymetry within each area was then adjusted by 1 m up and then by 1 m down and the model was run to examine the hydrodynamic response. Some smoothing using the TELEMAC-STBTEL routines was conducted on the adjusted bathymetry to reduce sharp edges at the boundaries before the simulations were conducted. The selection of the areas was subjective but it does identify some degree of sensitivity of the model to local changes in bathymetry as well as the identification for opportunities to increase conveyance.

For the state of nature analysis three areas were highlighted as potential areas for opportunities for hydraulic improvement, similar to what was conducted in the bathymetric sensitivity analysis for the modern steady-state simulations (see Section 6) and they are highlighted in Figure 39. Simulations were conducted with 1 m positive and negative adjustments in bathymetry at all three of the areas. For each

area two additional simulations were conducted, at a flow of 1000 m³/s. Results of the simulations are shown in Figure 40.

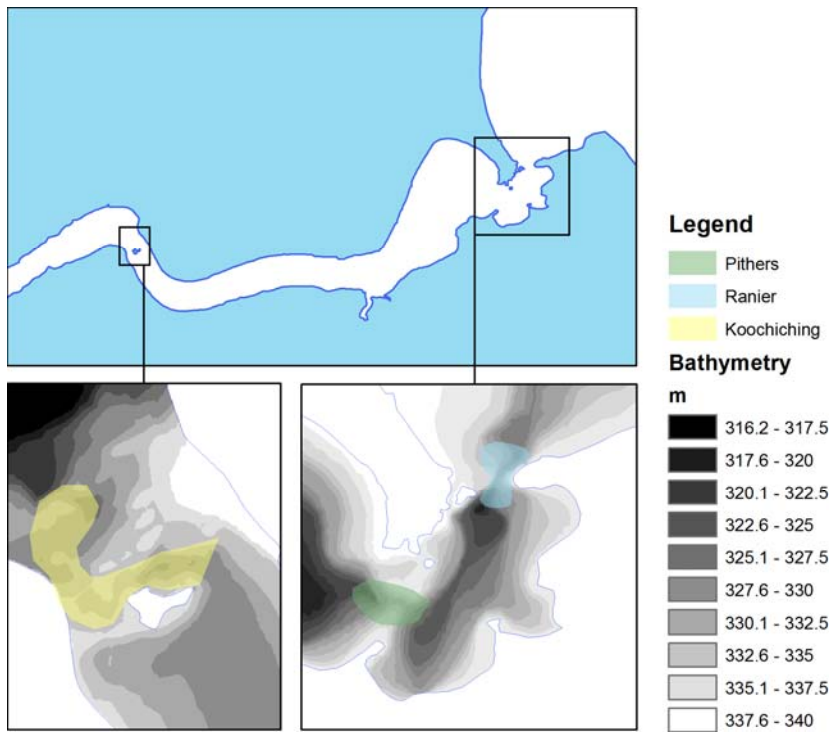


Figure 39 - Bathymetric Adjustment Regions

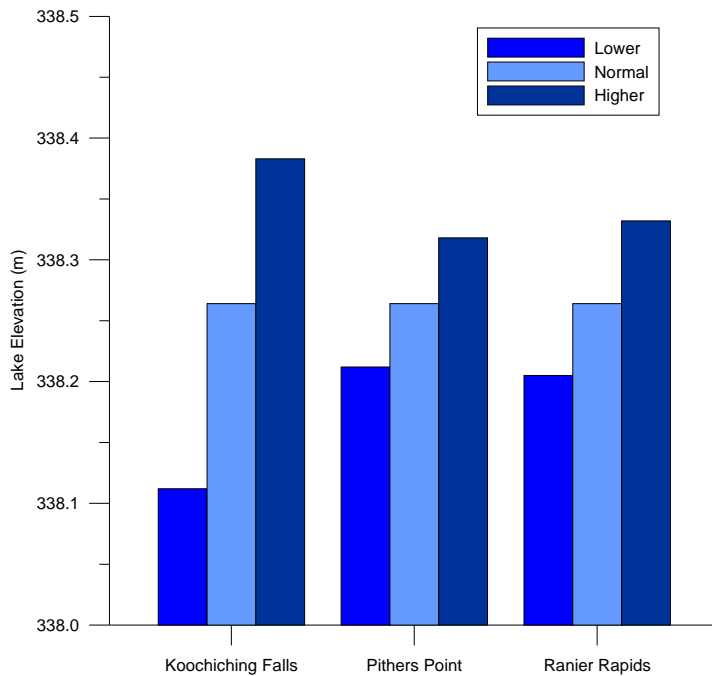


Figure 40 - Lake Level Sensitivity to ±1 m Local Bathymetric Change (Q = 1000 m³/s)

Here it can be seen the greatest adjustment in lake level is achieved by the changes in the Koochiching Falls dam area, with the ±1 m adjustment resulting in a 0.2 m lowering or a 0.12 m increase in lake level. The Rainer Rapids and Pithers Point influences were less, with the same bathymetric adjustments producing approximately ±0.05 m lake level changes. It appears that in the state-of-nature environment, without the extra capacity afforded by the adjustments in bathymetry and the addition of the canal, the Koochiching Falls remains the dominant hydraulic control at higher flows, based on these adjustments in bathymetry.

8 Summary and Conclusions

In summary, the 2D hydrodynamic model of the upper Rainy River and Rainy Lake developed in Phase I was improved and modified to answer a number of scientific questions relating to the conveyance, dam gate operations, variable powerhouse performance, and model sensitivity. Based on the simulations and analysis conducted the following conclusions may be drawn:

1. At a particular lake level beyond a certain number of open dam gates, the flow past the dam cannot be increased. Ensuring the lowest possible lake level would require all gates open only at very highest recorded flows, and such flows only occur on very rare occasions.
2. Comparison of the results of the four dynamic simulations to the observed lake levels shows that the model performs well at matching flows through the canal and dam gates. The model tends to underestimate peak lake levels, but only by a few centimetres (≤ 0.04 m).
3. The observed variable powerhouse performance does appear to be somewhat dictated by headwater levels, but the relationship is not as strong as expected and likely influenced by other factors as well, including the possibility of operational behaviour. The relationship between powerhouse performance and total outflow more closely matches observed results and provides more conservative set of conveyance curves, but it fails to provide a physical explanation for the variable powerhouse performance.
4. Adjustments to bathymetry at Ranier Rapids shows the greatest sensitivity to lake levels when compared to similar adjustments at Pithers Point and Koochiching Falls. Increasing overall conveyance of the upper Rainy River through bathymetric adjustment (e.g. dredging) would be best accomplished through closer examination of the Ranier Rapids.
5. The state of nature rating curve shows a relatively small sensitivity to changes in roughness. In the state of nature model lake levels show the greatest sensitivity to changes in the local bathymetry at Koochiching Falls, as compared to similar bathymetric adjustments at Pithers Point and Ranier Rapids.

9 Recommendations

1. The variable powerhouse performance could benefit from some closer examination, particularly with discussions of the powerhouse operators to get detailed explanations of why turbine flow-through rates are so much lower at high flows. Additionally, state variable analysis of the model, including flow vectors and turbulence upstream of the powerhouses, could provide more insight into the powerhouse performance behaviour.
2. Further investigation into the extra conveyance observed during the 1950 simulation period is warranted. Although the extra conveyance is only observed for a short period, and does not materially impact the prediction of lake levels, it does represent a deficiency in the modelling. A review of historical records would likely be required.
3. The bathymetric sensitivity analysis in this study was performed at a single high flow (1000 m³/s). A further investigation into the range of sensitivity over a range of flows could be examined, as could other dredging options in and around the Ranier Rapids area.
4. An investigation into potential increases into powerhouse performance could be investigated. Approximately 25% of the total outflow is passed through the waste gates (1999 – 2009 records). Theoretical increases in powerhouse capacity could be modelled and translated into an average annual increase in power production.

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