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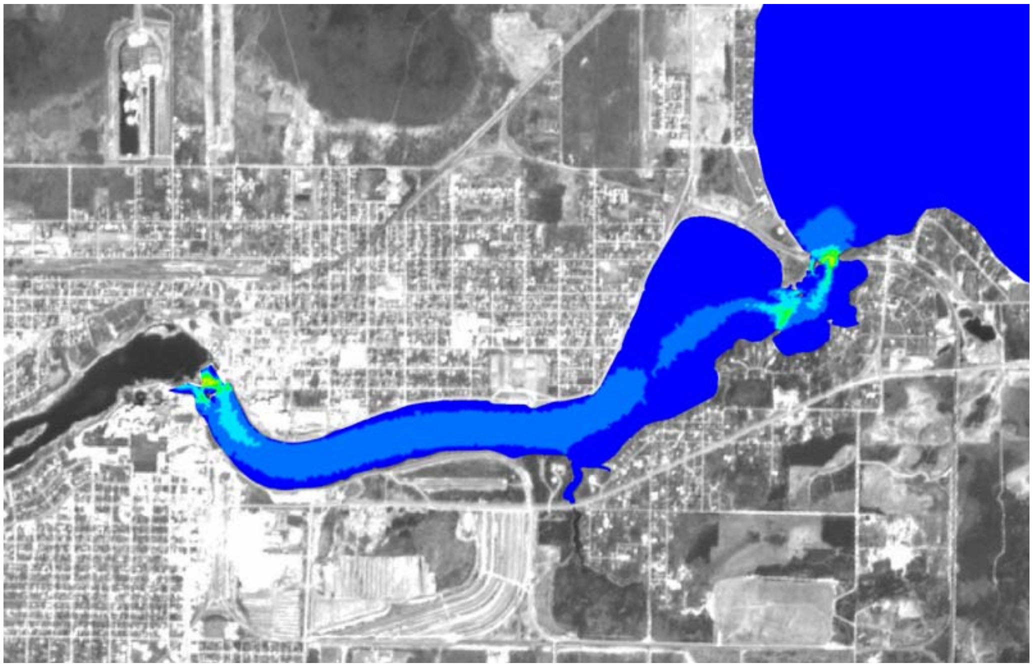
Rainy River 2D Hydrodynamic Model Conveyance Study



Controlled Technical Report CHC-CTR-112
September 2010

Prepared for:
International Joint Commission
234 Laurier Ave West
OTTAWA, Ontario
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National Research Council Canada
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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
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

NRC-CHC has prepared this report for the IJC in order to address some of the pressing issues in response to the communicated needs of the International Watersheds Initiative (IWI). The issues requiring investigation relate to Rainy Lake include the assessment of conveyance of the river reach from Rainy Lake to the dam structures at Fort Frances / International Falls.

In this study a two-dimensional hydrodynamic model was developed for the Rainy Lake / Rainy River system upstream of the dam at International Fall / Fort Frances. This model was calibrated and validated to sets of observed flow conditions.

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 1-1.

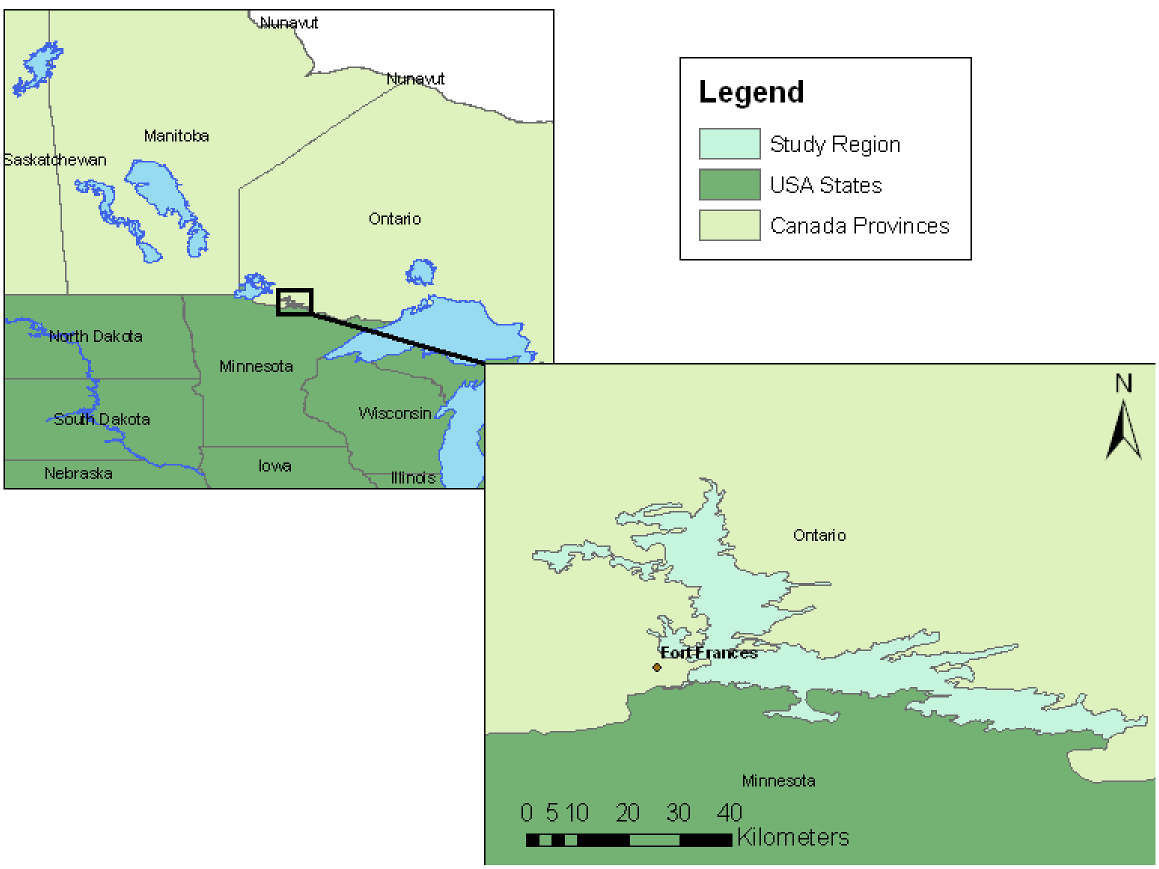

Figure 1-1 - Study Site Location - Rainy Lake

The Rainy River Basin is a shared resource between these jurisdictions and the Native Peoples for hydropower generation, water supply, navigation, recreation and tourism [5]. 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 15ft (4.6 m) deep [1]. 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 [6].

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 called the Namakan “Chain” of Lakes.

1.2 Project Scope and Objectives

The main immediate objective of the IJC and the local IJC boards is to determine, in a scientifically defensible manner, the impact that adjustments to the dam operating rules may have on flow from the Rainy Lake and consequently on lake levels. Related to this overarching objective is the requirement for a clearly defined communication deliverable that can explain to the Rainy River local stakeholders the following:

- How does the gate configuration affect conveyance in the Rainy River?
- Can a numerical model be developed that can simulate dynamic scenarios such as the 2002 flooding event?
- What is the “state of nature” conveyance of the channel?

1.3 Approach

The approach as outlined in the original proposal was to first assist with a bathymetric study and site visit, which has been conducted by Environment Canada of the upper

Rainy River. The modelling approach was to be selected based on the results of the bathymetric study and the observations made at the site visit. One-dimensional (1D) hydraulic and two-dimensional (2D) hydrodynamic modelling approaches were considered. In discussions with members of Environment Canada and after observing the degree of complexity in the bathymetric data and the two-dimensional flow, even at low flows, it was determined a 2D hydrodynamic model would be most appropriate approach.

The modelling approach selected involved the development of a TELEMAC 2D hydrodynamic model. The TELEMAC software is maintained by the Laboratoire national d'hydraulique et environnement d'Électricité de France (EDF) in Chatou. It solves the two-dimensional shallow water equation using finite element techniques. TELEMAC is used by more than 200 organisations around the world and as of January 2nd, 2010, TELEMAC 2D software is available as freeware. The pre- and post-processor for TELEMAC is BlueKenue, a model development and visualization tool developed by the National Research Council - Canadian Hydraulics Centre (NRC-CHC) [8].

The Rainy Lake / Rainy River model was developed in three stages to encompass the domain including the river and a small portion of the lake up to the nearest level gauge, a larger model to encompass most of Rainy Lake, and a third model that extended downstream to model the "state of nature" scenarios.

Bathymetry and land elevation data obtained in an Environment Canada Survey conducted as part of this study were incorporated into the model, as were details of the operation of the powerhouses and dam/canal gates. The model was calibrated to match measured lake levels at two near-steady state mean- and high-flow periods. The model was then validated against 2 independent periods. The validated model was then applied to in a dynamic context to evaluate its predictive performance during a large rainfall and a large snowmelt event, acting as a supplementary validation of the calibrated model.

The state of nature model was developed employing bathymetry from previous studies and was used in simulations to develop conveyance rating curves, which were then compared to other previously published state of nature rating curves.

1.4 Report Structure

Section 2 describes the development of the hydrodynamic model in terms of boundary delineation, mesh development, and the incorporation of bathymetric data and artificial structures.

Section 3 summarizes the available hydrologic and hydrometric data available for this study. Included are the available stations for flow input into and out of Rainy Lake, available lake level data, and the operation and calculations used in the dam and gate operations at the International Falls Dam.

Section 4 outlines the steps by which the model was calibrated and validated, and also reviews the boundary condition configurations employed in this modelling study.

Section 5 summarizes the results from the modelling simulations including the conveyance analysis, dynamic simulations and the "state of nature" analysis.

Sections 6 and 7 outline the conclusions and recommendations of this study, respectively.

2 MODEL DEVELOPMENT

For this study three separate two-dimensional (2D) hydrodynamic models were developed to investigate the upper Rainy River. The models were developed for use with the TELEMAC2D hydrodynamic model code, and required the construction of a triangular computational mesh for each model, which discretizes the domain in two dimensions. At each point or node of the mesh the program calculates the depth of water and the velocity components in two dimensions. This section outlines the detailed construction of the TELEMAC2D [2] mesh and model for the Rainy Lake / Rainy River.

2.1 Coordinate Systems

For this modelling effort a common vertical datum was employed USC&GS1912 / United States Coast and Geodetic Survey (1912) datum. All elevation data were either provided at this datum or converted to this datum and all elevations reported in this document reported at this datum unless otherwise stated.

The coordinate system employed in this study was UTM – Zone 15. During simulations the developed models used a modified coordinate system which adjusted the UTM values closer to the origin (Easting: -470000, Northing: -5380000), to reduce numerical precision errors in the visualization tools when reporting findings.

2.2 Model mesh description

TELEMAC2D is a depth-averaged two-dimensional model that requires a mesh to discretize the physical system into a set of numerical triangular elements. The mesh is unstructured, allowing the size of the elements to vary. A fine mesh will allow proper representation in the model of certain fine details such flow around bridge piers or jetties. A coarse mesh is less accurate in the representation of these details, but will result in a smaller number of elements, requiring less computing time.

Each of the 3 nodes of the triangular elements is assigned an elevation corresponding to the bathymetry of the river or the topography of the land, and the water velocity vector (averaged over the depth) and water depth are computed at these nodes.

Three different model meshes occupying three different physical domains were developed during this study:

1) Rainy Lake (Mesh 1)
2) Upper Rainy River (Mesh 2)
3) “State of Nature” Upper Rainy River (Mesh 3)

The first model (Mesh 1) included the Rainy River, starting from the international falls dam, upstream to all of the Rainy Lake up to Namakan Lake. The model domain was developed in two stages. A high-detail domain was delineated for the section from the dam at international falls upstream to include a portion of Rainy Lake approximately 4 km upstream of the railway bridge at Ranier Rapids. The high-detail domain around Rainy River was delineated employing 1:50 000 digital base maps provided by NRCan via GeoBase (www.geobase.ca), but was then refined using aerial photography data as provided by Google Earth (earth.google.com), to match coastal details. There are three islands in the Rainy River model domain. Two identified near Pither's Point and a third beneath the road bridge at International Falls / Fort Frances.

A second low-detail domain was delineated that included the remainder of Rainy Lake. The original boundary was delineated based on 1:50 000 digital base maps provided by NRCan via GeoBase. The domain as delineated from the 1:50 000 maps was smoothed to facilitate mesh generation and improve model performance.

Mesh 2 included a modified subset of the larger Mesh 1. This smaller mesh contains only the high resolution portion of Mesh 1 from the International Falls Dam to Rainy Lake approximately 4km upstream of Ranier Rapids. Mesh 2 was used to calibrate the Rainy River, as the smaller domain allowed for more rapid simulations.

The Mesh 3 domain was required for the simulation of the "State of Nature" environment. Mesh 3 was generated by extending Mesh 2 approximately 5km downstream from the dam, with the dam boundaries removed. This extension of the model allowed for a backwater curve to fully develop and properly estimate elevations downstream of the Koochiching falls.

The domains of all three meshes are shown in Figure 2-1. The domain of the Upper Rainy River (Mesh 2) is highlighted on the larger Rainy Lake (Mesh 1).

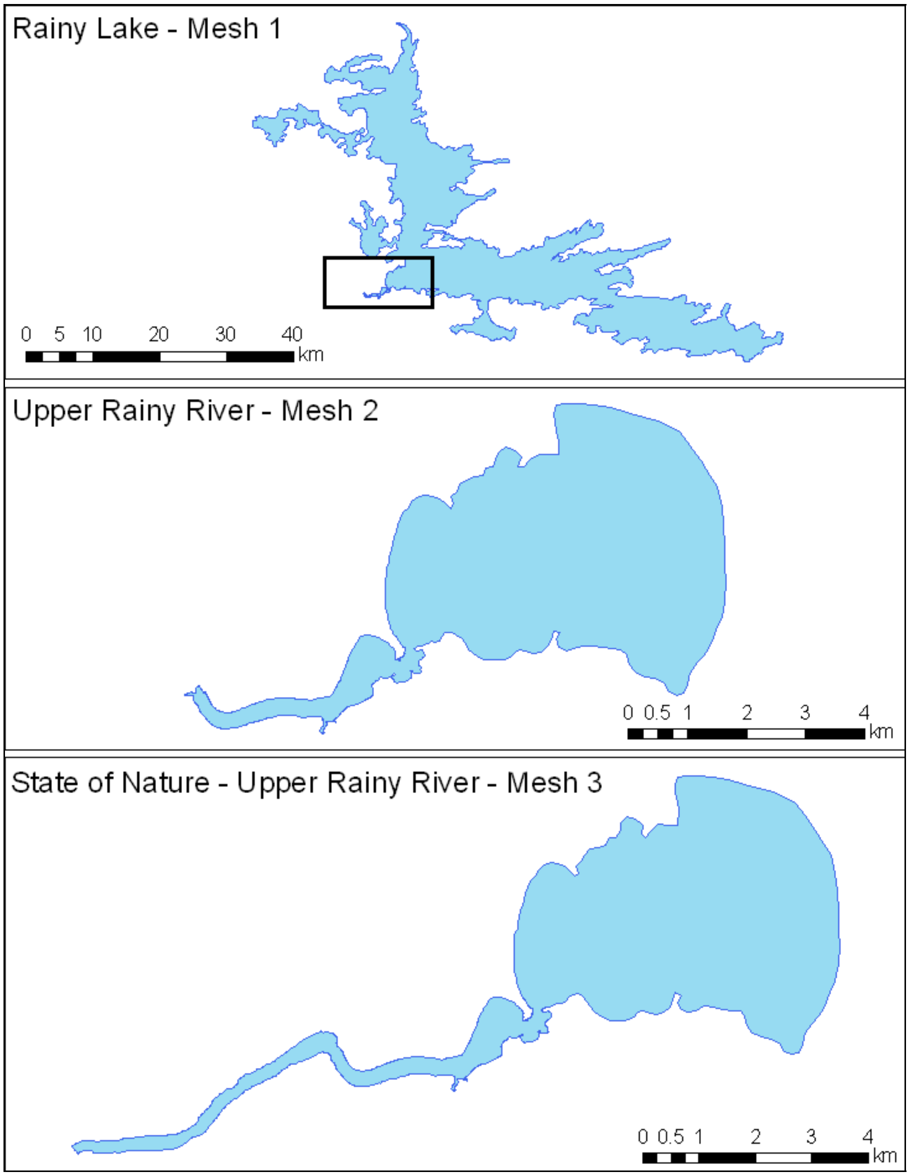

Figure 2-1 - Model Domains

2.3 Structures

A number of physical structures in place within the Rainy River required explicit description in the 2D hydrodynamic model. These included:

1. The piers of the railway bridge at Ranier Rapids
2. The piers of the road bridge between the towns of Fort Frances and International Falls
3. The dam / canal structure at Fort Frances and International Falls

2.3.1 Ranier Rapids Rail Bridge

A railway bridge crosses the Rainy River at the narrows at Pither's Point and Ranier Rapids. The size and orientation of the bridge piers was important information for inclusion into the hydrodynamic model.

As-built drawings of the rail bridge were obtained from Boise Inc., which included two separate drawings, one of the pier dimensions, created by Minnesota and Ontario Power Co., and a second of a vertical cross section, created by George A. Ralph Consulting Engr. of the rail bridge with channel bottom and pier positions. The drawings were digitized and geo-corrected. The resulting bridge pier locations are shown in Figure 2-2.

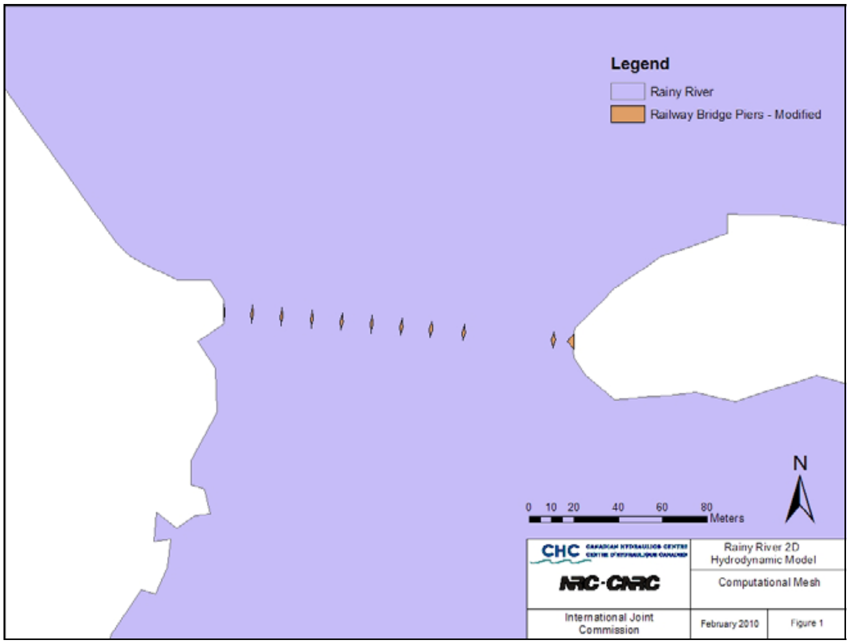

Figure 2-2 - Ranier Rapids Bridge Piers

2.3.2 Fort Frances / International Falls Bridge

A road and rail bridge stretches across the Rainy River connecting Fort Frances and International Falls. The bridge carries road and railway traffic with the railway traffic along the west side of the bridge. The bridge was constructed immediately over the shallows of the Koochiching rapids just upstream of the dam that was constructed in 1905. The bridge was constructed in two phases, and was widened (to the south east) to accommodate an increase in road traffic and a location for Canadian Customs inspection on the bridge (which has since been moved onshore). The drawings were digitized and geo-corrected. The pier and bridge locations are presented in Figure 2-3.

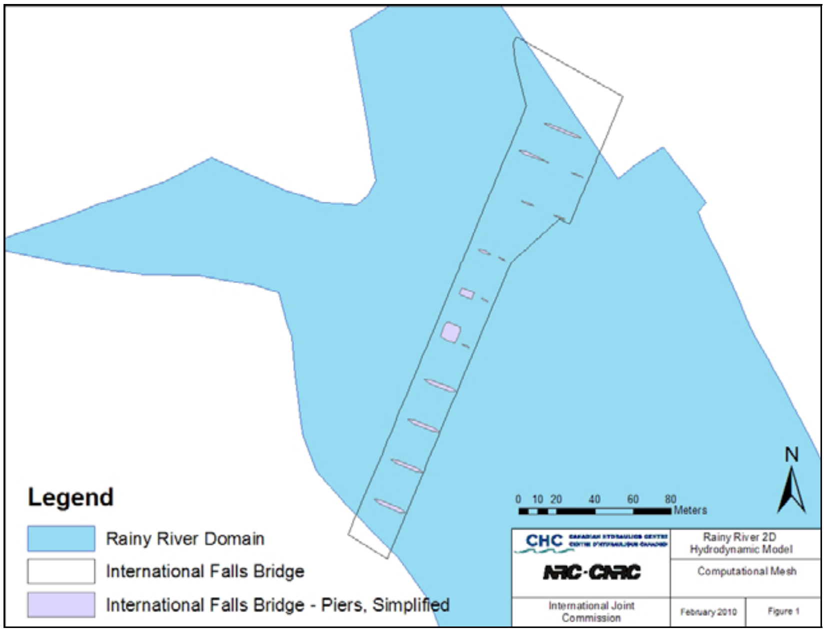

Figure 2-3 - International Falls Bridge Piers

2.3.3 Fort Frances Dam Power Generation and Gates

The dam at Fort Frances/International Falls was used as a downstream boundary for the model. The model follows the immediate upstream edge of the powerhouses, the dam, and the canal boundary. Boundary condition types and conditions for the powerhouses and the gates were varied depending on the type of simulation run, and are described more fully in Section 4.1.

2.4 Elevation Data – Current Scenario (Mesh 1 and Mesh 2)

Elevation data were obtained from a number of sources for the generation of the TELEMAC2D model bathymetry. The elevation data sources included:

1. EC Bathymetric Survey
2. EC Land Survey
3. Surveyed cross sections from as-built drawings of bridges
4. Nautical Charts published by the Canadian Hydrographic Services

All elevation data in this study were converted to USC&GS1912 datum if necessary.

2.4.1 EC Bathymetric Survey

A bathymetric survey was conducted by Environment Canada in October 2009 of the Rainy River upstream of the International Falls dam. Data were provided in the USC&GS1912 datum.

The resulting survey produced approximately 325 000 geo-corrected bathymetric data points over the domain. The results of the bathymetric survey are shown in Figure 2-4, which displays the high density of the data collected and the extent of the survey from the dam to approximately 500m upstream of Ranier Rapids.

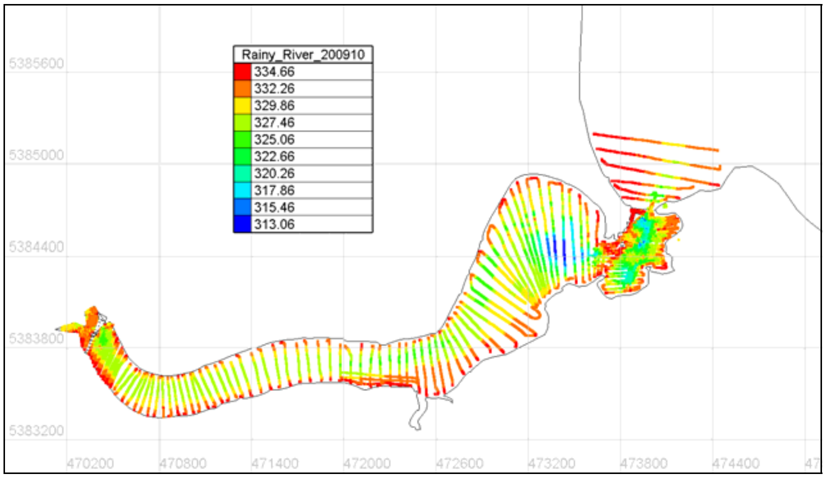

Figure 2-4 - EC Bathymetric Survey Extent

As the bathymetric data were geo-positioned using GPS, requiring line-of-site to satellites, the geometry under and very near the two bridges was unobtainable. The extent of the bathymetric survey at the two bridges is shown in Figure 2-5 and Figure 2-6. In these two figures it can be seen that much bathymetric data are missing at these critical points. In Figure 2-5 the bathymetric data show a good deal of complexity around the bridge, which is the site of the Koochiching Falls. Likewise the crossing at Rainer River shown in Figure 2-6 shows a similar degree of bathymetric complexity. However, the surveyed cross section just north of the bridge is approximately 50 m upstream from the narrows whereas the nearest downstream surveyed cross section is virtually adjacent to the bridge. This dataset provides some problems for bathymetric interpolation and the geometric complexity would unlikely have been accurately represented with the provided data. As such more data were obtained from previously conducted cross sectional surveys provided with the bridge construction drawings to provide better bathymetric estimates under the rail bridge (see Sections 2.4.3 and 2.4.4).

Figure 2-5 - EC Bathymetric Survey - International Falls Bridge

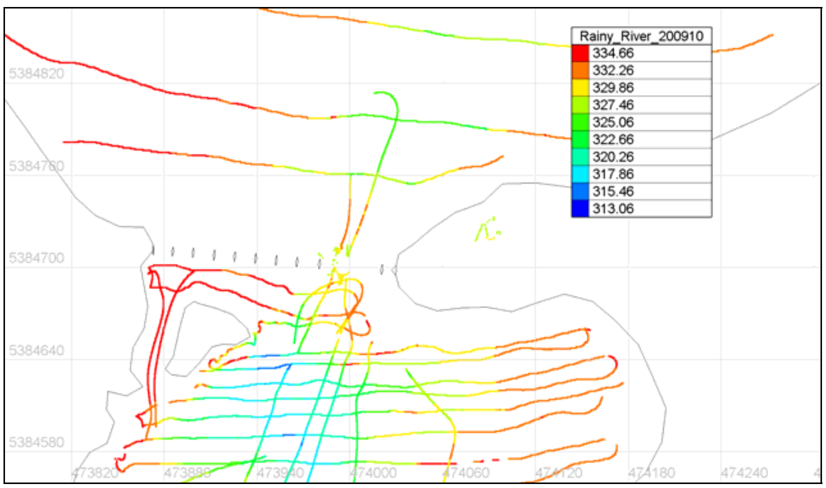

Figure 2-6 - EC Bathymetric Survey - Ranier Rapids

2.4.2 EC Land Survey

A land survey was conducted concurrently with the bathymetric survey by Environment Canada to delineate the shore line and provide elevations along the coast and near-shore. In addition to the elevations at the coast a number of points were collected at or on some of the structures, including the dam itself. A total of approximately 1900 survey points were collected and the extent of the survey is presented in Figure 2-7. Land survey data were provided with a CGVD28 datum and were adjusted to the USC&GSD1912 datum by adjusting the elevations by 0.25 m (Rick Cousins, personal communication). Water surface elevations were explicitly identified in this survey and these were used to verify the datum adjustments when compared to lake levels measured at the time of the survey. Although not a precise verification, there was general agreement between the two levels (+- 5 cm), which validated the applied elevation correction.

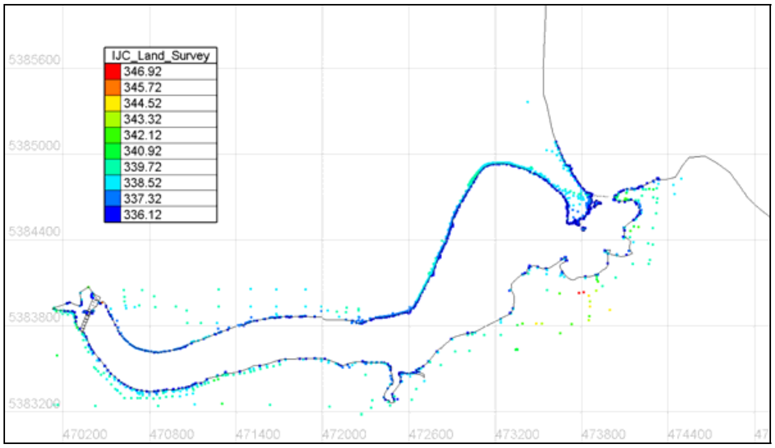

Figure 2-7 - EC Land Survey Extent

Survey details at the Ranier Rapids and the International Falls Bridge are presented in Figure 2-8 and Figure 2-9, respectively. In both cases the close matching of the survey to the computational boundaries can be observed, as well as the location of the islands within the domain.

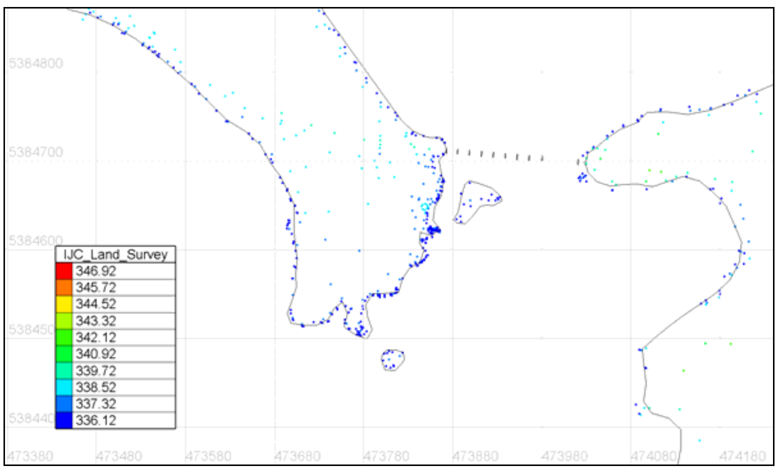

Figure 2-8 - EC Land Survey - Ranier Rapids

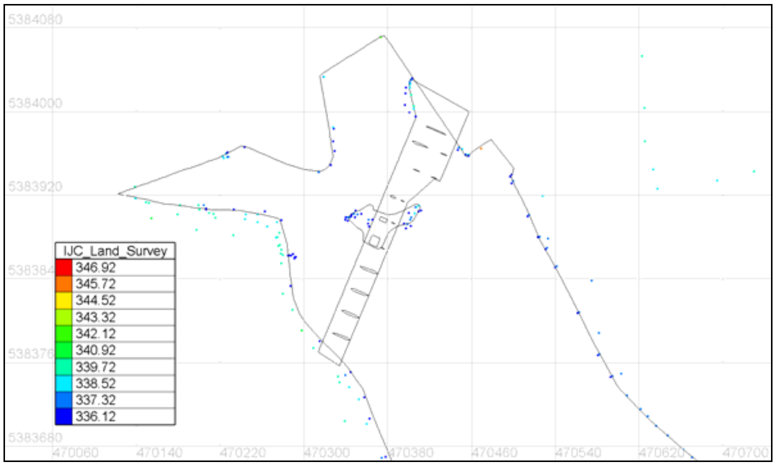

Figure 2-9 - EC Land Survey - International Falls Bridge

2.4.3 International Falls Bridge Contour Data

As mentioned previously in Section 2.4.1, a section of the river under the International Falls Bridge was unobtainable from the bathymetric survey due to the satellite line-of-sight requirement for the GPS system. The accuracy of the distance weighting interpolation underneath the bridge was deemed insufficient considering the complex bathymetry in the area. Other data were acquired that more accurately described the bathymetry beneath bridge from previously conducted surveys and cross sectional data. The as-built drawings of the bridge were obtained from which the pier size and positioning were extracted for the numerical model (Section 2.3.1). Also contained in these drawings were contours of the channel bottom around the river. The contour elevations were digitized from the drawings, geo-corrected and compared to the EC bathymetric data. The method of isolating and including the appropriate contours into the bathymetric dataset is outlined in Appendix A.

Although measured bathymetric data under the bridge would have been ideal, the inclusion of the contour patterns is believed to be the best possible representation of the existing bathymetry considering available data. The final interpolated bathymetry data at International Falls Bridge is shown in Figure 2-10.

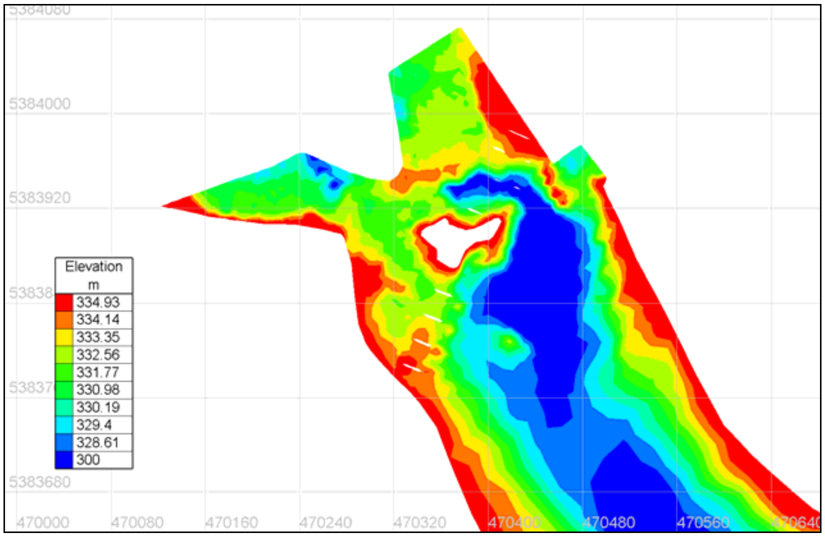

Figure 2-10 - Interpolated Bathymetry at International Falls Bridge

2.4.4 Ranier Rapids Railway Bridge Cross Section Data

The narrows at Ranier Rapids adjacent to the rail bridge represent an important potential hydraulic control point in these investigations. The importance of determining an accurate cross section at the narrows was considered of paramount importance. Difficulties were realized when the bathymetric data from the EC bathymetric survey were interpolated over the domain considering the 50 m distance between measured bathymetric cross sections on either side of the bridge. To mitigate this effect, cross section data obtained from the rail bridge as-built drawings used in the delineation of the bridge piers was added to the model. The details of this process is described more fully in Appendix A. Figure 2-11 shows the interpolated bathymetry when the bridge survey cross section is included in the calculations. It is important to note that the main channel is narrowed through this addition, and it fits within the bridge piers.

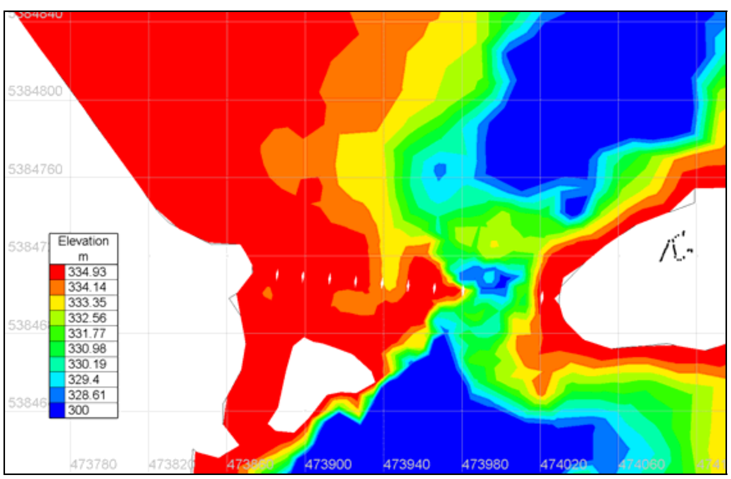

Figure 2-11 - Interpolated Bathymetry with Bridge Survey Cross Section

2.4.5 CHS Nautical Chart Data

Although not considered critical for the analysis of the conveyance of the Rainy River, some bathymetric estimates were required for the remainder of Rainy Lake to complete the model development. Without any detailed bathymetric surveys discovered, the best available bathymetric data were available from the Canadian Department of Fisheries and Oceans (DFO) – Canadian Hydrometric Service (CHS) Nautical Chart Data. Nautical charts for Rainy Lake were obtained which have recorded depths throughout the lake. These charts were digitized, geo-corrected, and converted to provide an estimate of lake bathymetry. In general, point measurements were extracted from the CHS charts, but for some areas detailed contours were digitized to compensate for localized bathymetric mis-representation due to the interpolation algorithms employed. A high-detail map (CHS Map Number: 6108, Scale: 1:25,000) was employed for the area of the lake nearest the Rainy River outlet and a lower-detail map (CHS Map Number: 6105, Scale: 1:100,000) was employed for the remainder of the lake. Figure 2-12 shows the bathymetric points from CHS employed in the TELEMAC2D model.

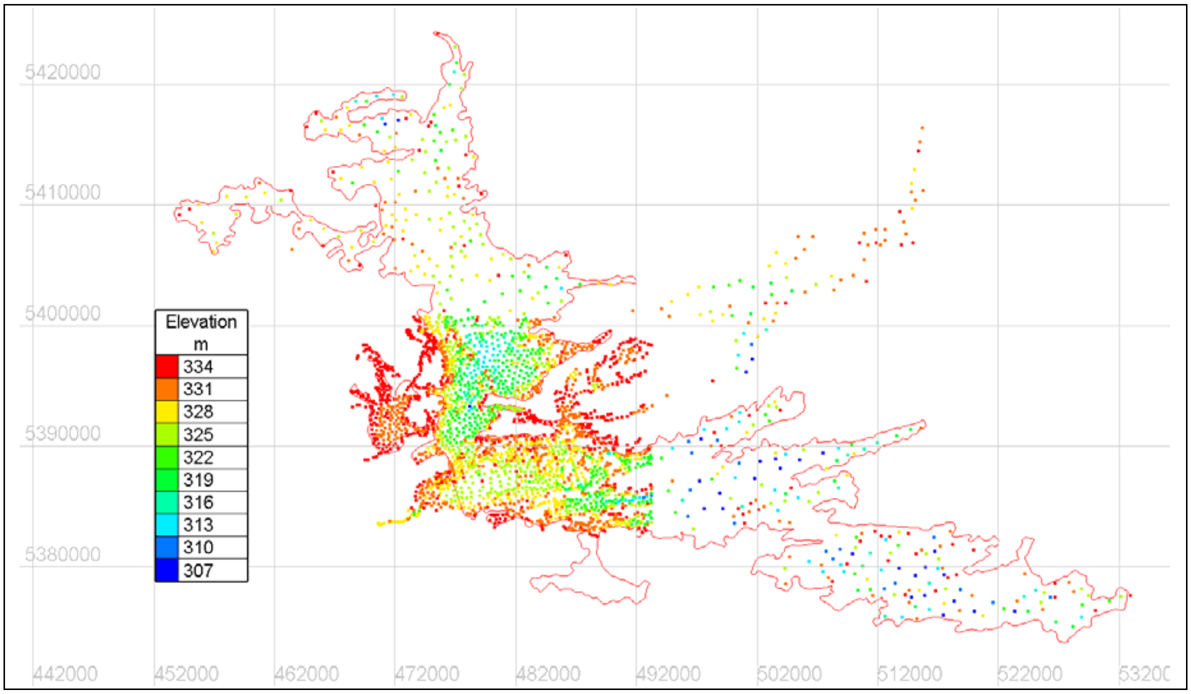

Figure 2-12 - CHS Bathymetric Points

2.5 Elevation Data – "State of Nature" Scenario (Mesh 3)

The assessment of the "State of Nature" of the Rainy River required the acquisition of the earliest possible collected bathymetric data for the river from Koochiching falls to Pither's point at Ranier Rapids. Plates containing estimated bathymetric contour maps from early reports were obtained from Environment Canada [10]. These maps were digitized and geo-corrected to match the UTM-15 coordinate system and USC&GS1912 datum employed in this study.

2.5.1 Model Extension

To examine the state of nature the model was extended approximately 5km downstream from the location of the Koochiching Falls Dam. No detailed State of Nature data were discovered for most of that section. In lieu of available state of nature bathymetric data downstream of Koochiching Falls, cross sectional data obtained by the USACE as part of the Rainy River study Downstream of the Koochiching Falls Dam was employed (USACE, unpublished data).

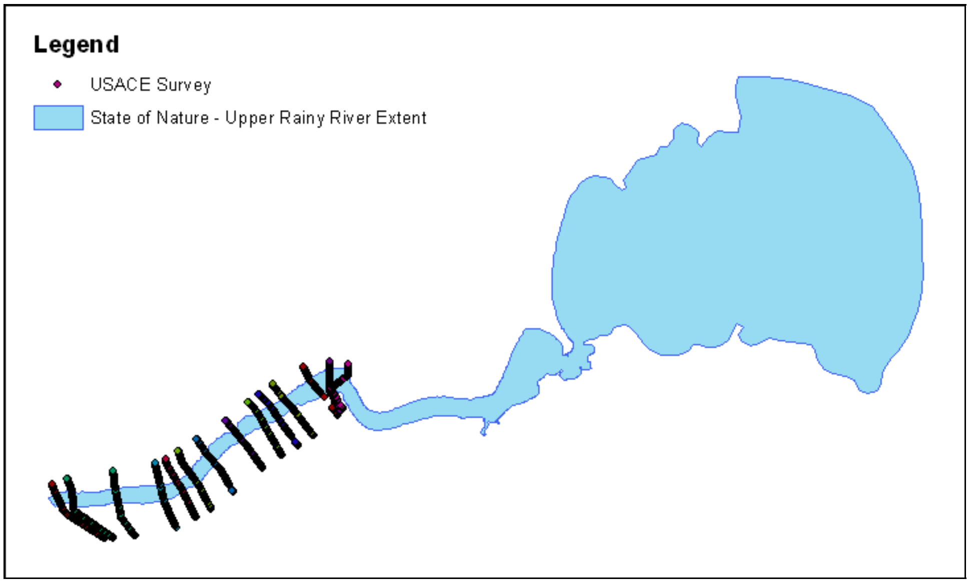

Figure 2-13 - State of Nature - Extended Model Domain and USACE Cross Section Data

The roughness values for this extension were also extracted from the USACE HEC-RAS model and were not otherwise adjusted.

2.5.2 State of Nature Bathymetry

The bathymetry for the state of nature was adjusted from the original bathymetry to try to best match the pre-dam construction. Contour data maps of the IJC 1916 study obtained from Environment Canada (Plates 76-79) [10]. Three plates were digitized, one for the Rainy River, and one for the Ranier Rapids and Koochiching Falls respectively. All figures were geo-corrected using at least 5 control points common to the mesh domain and the contour maps. Figure 2-14 shows the results of the digitized and geo-corrected contour data. For the bathymetric input the higher resolution contours were employed at the Ranier Rapids (5ft) and Koochiching falls (2ft) and the lower-detail Rainer River bathymetric data (10ft) was ignored in these sections. Contour data were geo-corrected and converted from the Public Works Department datum to the USC&GS1912 datum.

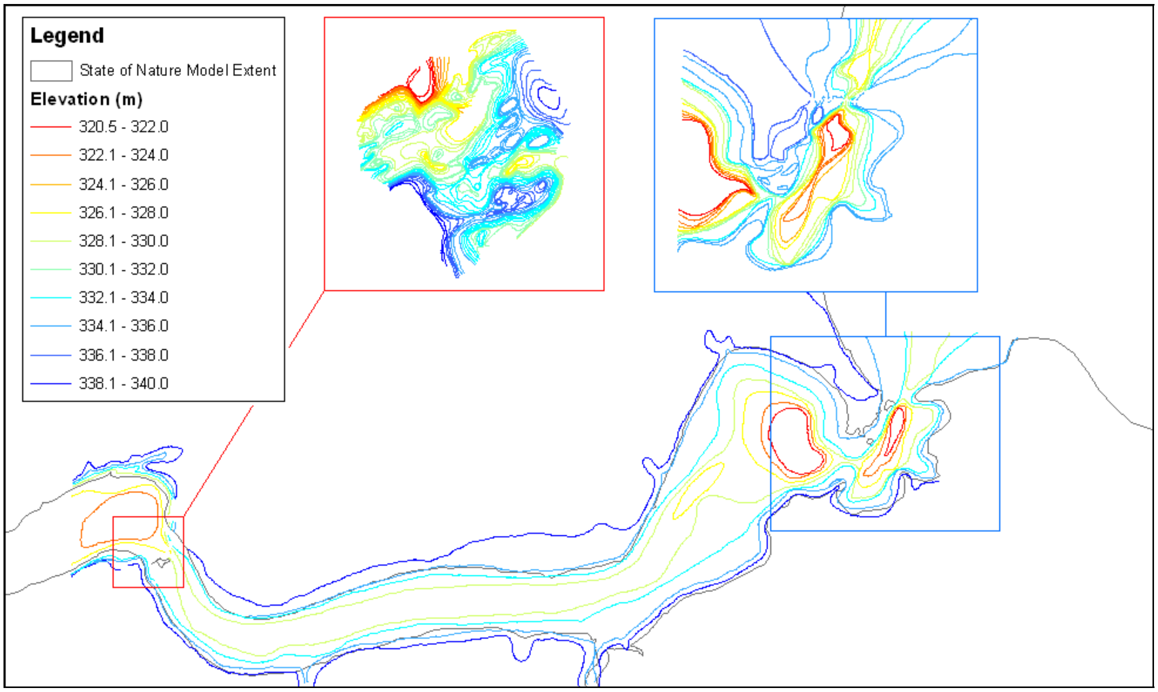

Figure 2-14 - State of Nature Bathymetric Data Contour Data

2.5.3 Bathymetric Comparison

The digitized bathymetric data of the state of nature were applied to the Upper Rainy River model in the same way the bathymetric survey data conducted in 2009 had been. The bathymetric interpolation results between the 2009 survey and the state of nature data were compared by extracting twelve of cross sections along the length of the river and plotting the cross sectional profiles. All figures are shown in Appendix D. In general the profiles agree well, but of note are the differences in the cross sectional data for Rainer Rapids and the Koochiching Falls. In both cases the differences are significant, and for Ranier Rapids in particular more cross sectional area is observed in the cross section in the current bathymetry than the state of nature bathymetry.

Concerns had been raised about deposition of materials within the channel over the intervening period from the early surveys to present day. These cross sectional comparisons are not conclusive. However, the stark changes in bathymetry near Koochiching falls point to deposition or excavation over the intervening period, provided the original surveys can be relied upon.

2.6 Computational Mesh Generation

The computational mesh was generated using the BlueKenue software system developed by NRC-CHC [8]. The BlueKenue mesh generator was employed using a Delauny triangulation algorithm constrained by boundary node spacing to generate the preliminary computational mesh. This mesh was then manually refined to improve performance and define boundary conditions. Finally, bathymetry data were incorporated into the model using a quadrant-based inverse distance weighting scheme to determine the elevation at each computational node.

The resulting computational mesh for the entire domain (Mesh 1) included approximately 25,000 nodes. The high-detail region of the Rainy River (Mesh 2) included approximately 9,000 nodes with the remainder accounting for the lake itself. The initial separation of the mesh into two regions (Rainy River and Rainy Lake) allowed for the easy separation of the two computational domains once boundary conditions at the interface could be established. In this way the Rainy River sub-mesh may be run in isolation of Rainy Lake for calibration, therefore using a small model which would run more quickly. The state of nature model (Mesh 3), which included a downstream extension of the original Rainy River mesh contained approximately 14,000 nodes. Figures of the meshes are presented in Appendix B.

3 HYDROLOGY AND HYDROMETRIC DATA

This section summarizes the available hydrologic and hydrometric data employed in the development of the hydrodynamic model.

3.1 Summary of Available Hydrometric Data

Hydrometric data were obtained from a number of sources to facilitate operation of the TELEMAC2D model of the Rainy Lake / Rainy River. Hydrometric and operational data were obtained from the following sources:

1. Environment Canada – HYDAT hydrometric Database [3]
2. USGS – Online River Data [9]
3. Environment Canada, LWCB – Historical Records of Flow and Lake Level Data
4. Boise Inc – Operational rules for turbines on US side of River
5. Abitibi – Operational rules for turbines and gates on Canadian side of River

The network of available data were relatively sparse for the Rainy Lake / Rainy River model. Figure 3-1 shows a map of the region with the EC and USGS hydrometric stations included. Five level gauges are available in the region for the Rainy and Namakan Lakes. Ten flow gauges are available for this region. Analysis of the data and their utility in this study are described in the following sections.

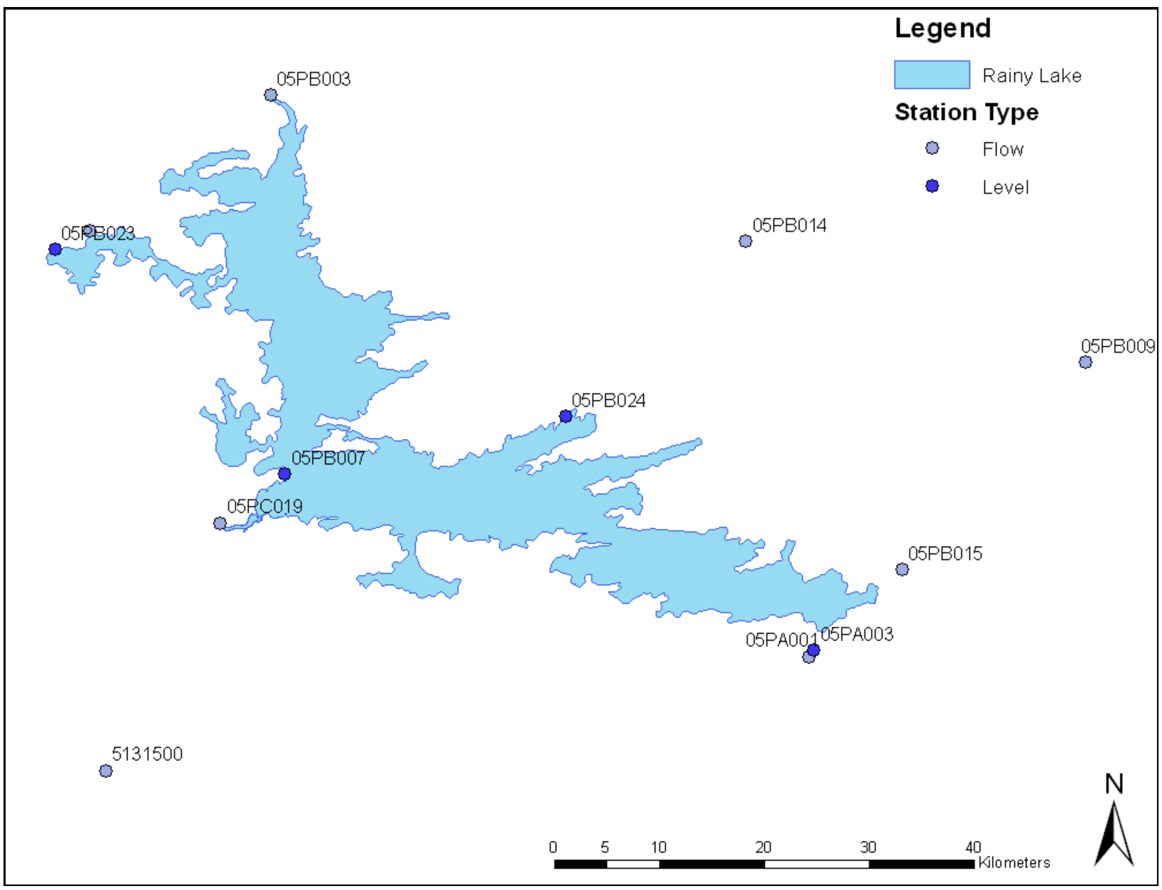

Figure 3-1 - Rainy Lake Hydrometric Network – EC and USGS

3.2 Stream Flow Data

There are a number of rivers contributing to Rainy Lake. Environment Canada has substantial continuous records within the HYDAT database for a number of stations feeding into Rainy Lake as well as the Rainy River outflow at Fort Frances. Other flow data were obtained directly from Abitibi Bowater (Marc Mantha) and LWCB (Rick Cousins), including outflows from Namakan Lake and calculated total Rainy Lake inflows. All streamflow is reported as daily averages.

Table 1 presents the available Environment Canada flow station data, including the drainage areas above the stations and the mean and 30^{th}, 50^{th} and 70^{th} percentile flows. The flow duration curve (FDC) for each of the stations for the last 20 years of available data are shown in Figure 3-2. Stations with a full Station number (e.g. “05PB009”) are obtained from HYDAT. Those with a different station number (e.g. “STN 54”) are retained by the EC-LWCB and were provided independently. As HYDAT is published infrequently, the data from LWCB was most current and included 2010 data, although they were not subjected to the QA/QC procedures conducted by the Canadian Water Survey. Data from the LWCB was provided from August 1999 to February 2010.

The Seine and Turtle rivers are the two largest contributors to lake inflow along with the Namakan Lake discharge. The Seine River discharge is regulated from the Sturgeon Falls generating station by Abitibi Bowater. The Turtle River discharge near mine centre is an unregulated discharge source. Pipestone River and Atikokan River are unregulated but small total flow contributors and the Pipestone River gauge was discontinued in 1998. The Rainy River at Fort Frances station is a calculated flow based on turbine flow-through and gate flow estimates provided by Abitibi Bowater and Boise to Environment Canada.

Table 1 - Stream Flow Stations

Station Name	Station Number	Drainage Area (km²)	Mean Flow (m^3/s)	Q_{30} (m^3/s)	Q_{50} (m^3/s)	Q_{70} (m^3/s)
Seine River at Sturgeon Falls Generating Station	05PB009/ STN 54	5880	43.8	24.6	37.4	45.6
Turtle River Near Mine Centre	05PB014	4870	37.8	19.3	29.7	48.1
Pipestone River Above Rainy Lake	05PB015	443	3.8	1.1	1.9	3.6
Atikokan River at Atikokan	05PB018	332	3.0	1.5	2.3	3.5
Rainy River at Fort Frances	05PC019	38600	277.2	135.0	218.0	319.0
Namakan-Kabetogama Total Outflow (calculated)	STN 47	n/a	156.3	84.4	117.8	175.8
Kabetogama-GoldPortage Outflow	STN 46	n/a	7.6	1.5	5.9	12.1
Namakan Kettle Falls Outflow	STN 44	n/a	148.4	79.4	113.0	166.9
Rainy Lake Inflow (calculated)	STN 176	n/a	293.5	144.5	204.2	313.9

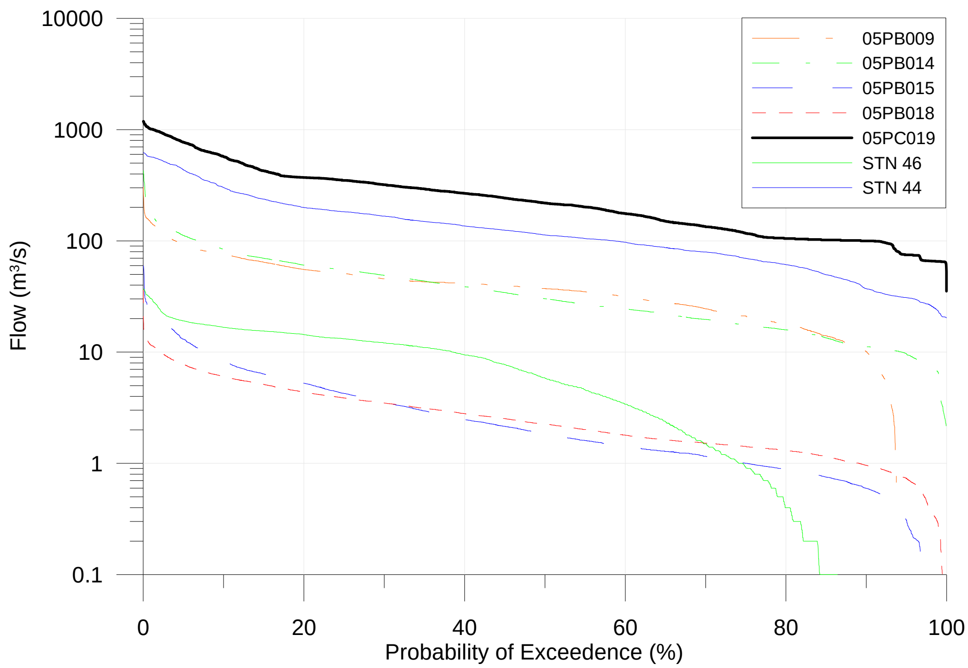

Figure 3-2 - Flow Duration Curves, Rainy Lake Flow Data

3.3 Lake Level Data

Lake level data were obtained from Environment Canada, and was critical for model calibration and boundary condition configuration. One station was found in HYDAT that had adequate records, the Rainy Lake level gauge near Fort Frances (Stn 57). The Bear Pass gauge was provided by EC-LWCB as were the forebay levels at the US and Canadian powerhouses. The forebay and gate levels, along with the Rainy Lake gauge were employed in the calibration and validation of the Rainy River model. A map of the locations of these level gauges is shown in Figure 3-3.

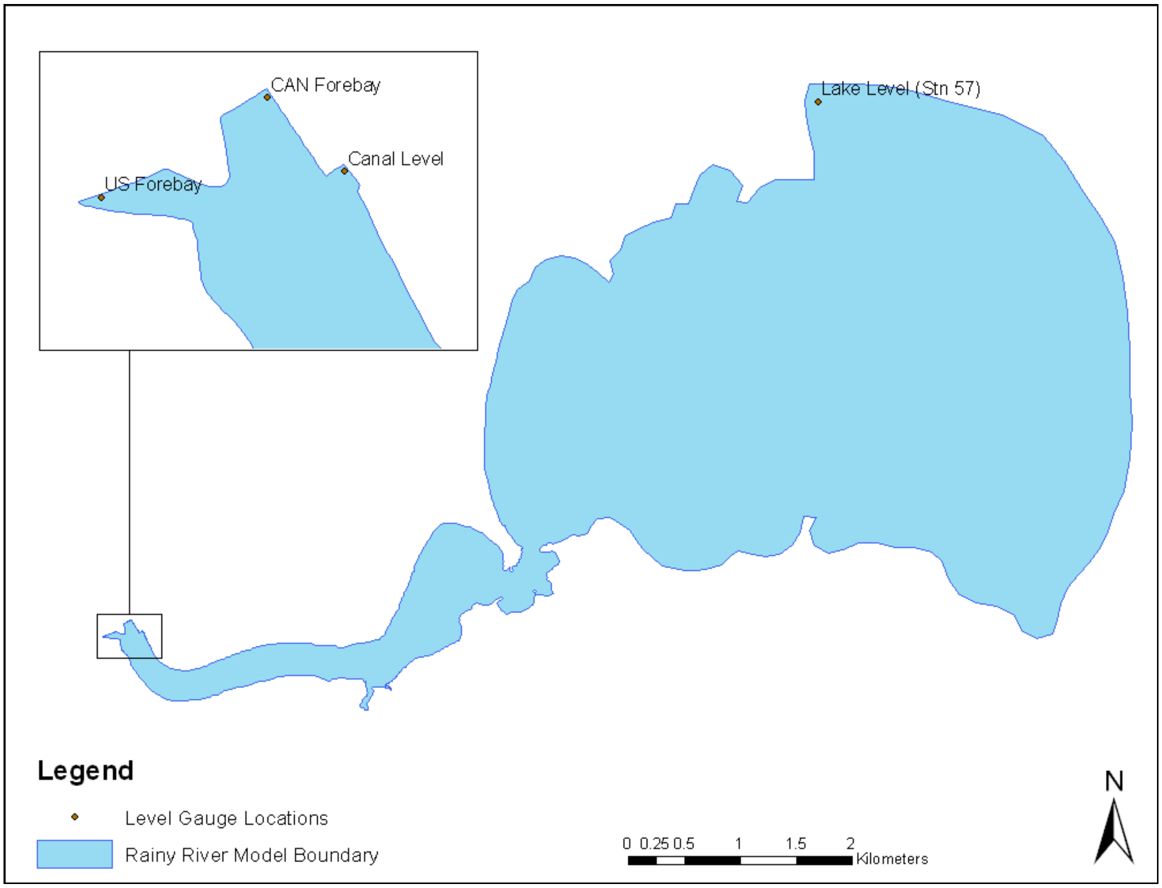

Figure 3-3 - Level Gauge Locations

The station summary data are shown in Table 2 including the mean and 30^{th}, 50^{th} and 70^{th} elevation percentile. The elevation duration curve (EDC) for each of the stations in Rainy Lake is shown in Figure 3-2. As seen in this figure the Canadian powerhouse forebay (STN 311) tends to drop to significantly lower levels that the US powerhouse forebay (STN 322). Continuous level data were also available at the two powerhouse forebays and the Bear Pass station. Level data were also available at the canal forebays, but data there were recorded only when the canal gates were operational.

Table 2 - Environment Canada Water Level Station Data

Station name	Station Number	Elevation (m) Mean	E_{30}	E_{50}	E_{70}
Namakan Lake above Kettle Falls Dam	05PA003	339.8	339.7	340.2	340.6
Rainy Lake near Fort Frances	05PB007	337.3	337.1	337.4	337.6
Bear Pass	STN 131	337.3	337.2	337.4	337.5
US Powerhouse Forebay	STN 315/322	337.0	336.8	337.1	337.3
Canadian Powerhouse Forebay	STN 311	337.0	336.9	337.1	337.3

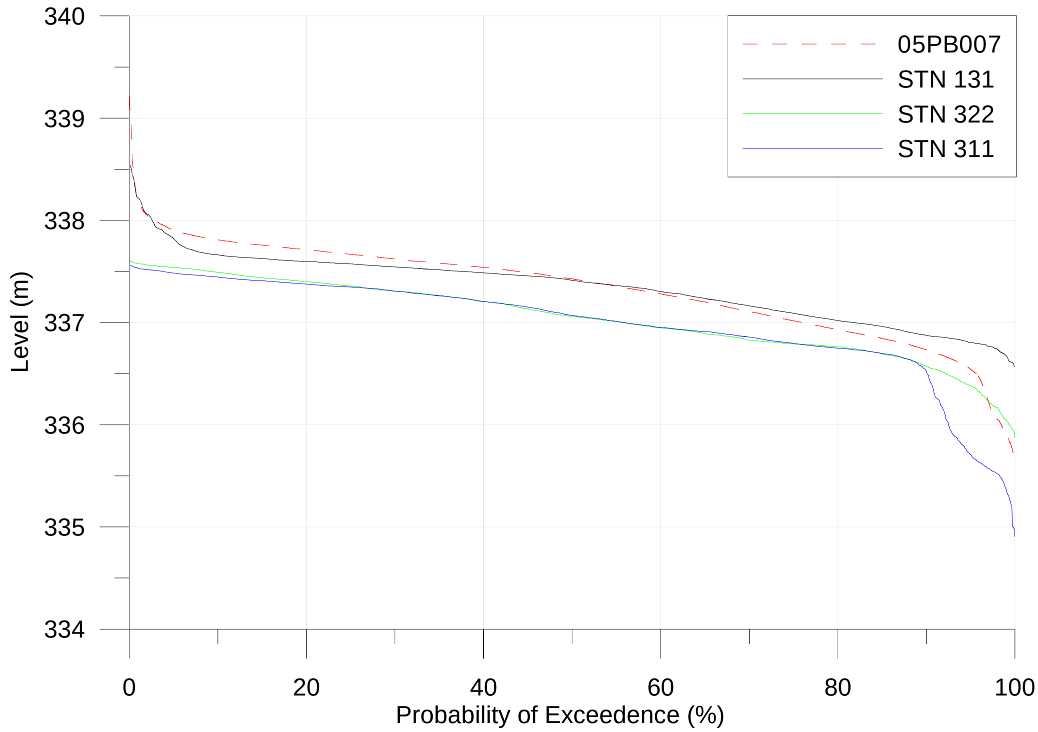

Figure 3-4 - Elevation Duration Curves for EC Lake Level Data

3.4 Dam Operational Rules and Calculations

Abitibi and Boise Inc provided a number of Microsoft Excel spreadsheets that contained the calculations for determining turbine and gate flow-through (Marc Mantha, Abitibi Bowater and Rick Cousins, LWCB). The spreadsheets contained operational calculations for flow through the gates as a function of the number of turbines in operation and the turbine head.

Gate discharge calculations are done with a discharge table rating curve. All of the gates (the 10 dam waste gates and the 5 canal waste gates) employ the same rating curve supplied by LWCB (Matt deWolfe, personal communication), which is shown graphically in Figure 3-5. The weir equation was provided by Environment Canada and is as follows:

$$Q = C\frac{2}{3}L\sqrt{2g}(h_1^{3/2} - h_2^{3/2})$$

where:

Q is the discharge passing through a gate (cfs);

C is the discharge coefficient (0.6);

L is the length of the gate (10 ft);

g is acceleration due to gravity (32.2 ft/s^2); and

h_1 and h_2 are total heads (including the velocity head approach) to the bottom and to the top of the orifice, respectively (ft).

For each gate, the flow was estimated based on the water level simulated about 10m upstream from the gate.

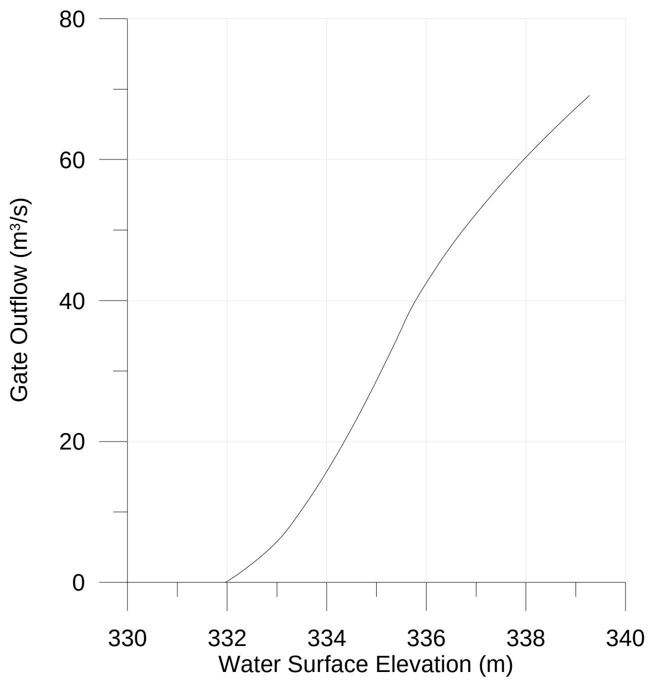

Figure 3-5 – Individual Gate Outflow Rating Curve

Total outflow for the gate array at the dam is calculated by determining an estimate of the water elevation using the following relationship:

$$h_1 = \frac{2h_{CAN} + h_{US}}{3}$$

where h_1 is the height used to calculate the flow through the dam gates, h_{CAN} is the Canadian forebay level and h_{US} is the US forebay level. The total flow is determined by multiplying the reading of the rating curve by the number of gates that are open. The outflow of the gate array at the canal is determined by the same procedure, except the elevation is determined from the water level measurements at the canal.

In order to characterize the flow through the powerhouses and dam gates some analysis was done to determine the operational patterns. Figure 3-6 shows the recent historical division of flow through the US and Canadian powerhouses and the sluice gates as a function of the total Rainy Lake outflow. It can be seen there are three distinct regimes:

1. For flows less than about 300 m^3/s, the flows are generally evenly split between the two powerhouses.
2. Between 300 and 400 m^3/s of total outflow the Canadian powerhouse is at its flow-through limit of approximately 150 m^3/s and the extra flow is taken up by the US Powerhouse.
3. At outflows above approximately 400 m^3/s both powerhouses are at capacity and the sluice gates are required to carry the extra flow.

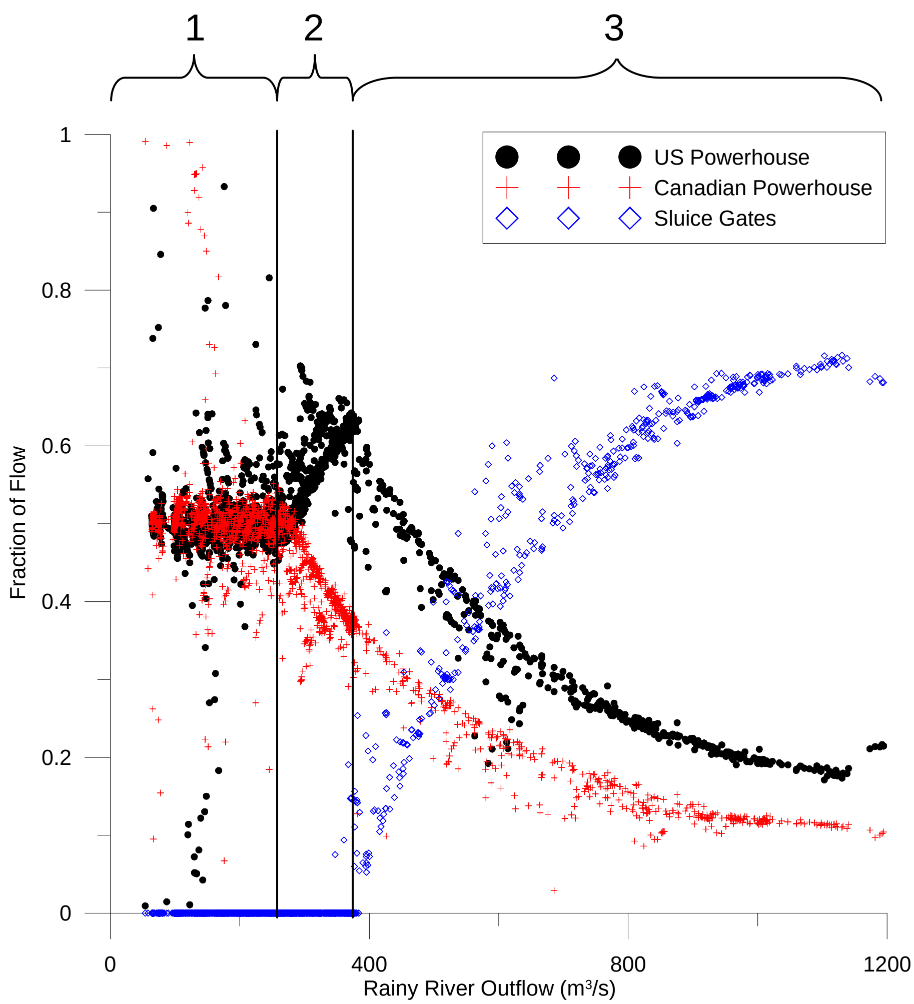

Figure 3-6 - Fraction of Flow through US/Canadian Powerhouses and Sluice Gates (28-Oct-2001 to 15-Nov-2009)

The results from Figure 3-6, when combined with the FDC data for the Rainy Lake outflow (see Section 3.2), indicate that historically the US turbines have carried more flow than the Canadian turbines approximately 34% of the time. Also, based on the historical FDC data, sluice gates have been open approximately 17% of the time.

Gates are opened in sequence to maintain compliance with the IJC rule curves. The canal gates are generally opened first and the dam gates are opened afterward as required. Dam gate operational history data were obtained from LWCB for 2001 to 2009. Figure 3-7 illustrates the operational sequence for 2008 and 2009, illustrating the preference for the use of canal waste gates over the dam gates.

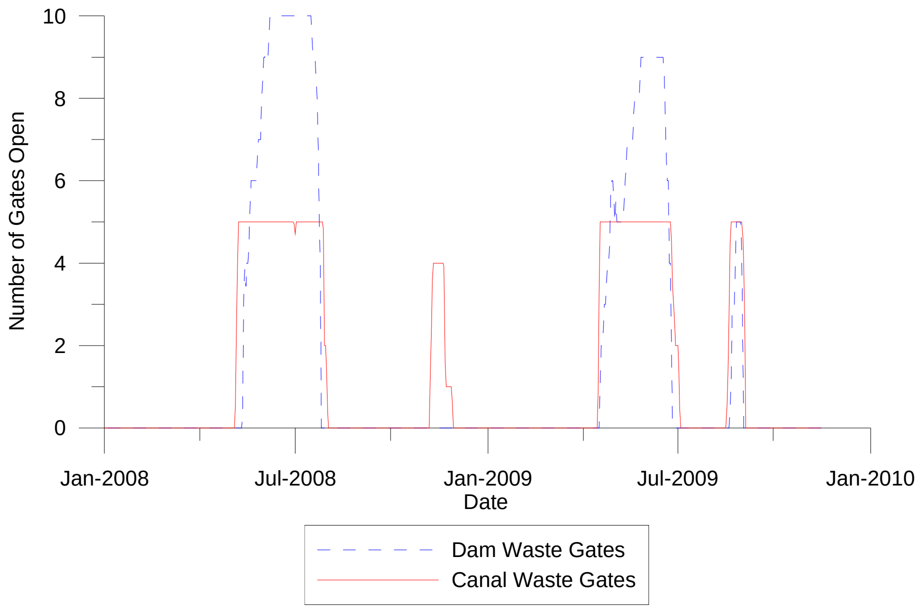

Figure 3-7 – Rainy Lake - Gate Operation History, 2008-2009

There is observed flow at the gate even when the gates are closed, due to imperfect seals at the gates Figure 3-8 shows the dam waste gates under closed conditions but still with some flow being conveyed. The flow around the gates when closed was not considered in this study.

Figure 3-8 - Gate flow under closed conditions (J. Bruxer, 2009)

4 MODEL CALIBRATION AND VERIFICATION

This section outlines the model calibration and verification procedures including the prescription of the boundary conditions for the model simulations.

4.1 Boundary Conditions

4.1.1 Inflows – Rainy River Model

For the Rainy River model (excluding the lake) the upstream flow was modelled as a fixed flow boundary condition with uniform flow rates along the entire length of the boundary. The boundary extended across the section of the Rainy Lake at the extent of the model domain.

4.1.2 Inflows – Rainy Lake Model

For the Rainy Lake model three inlet boundary conditions were included accounting for the three primary inflows into the lake: the Namakan lake outflows downstream of Kettle Creek Falls; Siene River and Turtle River. The balance of flow required to produce the total Rainy Lake inflow was added as a source to the northern end of the lake.

4.1.3 Outflows – Powerhouses and Gates

Four outflow boundary conditions were specified: one for each powerhouse, one for the dam gates and one for the canal gates. The boundary conditions were set differently according to the model simulation conditions.

Dam and Canal Gates
The gates at the dam and canal were simulated in one of two ways. During calibration when flows through the gates were specified, the gates at both the canal and the dam were simulated as a series of flow sinks at the boundary, with the total flow from each boundary being fixed.

During simulations when the flow through the gates was not pre-set, the gates were simulated as sinks with the flow calculated using a provided weir equation (Section 3.4). During the simulation each gate flow was calculated by using the simulated total head 10 m upstream from gate itself, as prescribed in the equation definition.

Powerhouses
Powerhouses were modelled either as a fixed level boundary or a specified outflow. During the calibration period, the US powerhouse was set as a level boundary, and the flow at the Canadian powerhouse was prescribed with a pre-set flow rate.

During simulations when the flow through the canals was not known, the flow in both powerhouses was prescribed with pre-set values.

4.1.4 Other boundary condition considerations

The dam overtopping was not simulated as a flow-through boundary in this model. Conditions with downstream elevations in excess of the top of the dam were not considered in this modelling effort. Measurements of the elevation of the top of the dam overflow were conducted by Environment Canada with an average elevation being 337.6m.

4.2 Preliminary Modelling Investigations

Prior to a rigorous calibration effort the model was examined to determine the general hydraulic performance. The model shows a number of constrictions along the flow-path that lead to substantial local losses. A hydraulic loss profile is shown in Figure 4-1, as water surface elevation upstream from the dam following the river centreline into Rainy Lake during a large event (outflow = 1000 m^3/s). Three locations of significant rapid losses are identified: Koochiching Falls near the bridge crossing, the narrows at Pithers Point and at the Ranier rapids rail bridge. Figure 4-2 shows the locations of these three points on a velocity profile map of the same simulation.

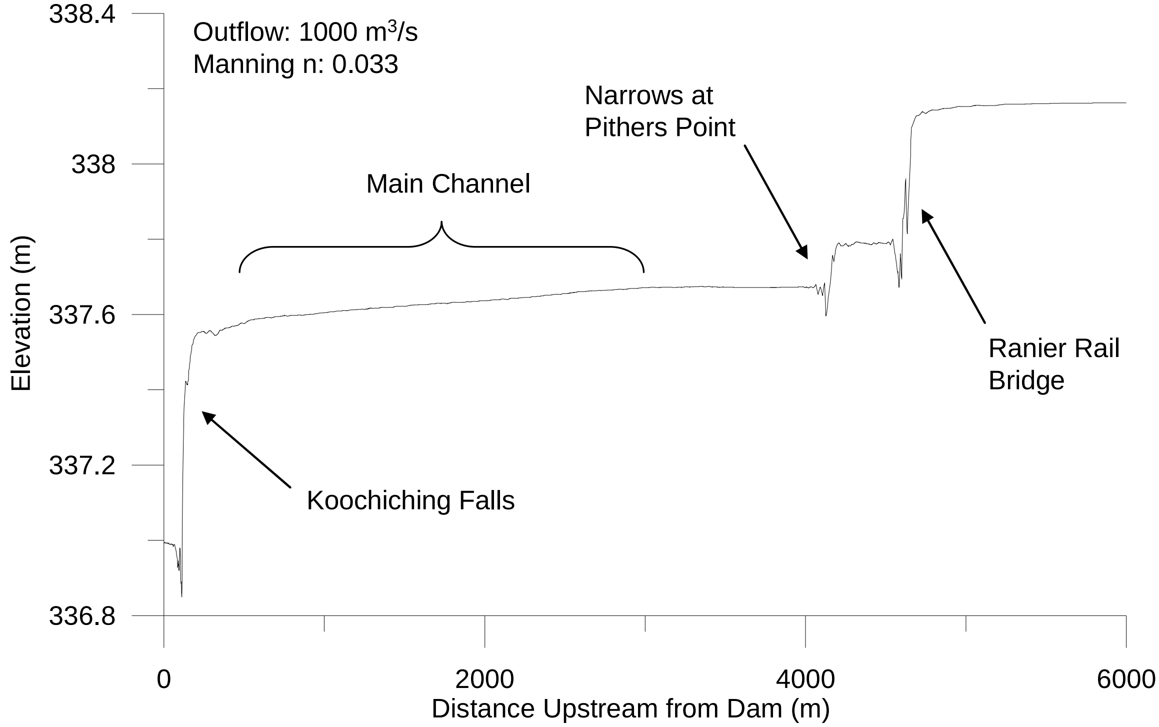

Figure 4-1 - Water Surface Elevation Profile - Regions of Hydraulic Loss

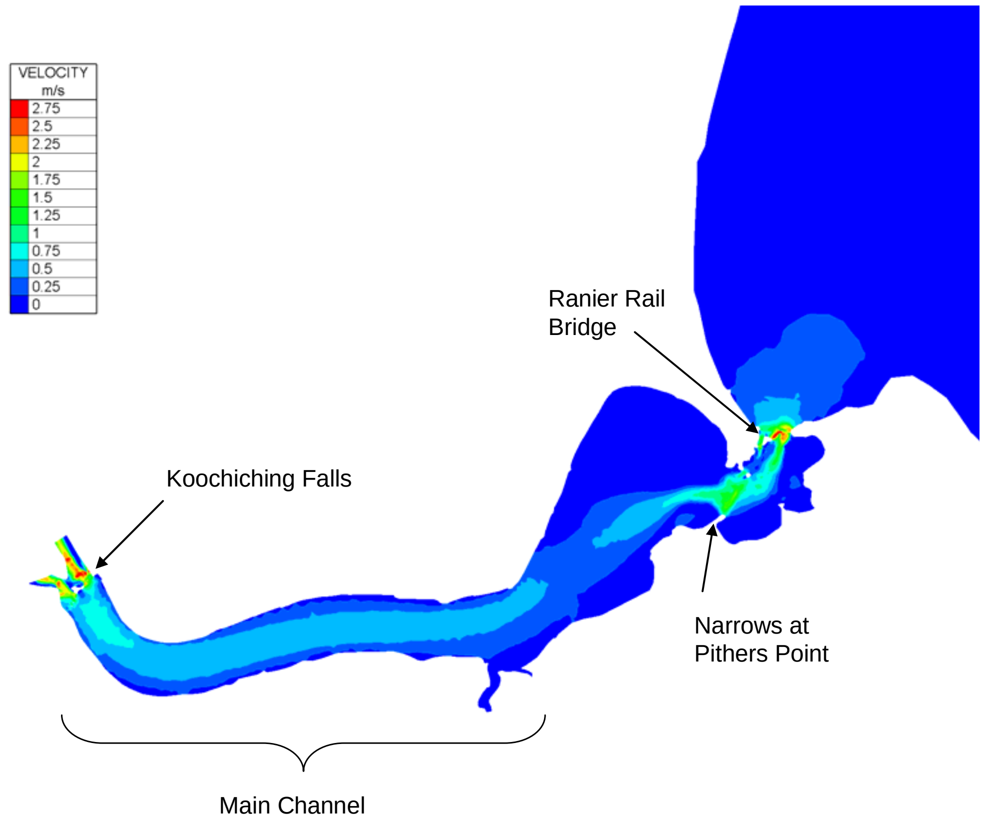

Figure 4-2 - Velocity Map – Locations of Hydraulic Loss (Outflow = 1000 m^3/s)

These preliminary investigation identified areas of sensitivity in terms of roughness calibration requiring special attention to be paid to the three areas of high velocity as well as the main channel.

4.3 Model Calibration and Validation

The model was calibrated by adjusting the channel roughness so that the simulated water elevations matched the observed values. Level data were available at the forebays and upstream of the canal, as well as the lake (Station 57), but no level data were available between these points. The model calibration was restricted by this and would have benefited from level data collected at points along the channel upstream of the dam before Rainer Rail Bridge. Further details of what would be required for a better calibration are highlighted in the recommendations section of this document (Section 7). In an attempt to mitigate this restriction, calibrations were performed at two flow levels – a near maximum flow (near 1000 m^3/s) and a near mean flow (near 300 m^3/s). The contributions of the various areas to total hydraulic loss along the river vary with different flow and surface water levels. Matching both higher and lower flow conditions constrains the calibration effort. Calibration was done by changing roughness in a number of regions within the domain, in particular at the Koochiching Falls, Pither's Point, Rainier Rapids and the remainder of Rainy River from the dam to the lake.

Two calibration and two validation periods were selected from the available period of measurement and were selected to match closely high and mean flow levels during several days of steady-state observations. The periods of calibration are graphically presented in Appendix C. All periods observe a period of near steady state for at least 7 days.

4.3.1 Calibration Results

The calibration results are presented in Table 3. The model was calibrated primarily to upstream lake levels, but canal levels and the level gauges at the forebays were also examined. The model was calibrated to within 0.01m at the lake level. Elevation errors at the forebay and canal headwaters were more difficult to minimize and varied between 0.03 m and 0.19 m.

Table 3 – Model Calibration

	Period 1	**Period 2**
Date	2008-06-17	2007-12-06
Meteorological Conditions		
Precip (prev. week) (mm)	36	26 (snow)
Max Wind Speed (km/h)	24	17
Wind Dir (deg)	35	27
Flow (m3/s)		
Total	1010	362
Dam Gates	445	0
Canal Gates	245	0
Canadian Powerhouse	122	137
US Powerhouse	198	225
Levels (m)		
CAN Forebay Level	335.89	337.20
US Forebay Level	336.71	337.21
Canal Headwater	336.62*	n/a
Lake Level	338.07	337.48
Average Level Drop	1.77	0.27
Simulated levels (Error in meter)		
CAN Forebay Level	335.96 (0.07)	337.28 (0.08)
US Forebay Level	336.68 (-0.03)	337.23 (0.02)
Canal Headwater	336.81 (0.19)	n/a
Lake Level	338.06 (0.01)	337.49 (0.01)

*- Back-calculated from recorded flow through Canal

4.3.2 Validation Results

The calibrated model was validated against two other periods and the results are shown in Table 4 . During period 3, a high-flow simulation, the error in the lake level was 0.06m and during period 4, a low-flow simulation, the error in the lake level was 0.02m. Again, levels in the forebays and the canal did not perform as well. The errors ranged from 0.01m to 0.41m, the highest error being at the level in the Canadian forebay, the most difficult of the levels to accurately simulate with the model. It is suspected this may be due to the imperfect modelling of the outflow at the dams with uniform pre-set flows through the turbines and the individual gate flows which may not be distributed properly, even though the total outflow was matched. In fact the flow may not be uniform across the turbine intakes and may cause localized drawdown which could influence the forebay levels in a manner not simulated in this model. The errors in elevation at the Canadian forebay for Period 3 suggest that losses are not being adequately accounted for in this model which would suggest that an even greater roughness would be required. As will be shown in the next section, the calibrated roughness values were already set to relatively high levels at the rapids to obtain an accurate calibration.

Table 4 - Model Validation

	Period 3	**Period 4**
Date	2009-06-03	2001-11-15
Meteorological Conditions		
Precip (prev. week) mm	4.8	0.0
Max Wind Speed (km/h)	24	n/a
Wind Dir (dir)	26	n/a
Flow (m3/s)		
Total	926	303*
Dam Gates	370	0
Canal Gates	244	0
Canadian Powerhouse	112	143
US Powerhouse	198	160
Levels (m)		
CAN Forebay Level (Station 311)	335.64	337.28
US Forebay Level (Station 322)	336.45	337.31
Canal Headwater	336.54	n/a
Lake Level (Stn 57)	337.86	337.50
Avg Level drop (m)	1.82	0.21
Simulated levels (Error in meter)		
CAN Forebay Level	336.05 (0.41)	337.33 (0.05)
US Forebay Level	336.47 (0.02)	337.32 (0.01)
Canal Headwater	336.60 (0.06)	n/a
Lake Level	337.92 (0.06)	337.482 (-0.02)

* - Calculated from mass balance through powerhouse flow records

4.4 Calibrated Roughness Map

The calibrated model is shown as a roughness map in Figure 4-3, which shows the regions with the various roughness coefficients for the regions identified. The roughness values shown here are the Strickler numbers which are the inverse of the Manning roughness coefficients. It can be seen that the roughness at the three narrows are substantial, and much higher than expected, but are required at this level to account for the extremely rough topography and losses observed in these regions. Indeed, the validation results for Period 3 suggest that even higher roughness would be required to match the Canadian forebay levels, assuming the flow estimates are accurate. This final roughness map was selected as it gave the best overall results in high and low conditions and best matched all four level gauges. Several other roughness configurations were considered, including uniform roughness, but the results produced very high roughness values throughout the model domain with the channel roughness being much higher than would normally be expected and did not match all level gauges as closely as the final roughness values. Nevertheless, the appropriateness of the roughness values is borne out in the model validation and again in the dynamic simulations described in subsequent sections of this report.

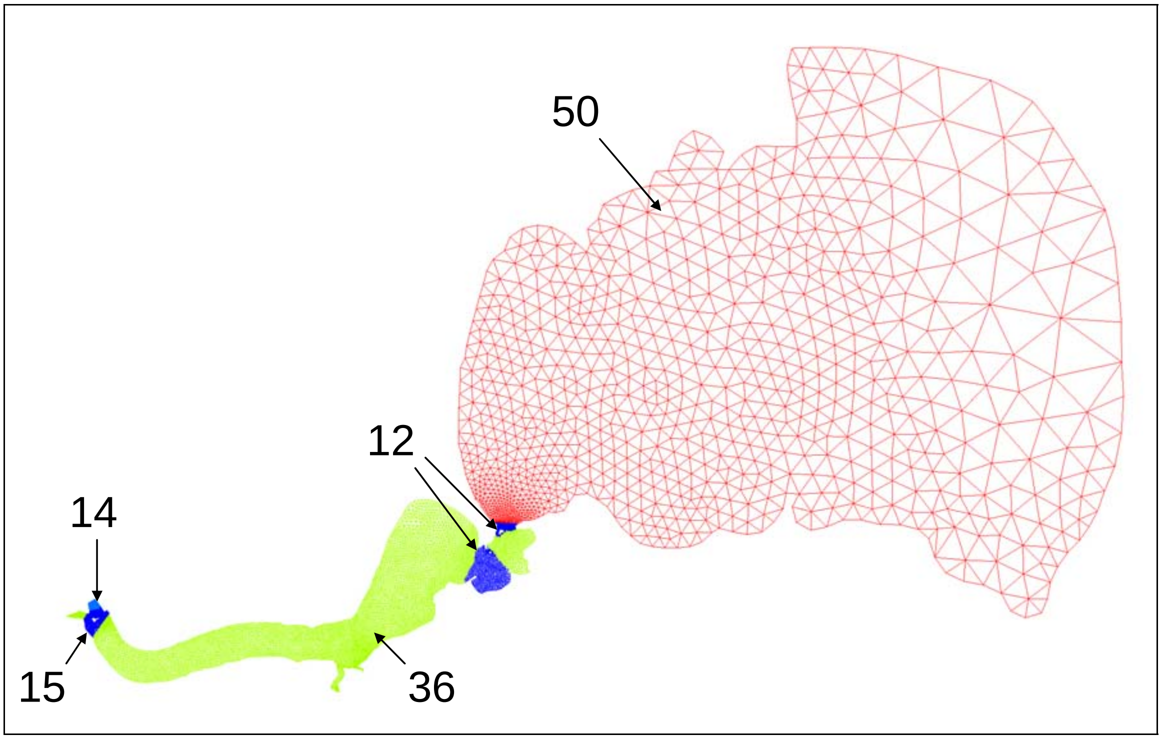

Figure 4-3 - Calibrated Roughness Map – Mesh 1 (Strickler Coefficient)

More level data along the length of the river would serve to further constrain the calibration of the model. With the data available, a number of roughness combinations would likely provide a similar calibration result. The model calibration does identify some important hydraulic considerations that are not explicitly addressed in this model. In the above simulations the roughness was assumed to be constant with the flow, but the effective roughness may vary with flow depth and observations seem to indicate that hydraulic losses over the Koochiching Falls and Ranier Rapids can be expected to vary with flow depth. More data would be required to identify these relationships. Finally, there may be errors with the prescribed flows at the dam and through the gates used for calibration. Although the reported flows at the powerhouses are presumed to be fairly accurate, the flow rates at the gates are unlikely to be as accurate, particularly the flows at the dam gates are calculated using the US and Canadian forebay levels. In spite of these identified limitations, these reported flows at the dam and canal gates represent the best flow estimates available.

5 MODEL SIMULATIONS

This section outlines the results of model simulations and is addressed in a number of sections:

1. General model performance and Observations
2. Channel Conveyance (steady state) results
3. Dynamic Simulations
4. State-of-Nature Simulations

5.1 General Model Performance and Observations

The general model results show interesting and strongly two-dimensional flow features. An important observation in the model of the Rainy River is that, with the complex bathymetry, the modelled flow paths change considerably with changes in depth within the river. Figure 5-1 illustrates this through a change in flow profiles in the model at different depths. At low depth the flow circulates counter-clockwise around the deep pool past Pithers Point narrows. As the flow depth increases the main flow path shifts approximately 200 m south to rotate clockwise around the same pool.

The flow patterns around Ranier Rapids also change significantly as the depths change. For instance, Figure 5-2 shows highly variable recirculation patterns behind the large Island at Ranier Rapids as depth conditions change. Figure 5-2 also shows strong 2D flow downstream of the rail bridge as the flow west of the main channel at Ranier Rapids tends to shift direction quickly after passing under the bridge from the shallows by the piers to the deeper waters to the south-east. This pattern also varies with flow depth.

The flow patterns around Koochiching Falls show a pronounced 2D flow patterns and some insights into the utility of the forebay level readings in flow estimation at the dam gates during high flows. Figure 5-3 shows both the 2D flow and the water surface elevations at Koochiching Falls for a high flow of 1010 m^3/s with all dam gates open and with the powerhouses conveying their maximum flow. In this figure we can see the dominant flow patterns at the north side of the bridge and through the canal gates, as well as quiescent areas behind the island at the bridge and at the shallows near both shores. Of interest as well is the modelled difference in elevations between the US and Canadian forebays (>1m). Differences of this magnitude are observed in the level records, but of particular interest is the modelled level near the dam gates. In the simulations, the modelled level just upstream of the dam gates appears to be lower still than at the location of the Canadian forebay level gauge (located near the shore). This would seem to indicate that the calculated flows through the dam gates are likely overestimated during high flows. If this model represents the true hydrodynamics the level used in the calculations (the average of the US and Canadian forebay levels) would be too high.

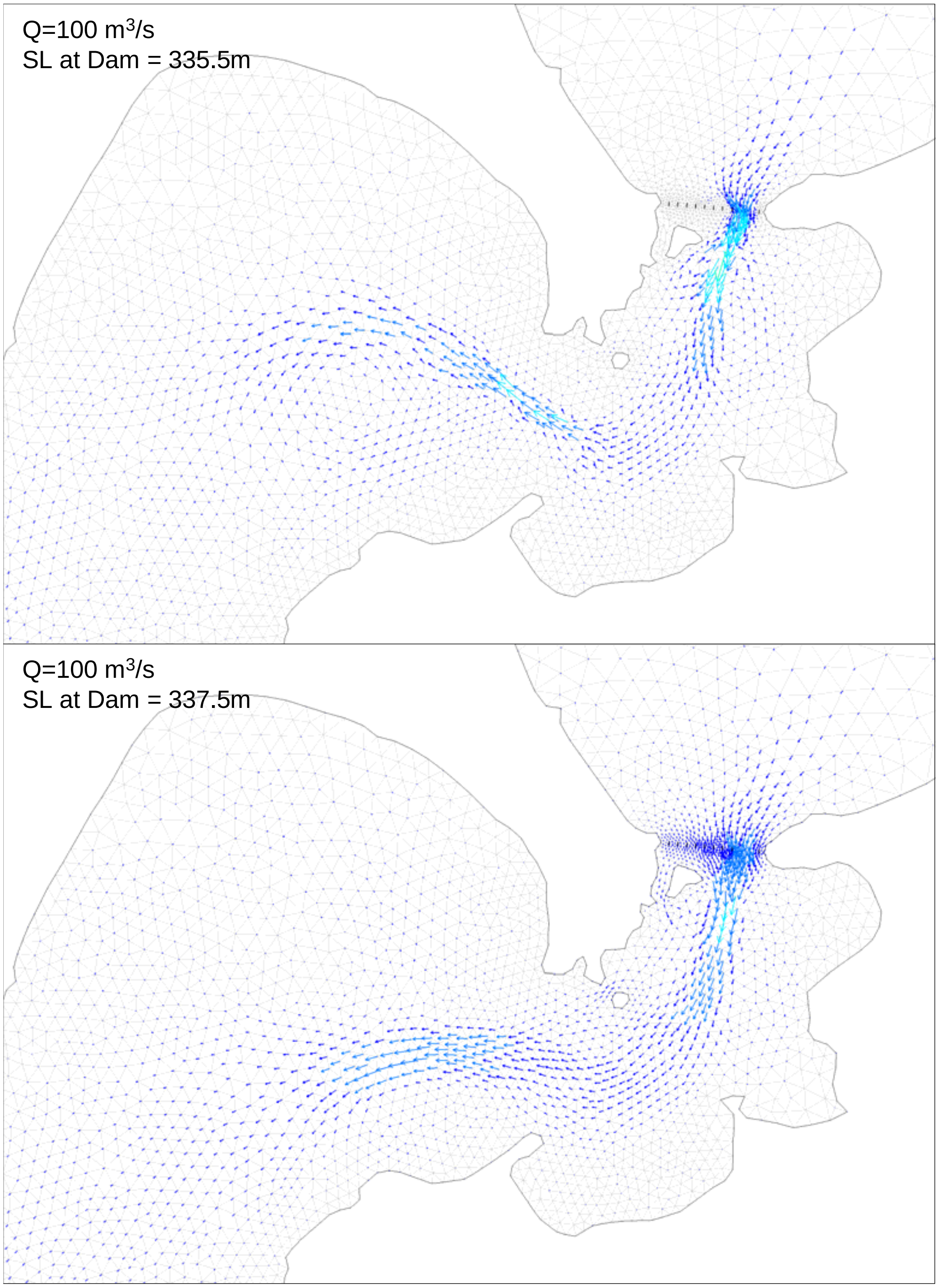

Figure 5-1 - Ranier Rapids Flow Profiles, Q = 100 m3/s

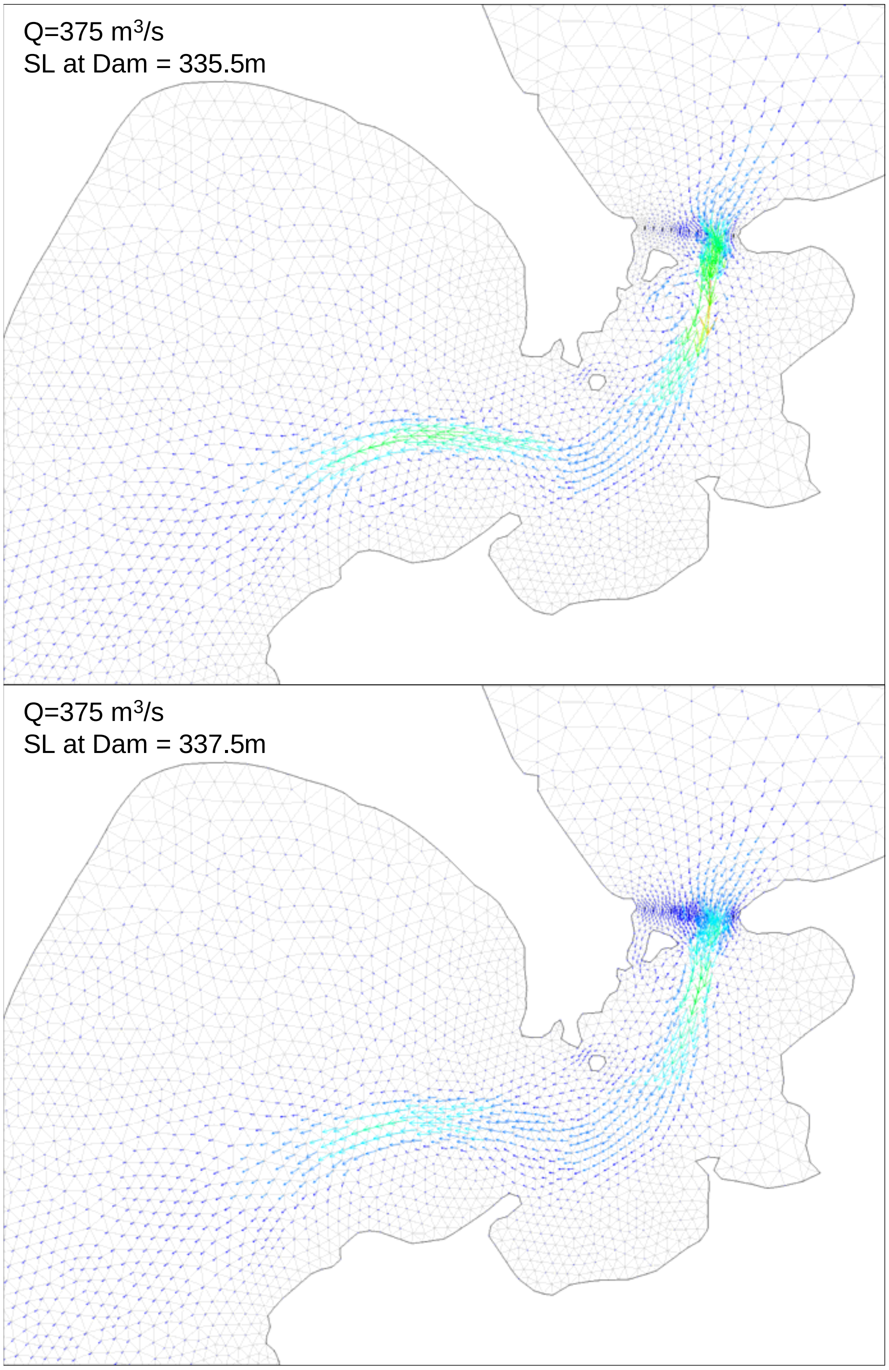

Figure 5-2 - Ranier Rapids Flow Profiles, Q = 375 m3/s

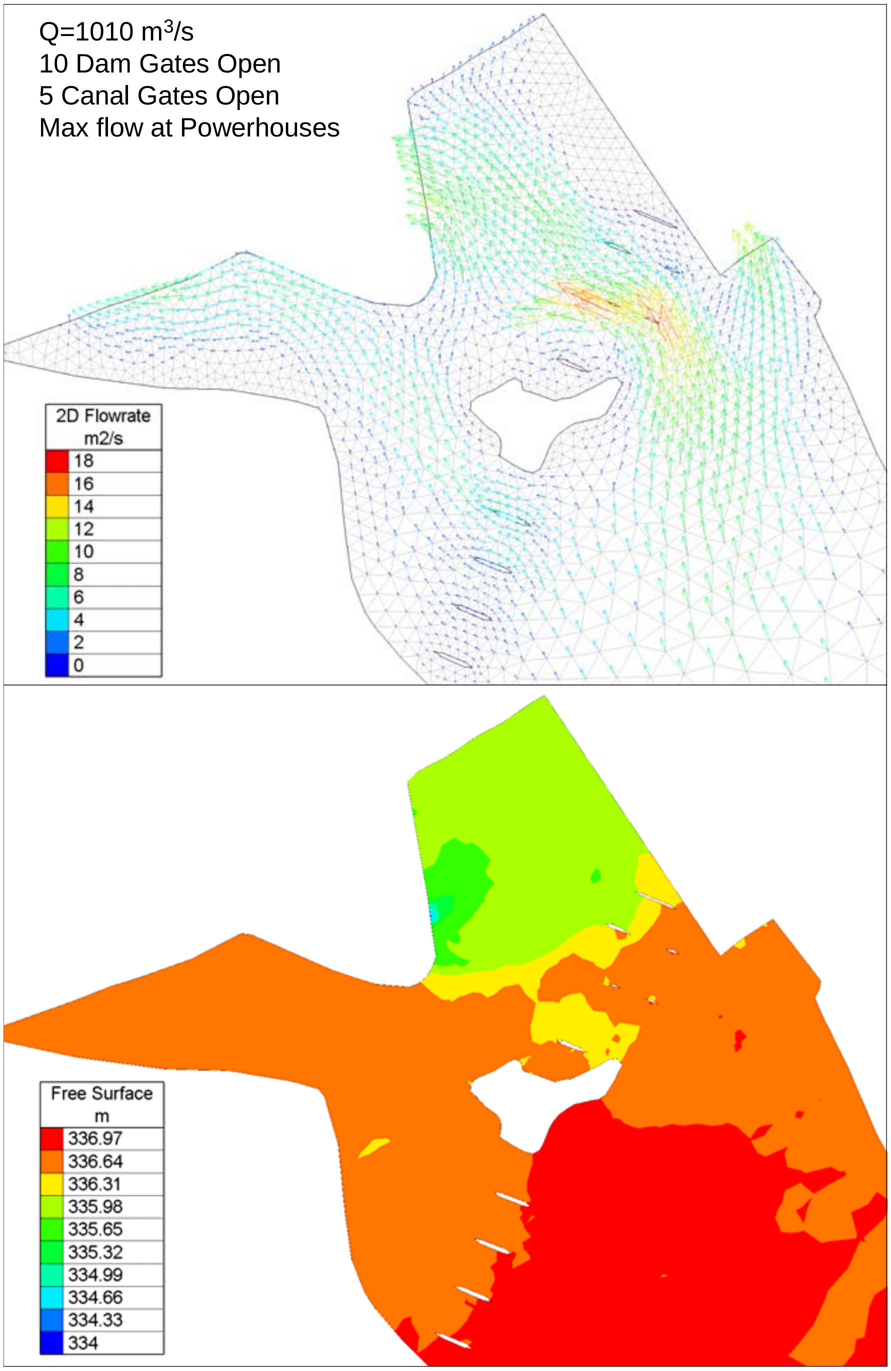

Figure 5-3 - Koochiching Falls, Q=1010 m3/s

5.2 Channel Conveyance

Channel conveyance studies were conducted against the calibrated model to investigate the hydraulic performance of the channel under a number of hydraulic configurations. The conveyance studies were separated into a number of individual cases. The three case types refer to the flow regimes as illustrated in Figure 3-6, with regime 1 being flows less than 300 m^3/s, regime 2 being flows between 300 m^3/s and 400 m^3/s and regime 3 being flows higher than 400 m^3/s. The cases are summarized in Table 5. Although the flow through the powerhouses is shown to vary historically, the flows during high flows tends to vary around the approximate powerhouse maximum. Indeed the highest recorded US powerhouse flow observed (259 m^3/s) is coincident with the highest recorded Rainy Lake outflow. The decision to use the near maximum capacity of the powerhouses as shown in Table 5 was deemed reasonable for the range of gate configurations for conveyance above 400 m^3/s.

Table 5 - Conveyance Study Cases

			Flow Conditions (Q = Total Flow)			
Flow Regime	**Q (m3/s)**	**Case**	**Canadian Powerhouse**	**US Powerhouse**	**Canal Gates Open**	**Dam Gates Open**
1	0-300	1.1	0.50 Q	0.50 Q	0	0
2	300-400	2.1	150 m^3/s	Q-150 m^3/s	0	0
3	400-1200	3.1	150 m^3/s	250 m^3/s	5	10
		3.2	150 m^3/s	250 m^3/s	5	0
		3.3	150 m^3/s	250 m^3/s	5	5
		3.4	150 m^3/s	250 m^3/s	0	10

Cases 1.1 and 2.1 – Flow Less than 400 m^3/s, No Gates Open

This scenario shows the conveyance of the channel from Rainy Lake to the dam outlet for flows less than 400 m^3/s. At this flow rate and below, the US and Canadian powerhouses are capable of passing all of the flow. In this conveyance simulation, all of the flow was split evenly between the two powerhouses for flows up to 300 m^3/s (Case 1.1). For flows above this level the flow was split unevenly with 150 m^3/s directed to the Canadian powerhouses and the balance directed to the US powerhouses (Case 2.1).

The hydraulic performance graph for the channel under these two ranges of steady-state conditions is presented in Figure 5-4.

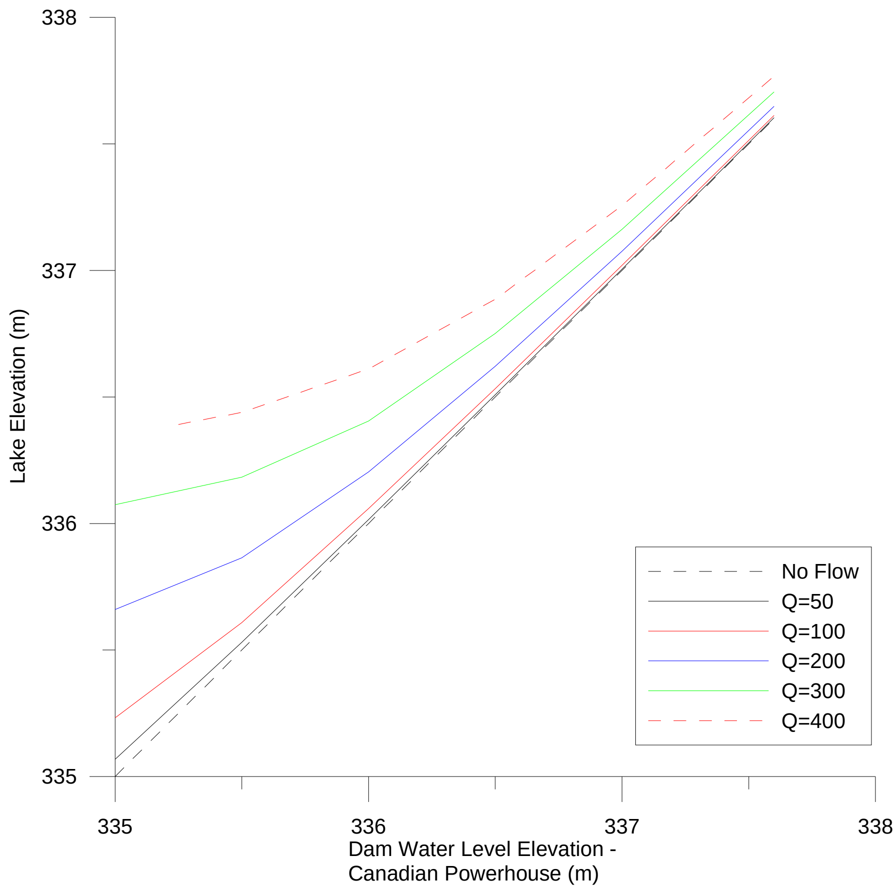

Figure 5-4 - Rainy River HPG, Cases 1.1 and Case 2.1, Q < 400 m^3/s

Cases 3.1 to 3.4 – Flow Greater than 400 m^3/s, Gates Operational

For cases 3.1 to 3.4 the boundary conditions were set to allow maximum flow through the two powerhouses (which accounts for 400 m^3/s), and to allow the gates to operate as prescribed by their typical flow rating curve (see Figure 3-5).

For case 3.1 – 3.4, the water level is controlled by the sluice gates and the equations that represent their flow-through rates as a function of water level. This section shows a relationship between lake level and flow for various channel configurations. The results for the various cases listed in Table 5 are shown in Figure 5-5. Here it is important to note that not all flows can be conveyed in all cases. Cases 3.2 – 3.4 were unable to convey flows of 1000 m^3/s or higher without overtopping the dam, which was not simulated in this study.

The model shows a lack of stability with the canal gates open between 400 and 600 m^3/s. This is not a numerical issue *per se* but represents a problem introduced when the gates are open at flows just over capacity of the powerhouses. In fact a steady state arrangement may be difficult to reach under these circumstances, as the relatively low required flow to be carried by the canal necessitates a low elevation at the canal forebay. An additional test case with fewer gates opened may have provided better convergence to steady state over this flow range.

Nevertheless the model does show, as expected, a maximum conveyance with all the gates open. The importance of the canal gates is stressed here as it seems the higher levels at the canal being upstream of the rapids can produce higher flow-through. Case 3.4 was interesting in this regard as it shows poor conveyance relative to 3.3, even though the same number of gates is open in each. With the hydraulic losses over the Koochiching falls, the simulations show the canal gates conveying much more flow than the dam gates pointing to the relative importance of the canal gates for conveyance. Simulation 3.2 shows that the opening of only 5 gates does not provide adequate conveyance for flows much higher than 600 m^3/s.

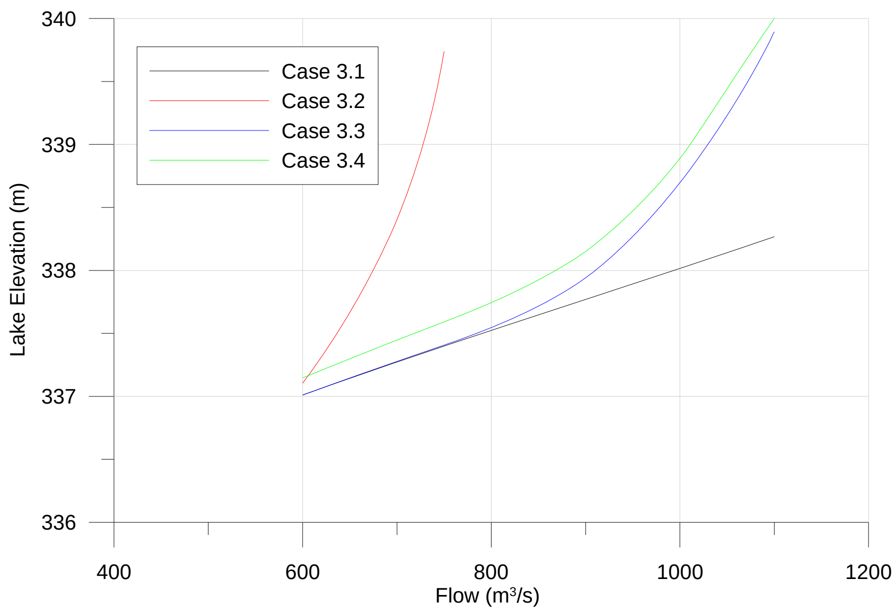

Figure 5-5 - Steady-State Flow-Lake Level Relationships

5.3 Dynamic Simulations

Two simulation periods were selected to test the model under dynamic conditions. The full Rainy Lake model was employed, which was area-adjusted to ensure that the total area modelled in the lake was 930 km^2, which is the approximate average area of the lake [1]. The roughness and bathymetry data employed in the calibrated model were identically in this model, with the lake roughness prescribed in the Rainy River model extended over the entire lake area. No other changes were made to the model employed in the steady state modelling above in Section 5.2.

Two large events were selected that were quite different in character for the dynamic simulation. The first event selected was the largest event in the recent record which occurred in June and July of 2002, characterised by high water levels and very high flows and a relatively short duration (66 days). The second event was a large snowmelt event occurring from April to July 2005, characterised by lower starting lake levels, high flows and a longer duration (117 days). The characteristics of these two dynamic events are summarized in Table 6.

Table 6 - Dynamic Simulation Characteristics

Simulation	**DS1**	**DS2**
Start Date	8 June 2002	1 April 2005
End Date	13 August 2002	27 July 2005
Duration (days)	66	117
Maximum Rainy Lake Outflow (m^3/s)	1195	982
Maximum Lake Level (m)	338.58	337.96
Minimum Lake Level (m)	337.47	336.85
Minimum Canadian Forebay Level (m)	335.44	335.39
Starting Canadian Forebay Level (m)	337.45	336.64
Starting Lake Level (m)	337.49	336.85

For each simulation the flows at the two powerhouses were prescribed as uniform flow sinks across the length of the powerhouse. The gate operation data were only provided in daily data. To provide a smoother operation the gates opening sequences were interpreted and approximated from the operation history spreadsheet if the number of gates open changed during a day. In general upstream gates were opened preferentially on the dam gates and the gates closer to the centre of the channel were opened preferentially for the canal gates. The flows through the gates were calculated based on the provided rating curve described in Section 4.1. For each simulation a spin-up period was required to bring the lake level and canal flows to levels that matched state at the start of the simulation.

The simulations were evaluated by comparing total simulated flows at the sluice gates with the observed (calculated) flows. This comparison examines at the model's capability to simulate flow through both the canal and dam gates, which is fundamentally a comparison of the model's ability to simulate the Canadian and canal forebay levels in aggregate. The model is also evaluated in its ability to simulate water surface levels through comparison to the lake level gauge data (Station 57) and the Canadian forebay levels.

The results of dynamic simulation 1 (DS1) are shown in Figure 5-6 (Lake Level), Figure 5-7 (Canadian forebay level), and Figure 5-8 (Flow simulations). It can be seen that the model simulates lake levels very well, although there is a slight delay in the hydrograph. The delay is more pronounced on the rising limb of the hydrograph but never exceeds approximately 20 hours. The time delay for the lake to peak is about 8 hours after the measured peak which is well within the daily resolution of the measurement data. The simulated peak is 338.57 m which is 0.01m lower than measured for that simulation. The Canadian forebay levels also show a good pattern match between simulated and observed levels, although the forebay levels are underestimated by approximately 0.20 m during the first low-level period (near 13 July 2002) and overestimated by approximately 0.11 m during the second low-level period (near 29 July 2002). Flow simulations show very good agreement of the simulated total gate flow with the observed (calculated), with some sub-daily resolution errors during the rising and falling hydrograph due to the step-wise opening and closing of the gates in the model simulation.

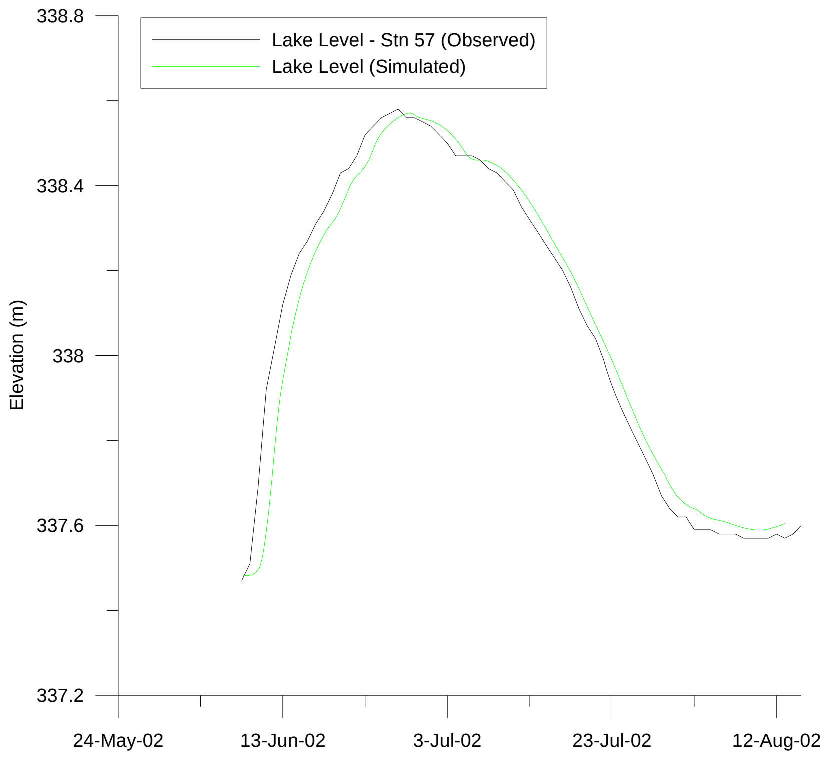

Figure 5-6 - DS1 - 2002 – Lake Levels

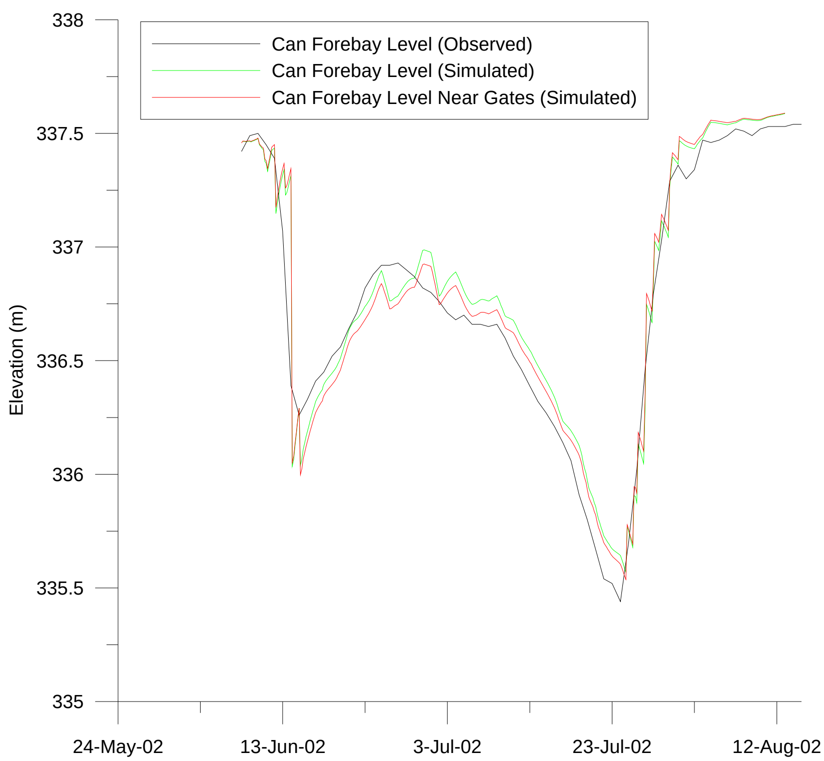

Figure 5-7 - DS1 - 2002 - Canadian Forebay Levels

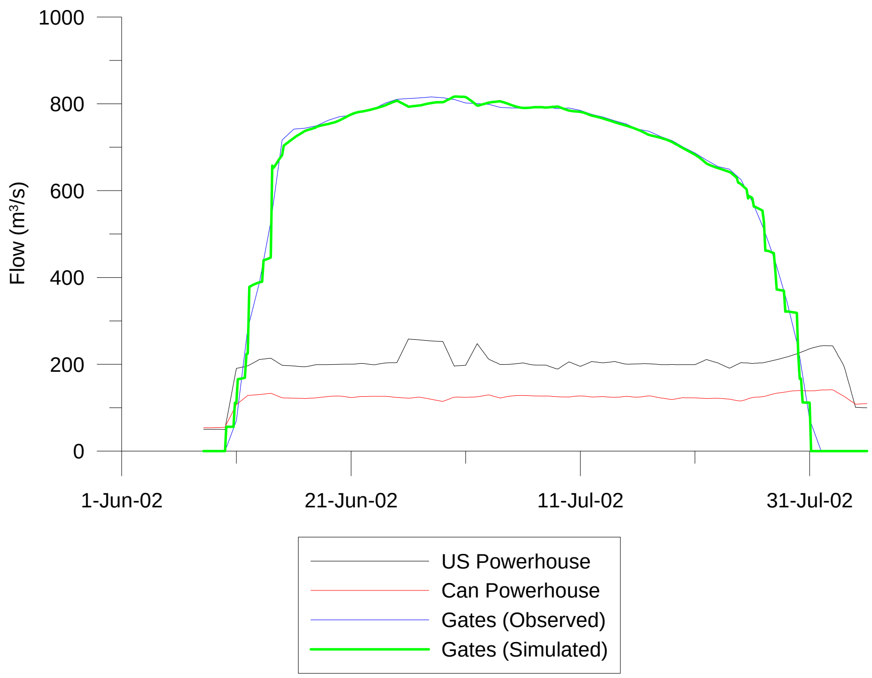

Figure 5-8 - DS1 - 2002 - Flow Simulations

The results of the second dynamic simulation (DS2) show a somewhat less accurate performance when compared to the first simulation. The results are shown in Figure 5-9 (lake levels), Figure 5-10 (Canadian forebay levels), and Figure 5-11(flow simulations). The lake levels show a slower increase in the lake levels leading up to the peak flow. The maximum error in lake level simulation is 0.11m (underestimated) on 27 May 2005. The peak water level at 16 June 2005 is underestimated by 0.07 m. These errors in the elevation early in the hydrograph may be due to a change in lake area at lower lake levels that is not accounted for in the model.

The Canadian forebay levels are modelled very closely as seen in Figure 5-10 (green line). Out of interest one of the forebay levels at the locations used to calculate the total head for the gate equation (approximately 10 m upstream) is also shown (red line). This shows that during high flow the simulated water levels drop substantially from the location of the forebay level gauge and the levels upstream of the gates (up to approximately 0.3 m). In the simulations, the dynamic head is used to calculate the total head upstream of each individual gate, along the length of the dam, in order to calculate each individual gate flow. These simulated totals tend to be lower than the head used for the estimate of the flow, which is based on one level at the Canadian forebay. This is reflected in Figure 5-11 which shows less simulated flow when all the dam gates are opened during the highest flows. The maximum difference between simulated and estimated flow is approximately 5%.

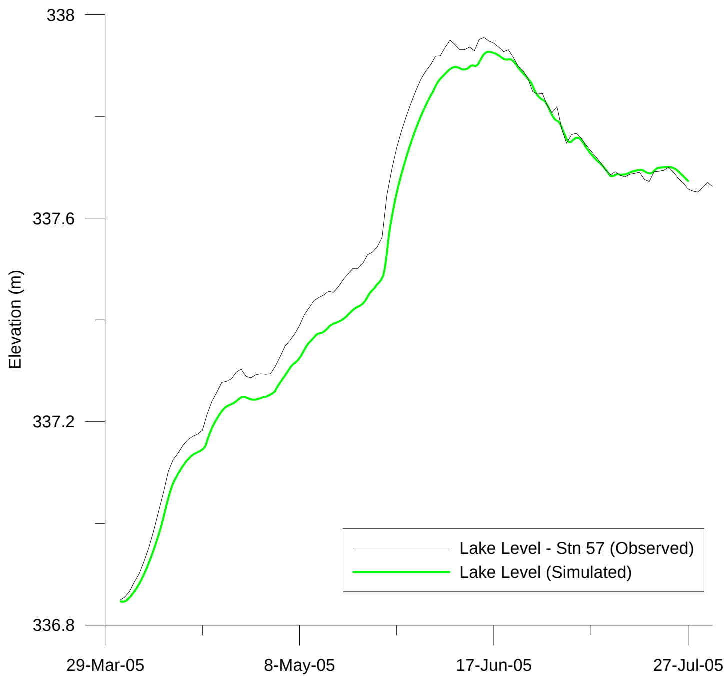

Figure 5-9 - DS2 - 2005 – Lake Levels

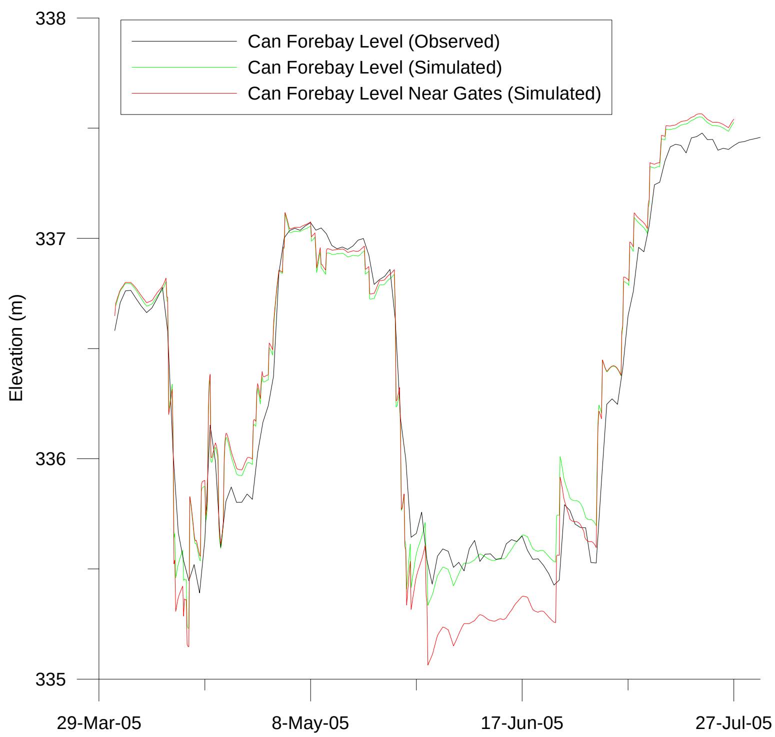

Figure 5-10 - DS2 - 2005 - Canadian Forebay Levels

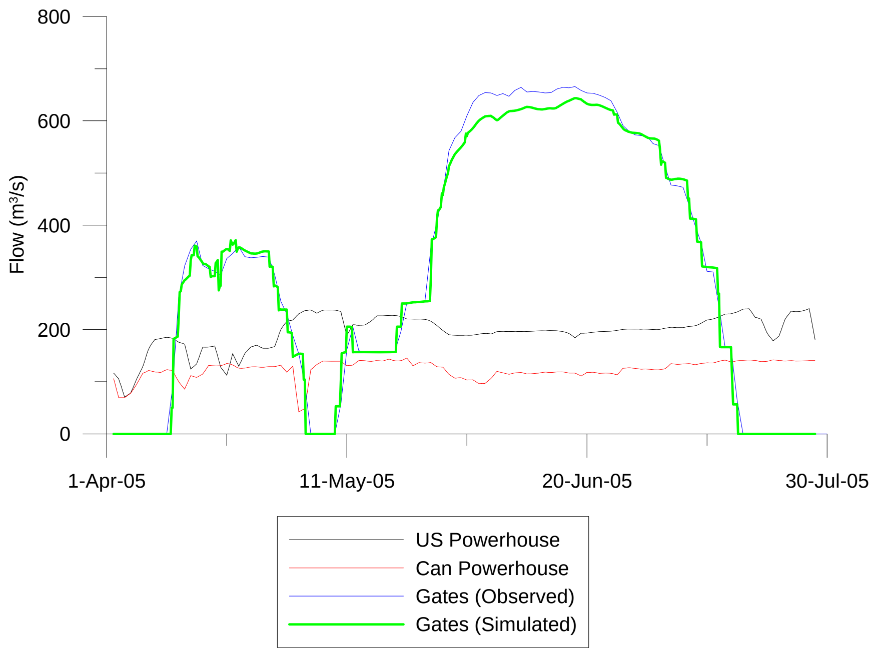

Figure 5-11 - DS2 - 2005 - Flow Simulations

5.4 State of Nature Model Simulations

The state of nature simulations employed the model described in Section 2.5. Boundary conditions were set as level boundaries at the downstream section and a steady state flow at the upstream section. Flow ranges from 100 m^3/s to 1200 m^3/s were employed. A number of downstream elevations were considered with downstream average water depths from 2.2 m to 4.5 m, but the Koochiching falls acted as a hydraulic control in all situations, and the upper river levels and lake levels were insensitive to downstream elevations for this model. The same roughness values were used as with the Mesh 1 and Mesh 2 simulations with the downstream extension employing a Strickler number of 36, which matched closely the HEC-RAS model value.

Simulated elevations were examined within the Rainy Lake, between the Rainier Rapids and the narrows at Pither's Point and within the Upper Rainy River below the narrows at Pither's point. The locations of the examined points are shown in Figure 5-12, and the simulation results at these points are shown in Figure 5-13. The water level drop across the Ranier Rapids and the total water level drop from the lake to the Upper Rainy River is shown in Figure 5-14. In both figures it can be seen that the drop in elevation across the Ranier Rapids is small at low flows with larger elevation losses observed downstream, however at higher flows the constriction at the Ranier Rapids incurs greater losses and represents the greatest contributor to elevation difference between the Rainy Lake and the Upper Rainy River.

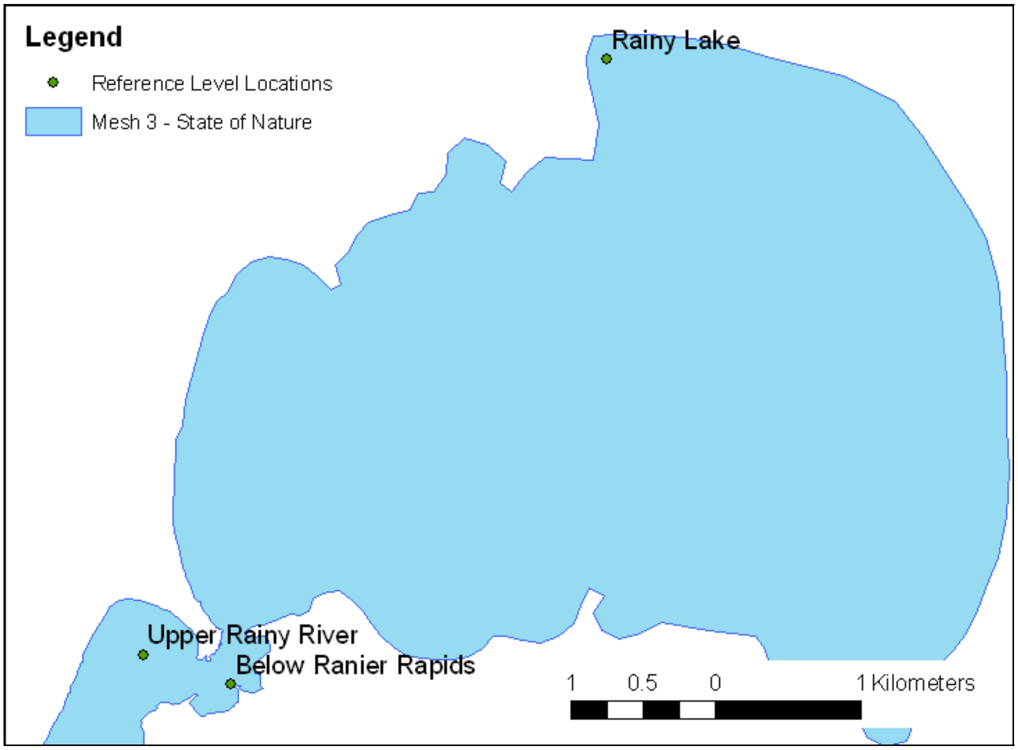

Figure 5-12 - State of Nature Rating Curve – Reference Level Locations

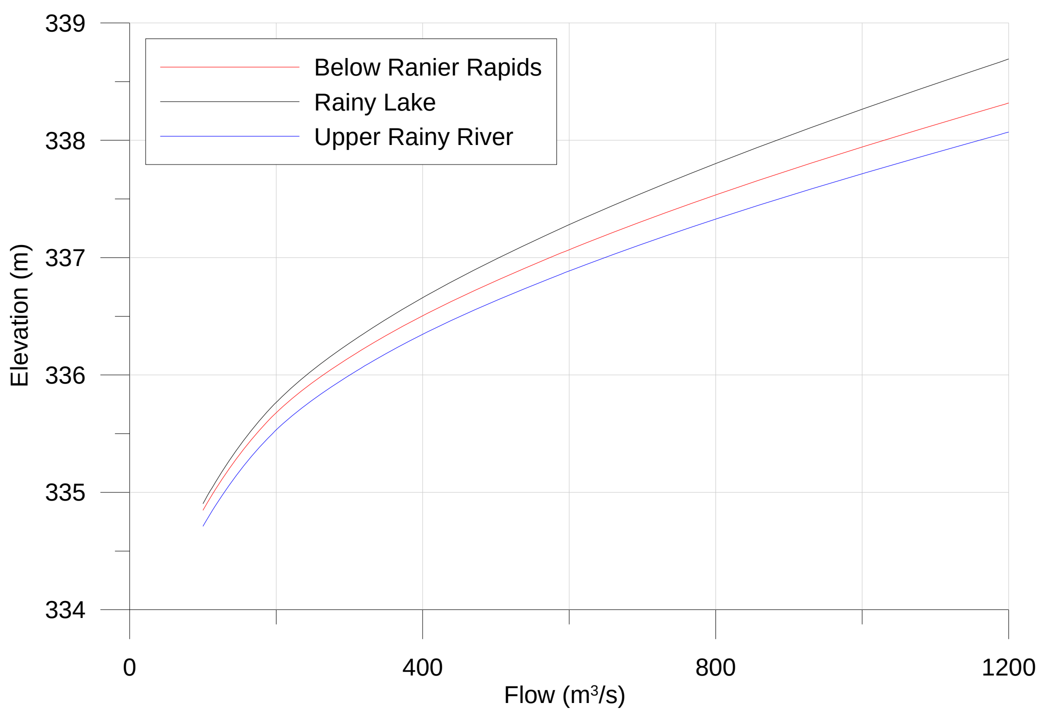

Figure 5-13 - State of Nature Rating Curve

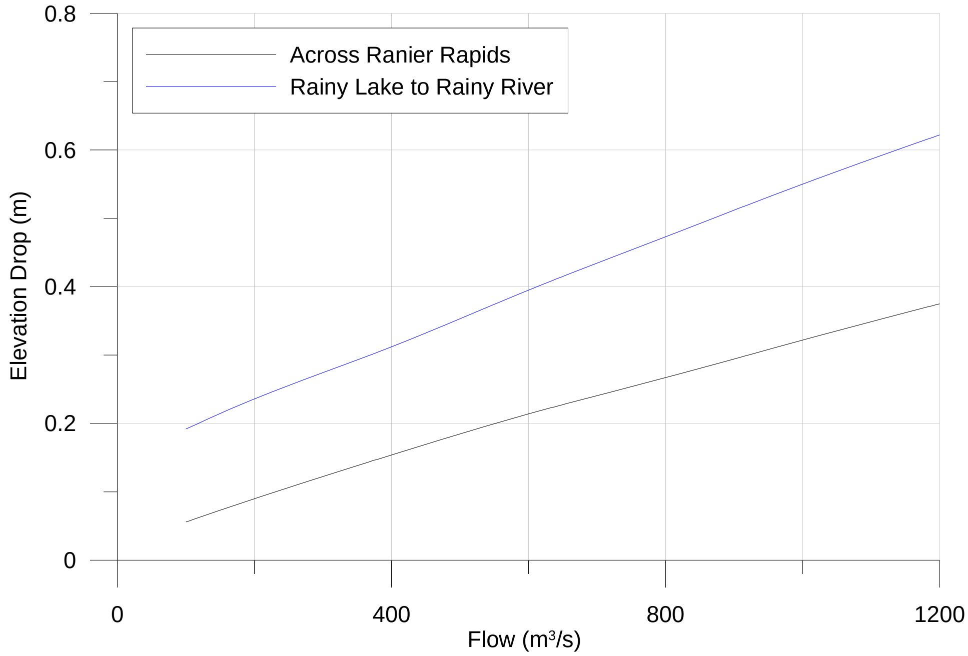

Figure 5-14 - State of Nature - Elevation Drop by Flow Rate

5.5 Historical Rating Curves and Current Conveyance Comparison

The rating curves developed by the state of nature simulations were compared with rating curves developed historically as well as the maximum conveyance curve developed for current operations. The two curves compared to the simulation was the Meyer-IJC curve, which was developed by the IJC engineers in 1916 and 1929 and extended by Meyer, and the second curve was the curve developed by the U.S. Engineers in 1932 [7]. Additionally the simulated state of nature rating curve was compared with the conveyance simulation curve for the current conditions with maximum outflow capacity (all gates open and powerhouses carrying full capacity), identified as Case 3.1 (see Section 5.2). The results of the comparison are shown in Figure 5-15.

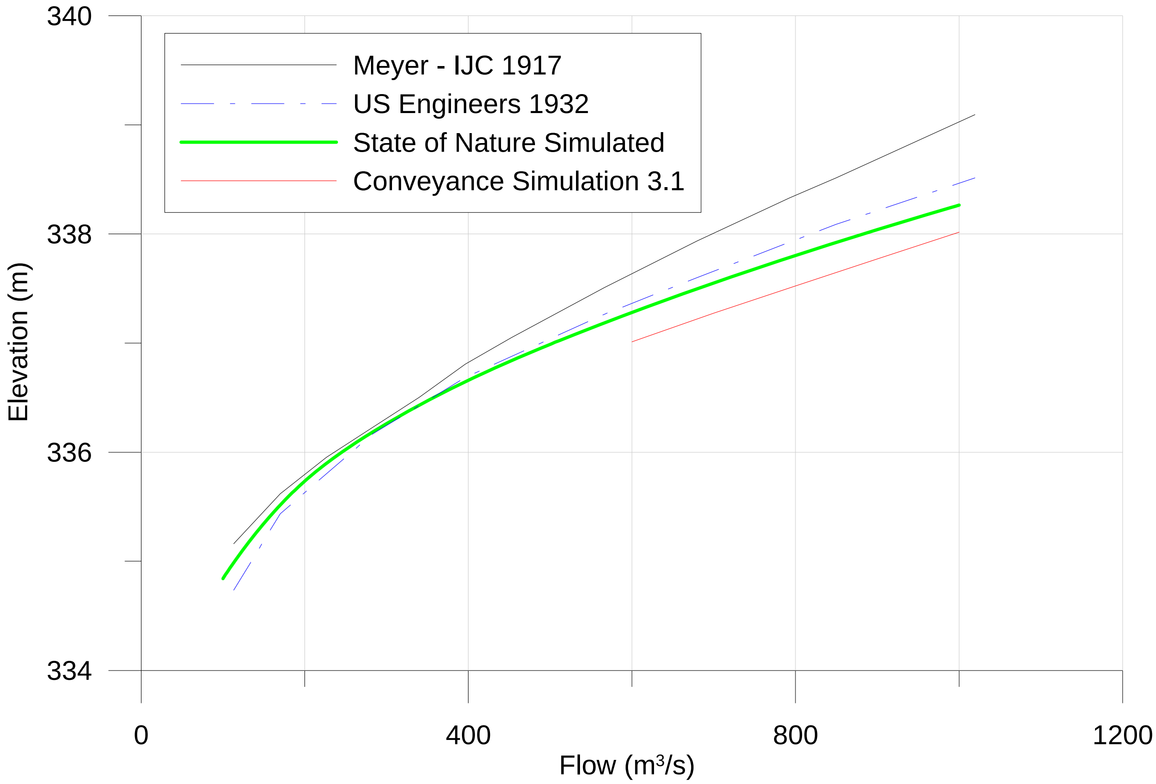

Figure 5-15 - Rating Curve Comparison for Rainy Lake Levels in a State of Nature

Here it can be seen that the simulated curve generated in this study falls between both curves for flows less than 400 m^3/s, it more closely follows the U.S. curve for flows above that but suggests lake elevations below both curves for flows above 500 m^3/s. The hydrodynamic model therefore suggests more conveyance through the upper rainy river at the more critical high flows in a state of nature than those previously suggested. When compared to the current conditions with maximum conveyance, the simulated state of nature rating curve predicts higher lake levels. This is likely due to a number of factors. The comparison between the bathymetry of the current condition and the state of nature conditions shows greater effective cross sectional areas at the critical sections of Ranier Rapids and around the Koochiching Falls (see Section 2.5.3). Furthermore, the addition of the extra flow conveyance by the canal, not available in the state of nature simulations, provides a substantial increase in flow past the Koochiching falls on the order of 220 m^3/s.

6 SUMMARY AND CONCLUSIONS

In summary, 2D hydrodynamic models were constructed of the Upper Rainy River and Rainy Lake for current for current and "state of nature conditions". The current models included a full model of the dam with all fifteen sluice gates and the two powerhouses.

Based on the simulations the following conclusions may be drawn:

1. The calibrated model performs well in validation during steady state as well as dynamic simulations with good simulation of hydrographs, lake levels, and flow through the dams. However, to achieve the calibration very high local roughness values were required at the Koochiching falls and the Rainy Rapids area. These high roughness values could be in part influenced by missing bathymetry data under the two bridges, both of which are located at important locations hydraulically, and alternate data sources were required to fill in the missing areas.

2. There are three important hydraulic areas within the upper rainy river – Koochiching Falls, the narrows at Pither's Point and the Ranier Rapids at the rail bridge crossing. All three contribute to the determination of lake levels. The state of nature analysis shows that the Koochiching falls represents the primary control in the system but the narrows at Ranier rapids exerts an increasing influence with higher flows.

3. The position of the dam, downstream of the major crest of the Koochiching falls has an influence on the amount the dam gates can convey. In the simulations large head losses are observed over the falls at high flows resulting in reduced elevations and reduced capacity for conveyance of the dam gates particularly for the gates furthest away from the dam. The canal gates, upstream of the Koochiching falls, will convey more flow on a per-gate basis due to the persistently higher hydraulic head at this location, and represent an important factor with regard to total conveyance.

4. When comparing the state of nature rating curve for the Upper Rainy River to the other rating curves developed in the past, the simulations compare well. At lower flows (< 500 m^3/s) the simulated rating curve lies between the curves developed by Meyer and that developed by the U.S. Engineers. At flows greater than 500 m^3/s the new curve in fact predicts a lower lake elevation for equivalent flows than either of the aforementioned curves.

5. Comparison of state of nature simulations to the conveyance simulations for current conditions show that the current conditions with all gates open and all powerhouses at capacity can convey more flow than the state of nature condition. This is due in part to the differences between the bathymetry at the critical sections which provides more conveyance at Ranier Rapids and Koochiching falls under current conditions. This also indicates that, with the addition of the canal, the dam configuration can convey more flow.

6. The method by which the flow through the dam gates is calculated and reported, namely the averaging of the US and Canadian forebay levels as done in the calculation spreadsheets, may overestimate flow. Simulations indicate that using simulated head upstream of the dam will provide lower flow estimates under certain high-flow conditions.

7. This report highlights some distinct differences in terms of flow capacity and power generation between the US and Canadian sides of the Fort Frances - International Falls Dam. Based on the flow frequency and the division of flow through the dam, the US turbines carry more flow, and presumably generate more power, than the Canadian turbines approximately 34% of the time. Additionally, the bathymetry upstream of the dam causes severe draw-down on the Canadian side during high flow conditions. Although not within the scope of this study, nor the auspices of the Rainy River IJC boards, this study could be expanded to investigate options that would improve the equitable allocation of flow between the two powerhouses. Furthermore, adjustments to the operation of the turbines, local upstream bathymetry, or other system changes could be examined to improve overall power production of this dam. The waste gates are open approximately 17% of the time in this system, and the waste gates pass some flow even when closed, which represent a direct loss of potential hydropower production for the dam.

7 RECOMMENDATIONS

1. In order to more accurately calibrate the roughness in the Rainy River model, further studies are recommended. In particular three additional level measurements would be useful in determining roughness along the river: a level measurement upstream of Koochiching Falls, downstream of the Narrows at Pither's Point, and between the Narrows at Pither's Point and Ranier Rapids. These three level measurements obtained during a range of ice-free flow conditions would allow for more complete quantification of the bottom roughness across each of the major areas of loss within the model.
2. Further study into modelling the powerhouses may prove useful for fully dynamic simulations. The powerhouses were modelled here as outlets with a known flow rate. A full integration of the flow equations using the upstream head, turbine flow-through rating curves, and the modelling of the sequence of operation could provide a useful simulation addition, and may more accurately represent the levels immediately upstream of the powerhouses.
3. Considering the uncertainty associated with the flow estimates through the US and Canadian powerhouses, as well as the waste gates at the International Falls dam, it is recommended that a flow gauge be installed downstream of the dam to assist in model verification and enhancement as well as verification of reported flows.
4. Further simulations should be conducted using the dynamic Rainy Lake model to examine how different gate timing configurations could have mitigated flooding in the Rainy Lake during large events (particularly 2002).
5. The uncertainty with regard to the flow through the gates remains a concern, as assumptions about these flow measurements influence many aspects of this study and its principal findings. It is recommended that verification of the rating curve be conducted, perhaps using a physical model setup of the dam-gate configuration to develop a verifiable set of rating curves for this and future analyses.
6. Further investigation into the complex flow around the Canadian dam forebay is recommended. It is imperative to determining the correct effective level when estimating flow through the dam gates, especially at higher flows.
7. This study highlights the hydraulic importance the Ranier Rapids and the Koochiching Falls, which control conveyance through the upper Rainy River. The speed with which the lake can be drained and the lake levels can drop is largely dictated by the geometry at these two sections. It is recommended that some simulations with adjustments to the bathymetry in these two areas be conducted to simulate the effects of dredging or otherwise increasing the conveyance in these areas and the consequent effect on lake dynamics.

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APPENDIX A – BATHYMETRIC DATA AND MODEL DEVELOPMENT

This appendix outlines steps taken to set up the bathymetric data, particularly involving the extra data acquired under the Ranier Rapids bridge and the International Bridge near Koochiching Falls.

The lake shore polygon was resampled to a node spacing of 150 m to 175 m to smooth the jagged coastline and provide a reasonably low mesh density for the lake. Narrow rivers and inlets less than 150 m wide were removed from the model. Additionally, in some cases where the distance between the shore and nearby islands were small and had a shallow water depth, the islands were merged with the coastline.

Figure A-1 shows the bridge drawing bathymetric contours plotted with the EC bathymetric data, where the contour patterns are shown to be somewhat consistent, particularly with the deep channel in the northern half of the bridge crossing.

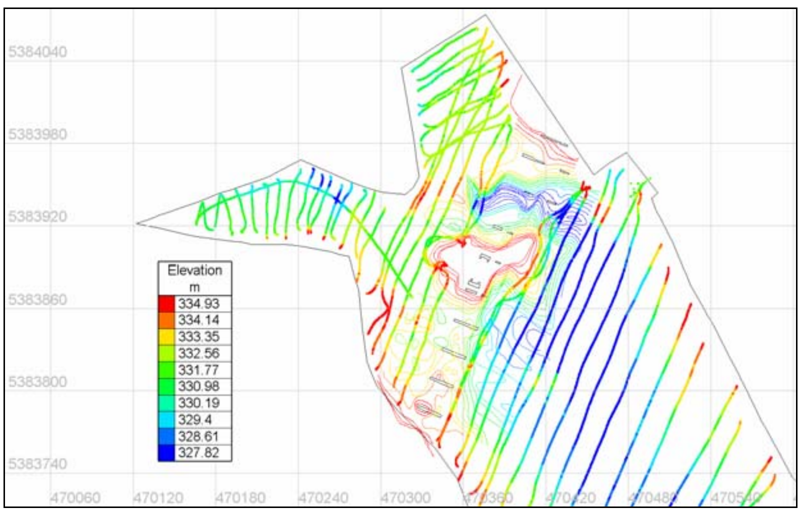

Figure A-1 - Bridge Bathymetry Contour and EC Bathymetric Survey Data

It was desirable to employ the contour patterns under the bridge where possible, while preserving the influence of the measured bathymetric data when generating a final bathymetry. As the datum of the contour maps was not consistent with the bathymetric data, and some of the bathymetry may have changed over the period the contour data were compared with the bathymetric data whenever a contour line crossed a measured bathymetric path. The contours with a low standard deviation in the differences from the bathymetric survey were preserved and those with a high standard deviation were rejected. The argument for this screening approach was that if a contour is valid it should differ from the measured bathymetry consistently. Standard deviations varied from 4cm to 3m. Contours with standard deviations less than 0.5 m were retained, which amounted to slightly less than half the available contours. The retained contours were adjusted in elevation by the median difference between the observed and measured elevations (0.18 m) and were added to the bathymetry dataset.

The remaining contours were then clipped to only include points under the bridge itself. Where the retained contours showed sharp elevation differences when compared to adjacent bathymetric survey data, the contours were clipped further to allow for a greater influence of the recent bathymetric survey. Figure A-2 shows the combined data from the contour and EC bathymetry data.

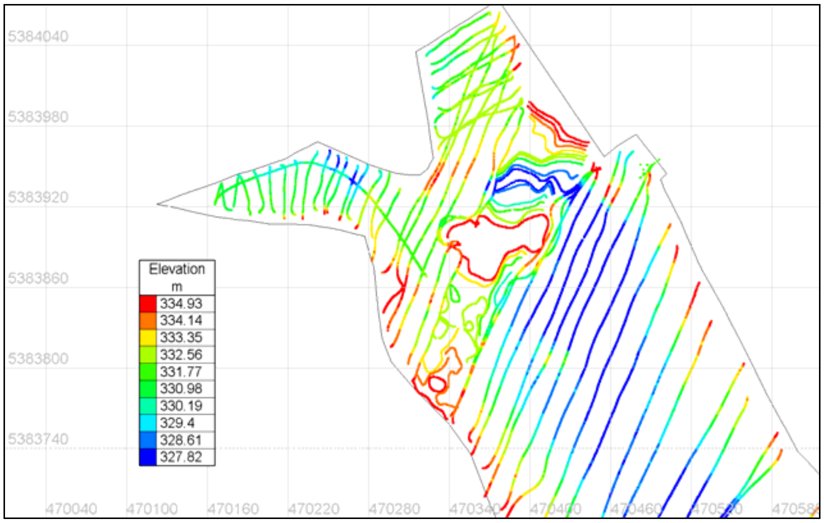

Figure A-2 - Adjusted Contour Data and EC Bathymetric Data - International Falls Bridge

The as-built drawings from which the bridge pier locations and dimensions were extracted also contained a detailed bathymetric cross section at the railway bridge location. This cross section was compared with the bridge cross section generated from the bathymetric interpolation based just on the EC bathymetric survey, as well as a cross section obtained from the same bathymetric interpolation 10 m downstream from the bridge intersecting measured bathymetry. Figure A-3 shows the differences between the various cross sections. It can be seen that the cross section interpolated at the bridge shows a much wider channel than either the bridge survey cross section or the cross section from the interpolated data 10 m downstream which follows a measured bathymetric cross section. In fact, the bridge survey cross section and the downstream interpolated cross section show very similar profile shapes, with only a shift in easting position by approximately 30 m. As such it was decided that the bridge survey data would be digitized and included into the model bathymetric input to more accurately estimate the bathymetry at the rail bridge.

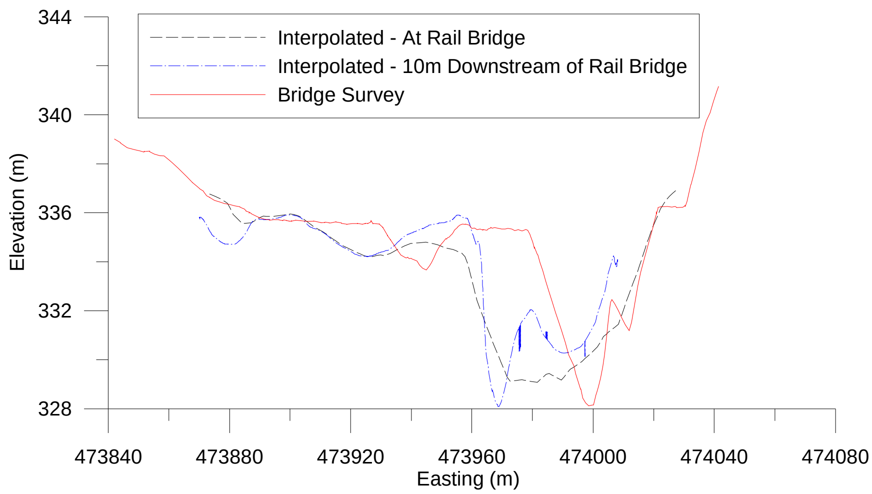

Figure A-3 - Bathymetric Cross Sections near Rail Bridge

As a verification of the new cross section's validity the bridge survey data were plotted along with nearby survey data points from the EC bathymetric survey which is illustrated in Figure A-4. Survey points selected for comparison were closer than approximately 10 m upstream or downstream from the bridge cross section and were selected such that an equal number of upstream and downstream sample points were included in the comparison. The sampled data do not vary substantially from the measured cross section from the bridge drawings, nor the interpolated bathymetry. However, considering the great differences in cross sectional area, and the positioning of the piers, the bridge survey was judged the most appropriate cross section at the rail bridge.

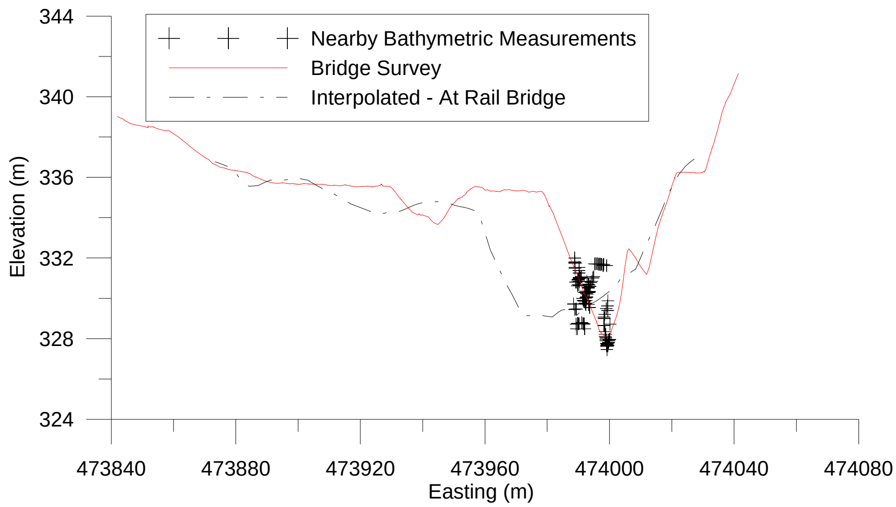

Figure A-4 - Bridge survey cross section with nearby bathymetric measurements

APPENDIX B – COMPUTATIONAL MESH GENERATION

This appendix shows figures of the computational meshes used in this study. Mesh 1 of the whole lake is shown in Figure B-1. The detail of the International Falls dam for Mesh 1 and Mesh 2 is shown in Figure B-2. The detail of the Ranier Rapids rail crossing for Mesh 1 and Mesh 2 is shown in Figure B-3. The greatest detail (smallest node spacing) within the computational domain is found near the International Falls Dam and the Ranier Rapids bridge crossing. These two areas possess complex boundary conditions due to the presence of bridge piers, but also include the most complex and rapidly changing bathymetric data. The minimum edge length is approximately 3 m with the smallest edge lengths occurring adjacent or near the piers of both bridges.

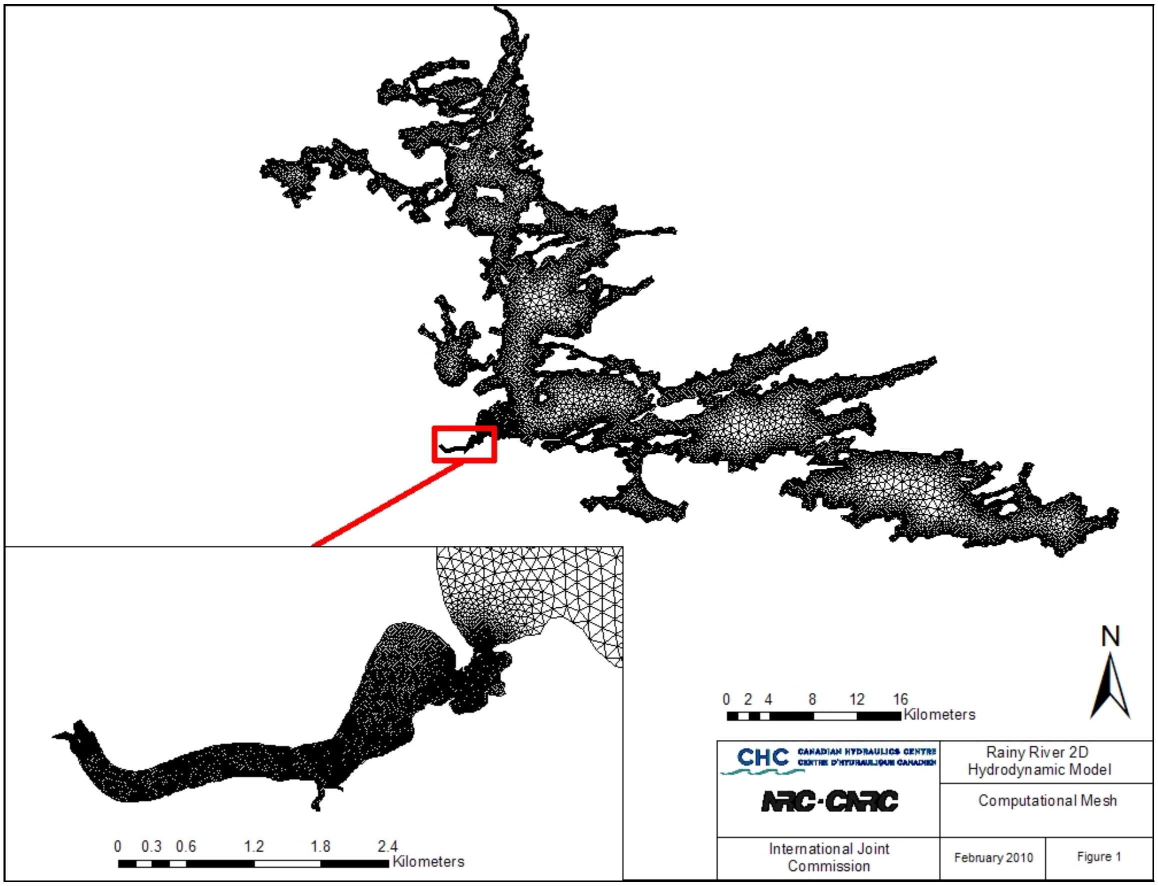

Figure B-1 - 2D Computational Mesh (Mesh 1)

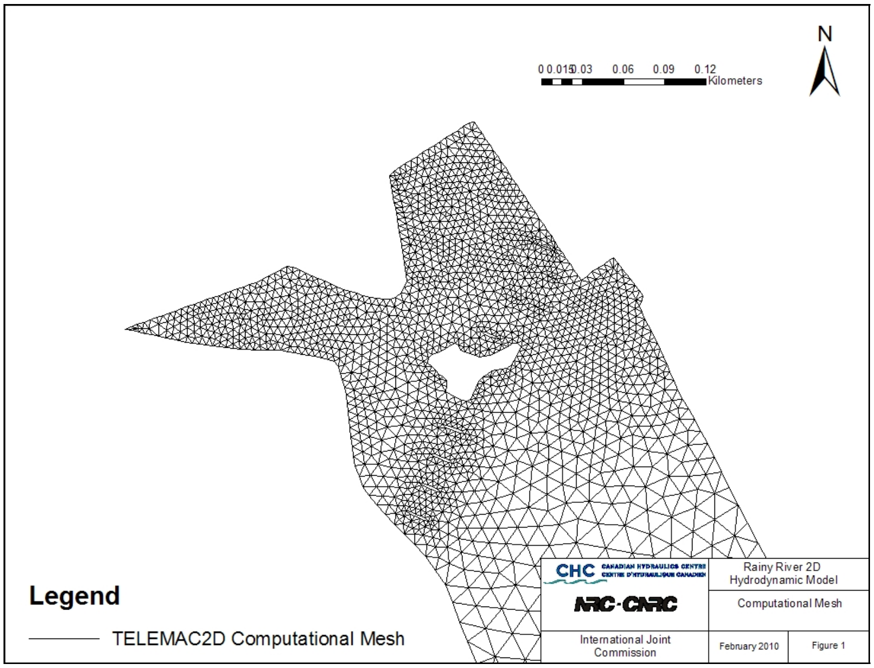

Figure B-2 - 2D Computational Mesh - International Falls Bridge (Mesh 1 and Mesh 2)

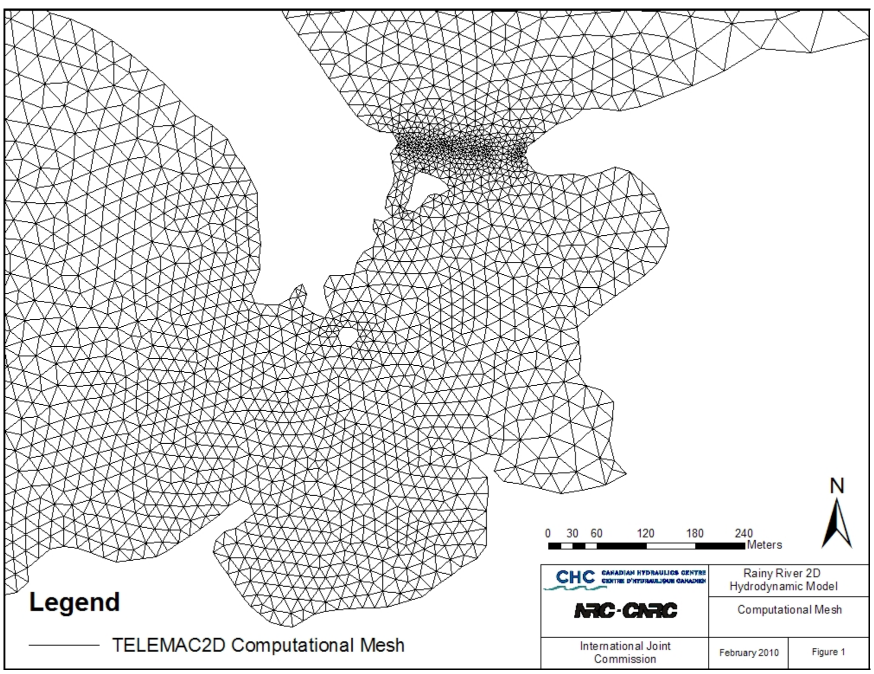

Figure B-3 - 2D Computational Mesh - Rainier Rapids (Mesh 1 and Mesh 2)

APPENDIX C – CALIBRATION AND VALIDATION PERIODS

This appendix outlines the calibration and the validation period employed in the Rainy River model development. The two calibration periods are shown in Figure C-1 and Figure C-2. The two validation periods are shown in Figure C-3 and Figure C-4. Each figure shows a grey highlighted period in which the calibration or validation was performed. These periods were chosen because of the near steady-state nature of all flow and level measurements.

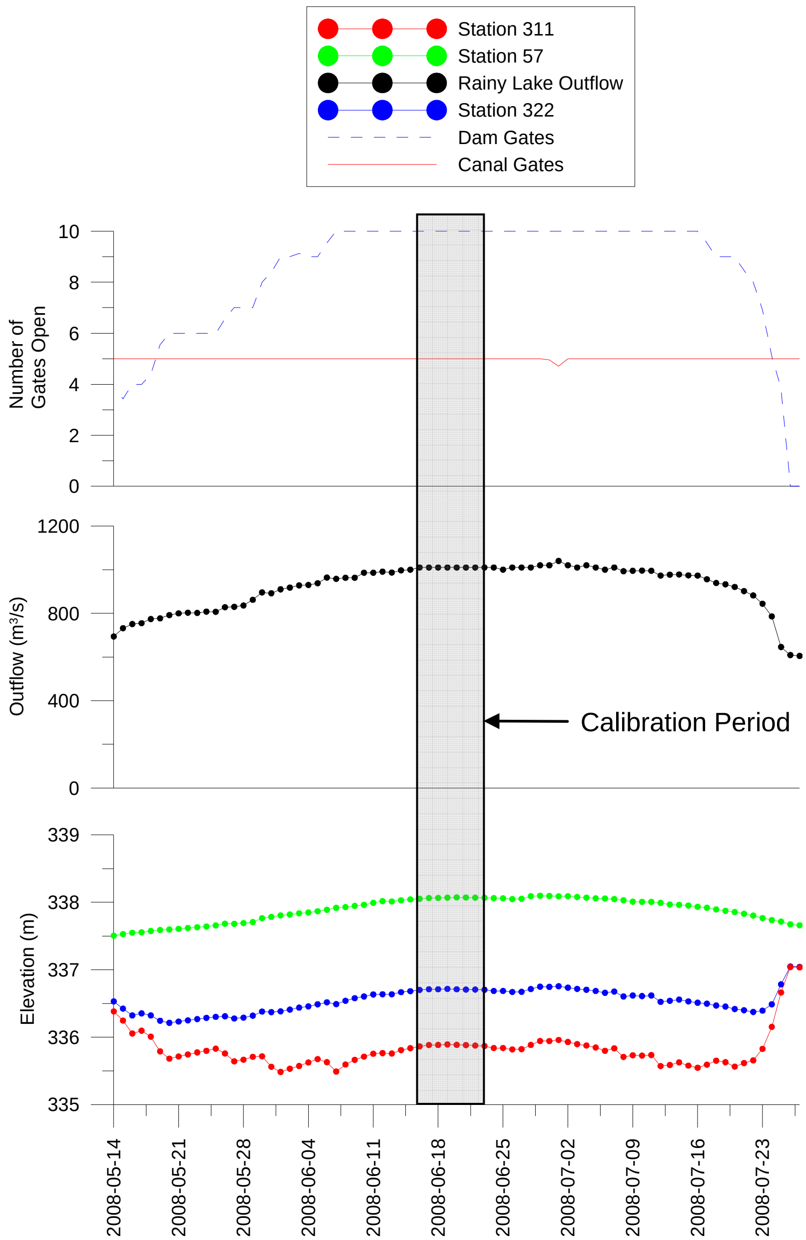

Figure C-1 – Model Calibration - Period 1

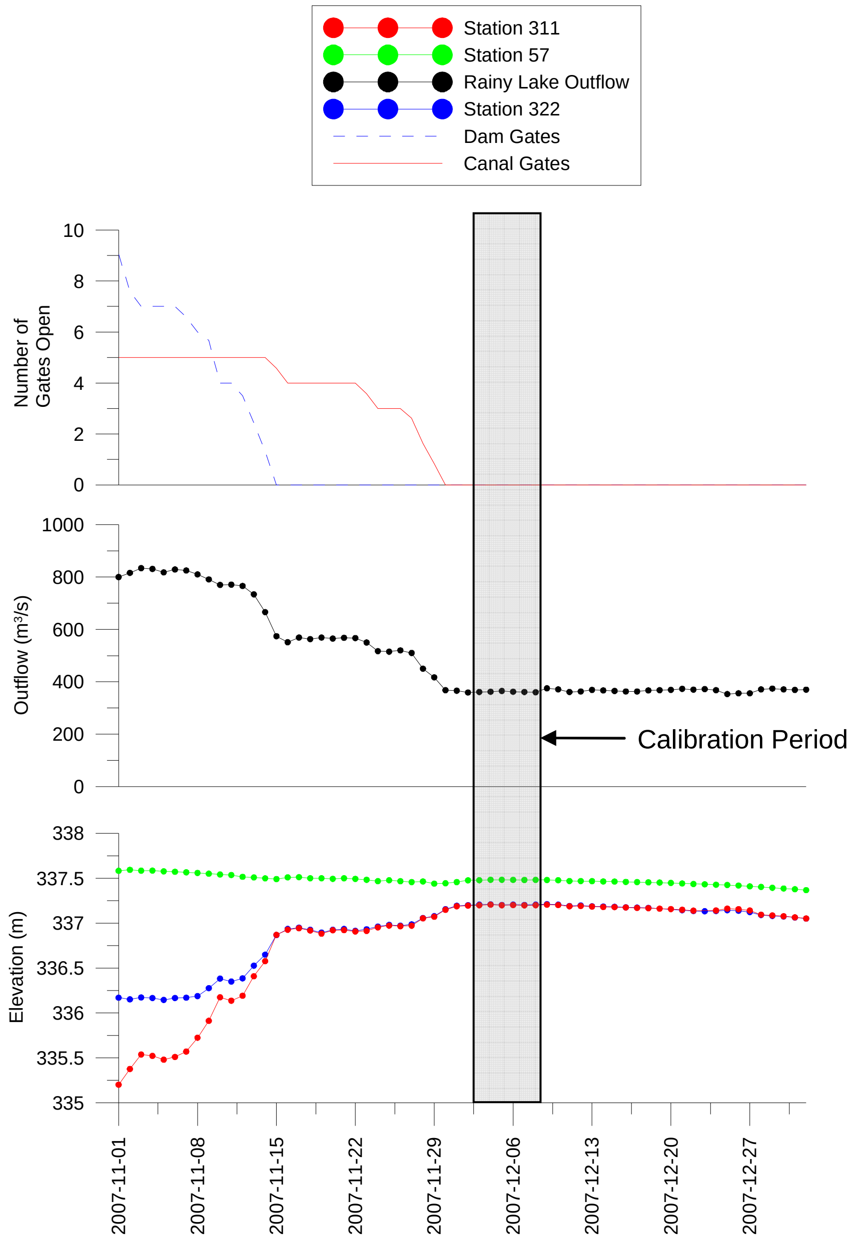

Figure C-2 – Model Calibration - Period 2

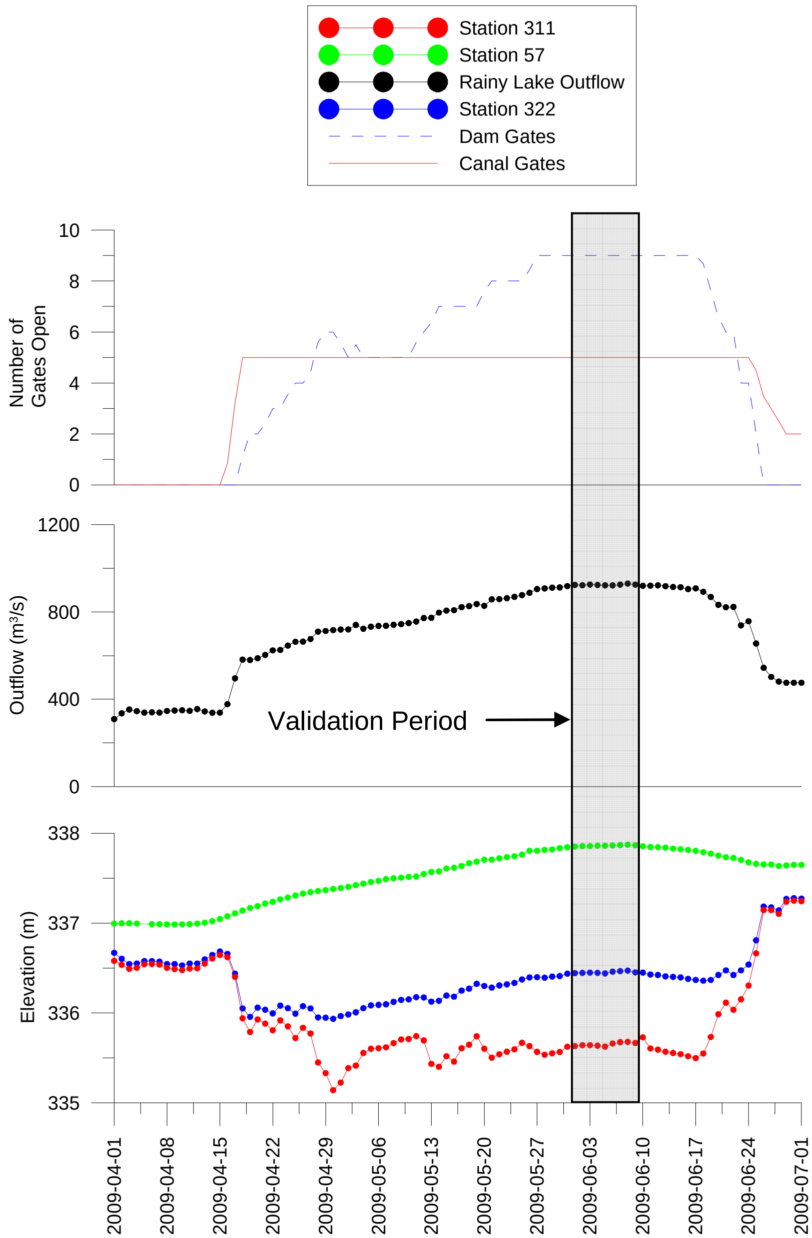

Figure C-3 – Model Validation - Period 3

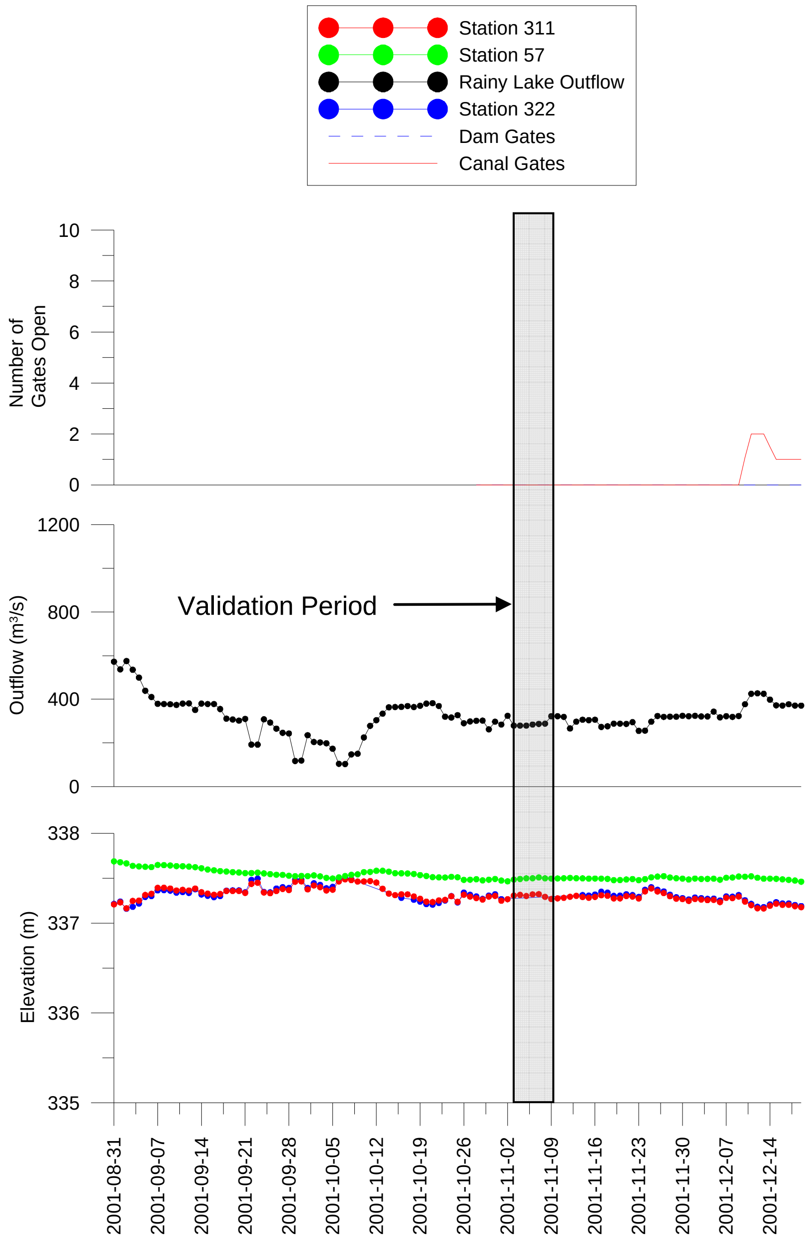

Figure C-4 – Model Validation - Period 4

APPENDIX D – STATE OF NATURE BATHYMETRIC COMPARISONS

This section outlines the comparison of the 2009 bathymetry to the “state of nature” bathymetry determined from contour maps (see Section 2.5.2 in the main text).

Figure D-1 shows the locations of the various cross sections that are compared. The remaining figures in this appendix (Figure D-2, Figure D-3, Figure D-4, and Figure D-5) compare the identified cross sections.

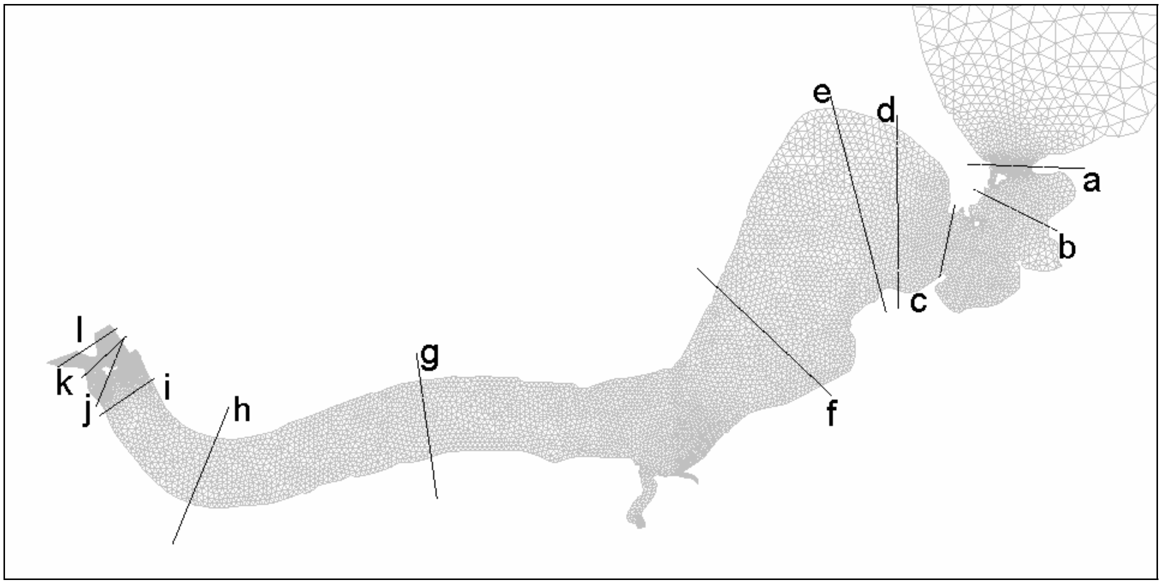

Figure D-1 - State of Nature Bathymetric Comparison - Cross Section Locations

The cross-sections themselves are compared in Figure D-2 (A,B,C), Figure D-3 (D,E,F), Figure D-4 (G,H,I), and Figure D-5 (J,K,L). The cross sectional data are plotted along an arbitrary cross sectional axis from left-bank to right-bank.

The cross sections show generally good agreement between the two datasets. Generally, the differences in data density are observed with the locations of the cross sections clearly visible on most cross sections. Section A (Ranier Rapids, Rail Bridge), is very similar although the 2009 data are approximately 1m different at the deepest point of the channel. Section C, also an important cross section, is very similar between the datasets with the 2009 survey showing a slightly shallower channel. The smallest discrepancies between the datasets are observed in the man channel (Sections D to I), showing the channel geometries have not changed much. The possible exception is section E, which shows a deeper and narrower channel at the south end of the river when compared to the earlier surveys. The cross sections at Koochiching Falls (Sections J to I) show significant differences between the two data sets. The depth on the south side of the International Bridge (Section J) is substantially shallower with the new bathymetry (by approximately 2 m). The section just upstream of the dam (Section K) shows the opposite trend with the new survey data being substantially shallower at the north end of the channel than the original bathymetry. Finally, just upstream of the turbine intakes (Section L) the bathymetric elevations have increased on the US side by several meters for most of the cross section, while on the Canadian side the cross section seemed to have levelled off with higher elevations at the south end of the Canadian turbines and lower elevations near the shoreline.

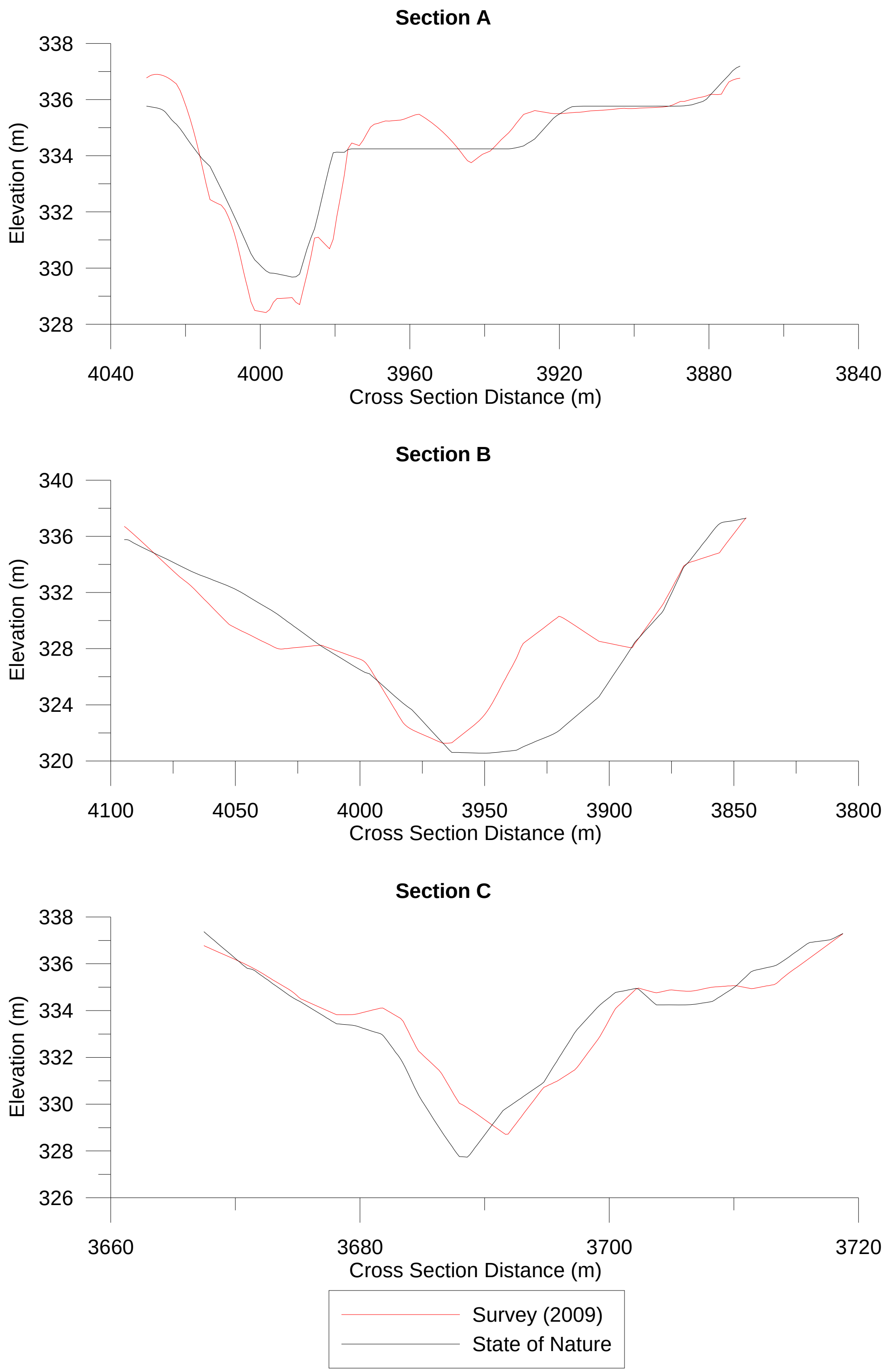

Figure D-2 - State of Nature Cross Section Comparison - A,B,C

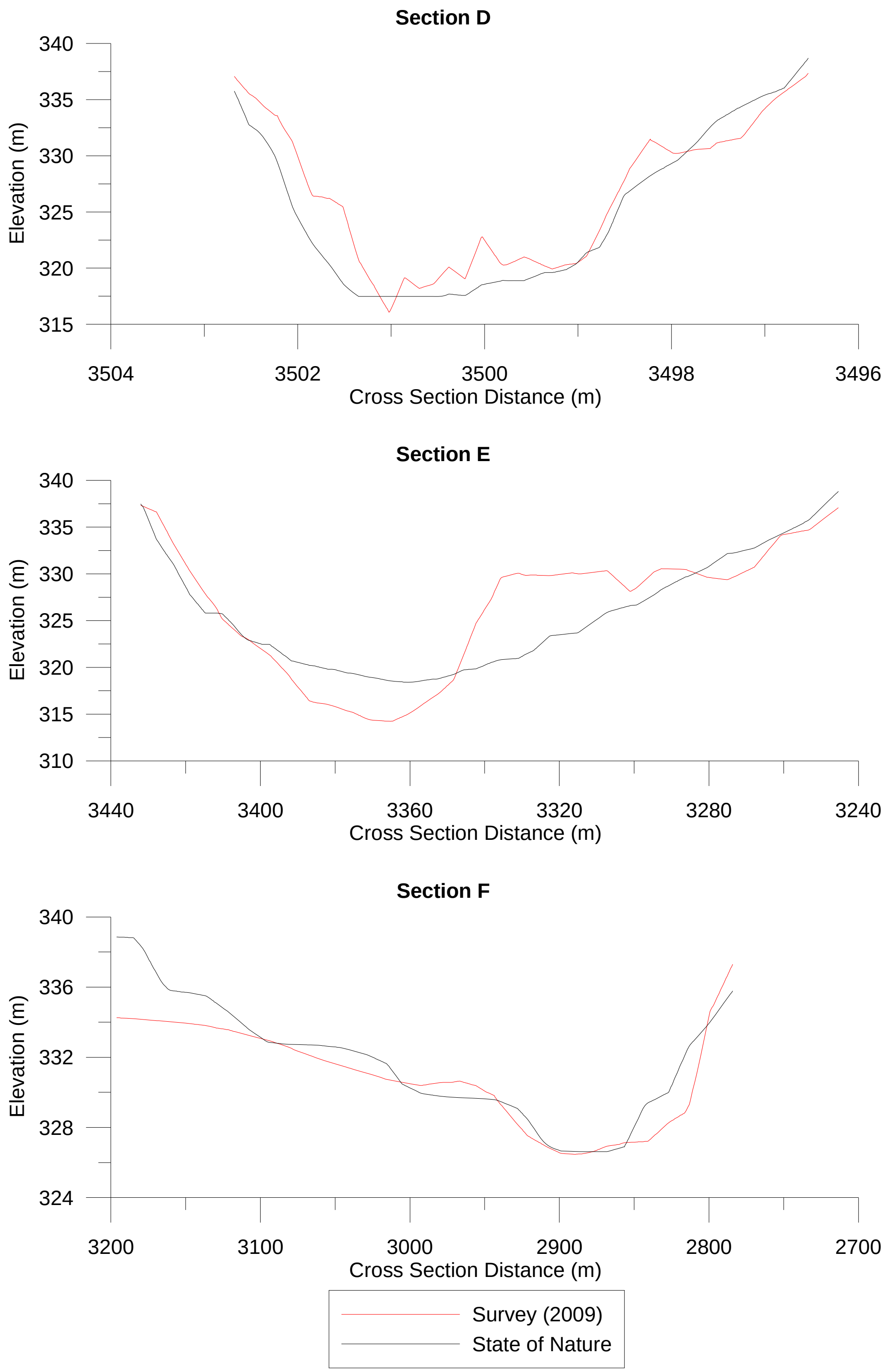

Figure D-3 - State of Nature Cross Section Comparison - D,E,F

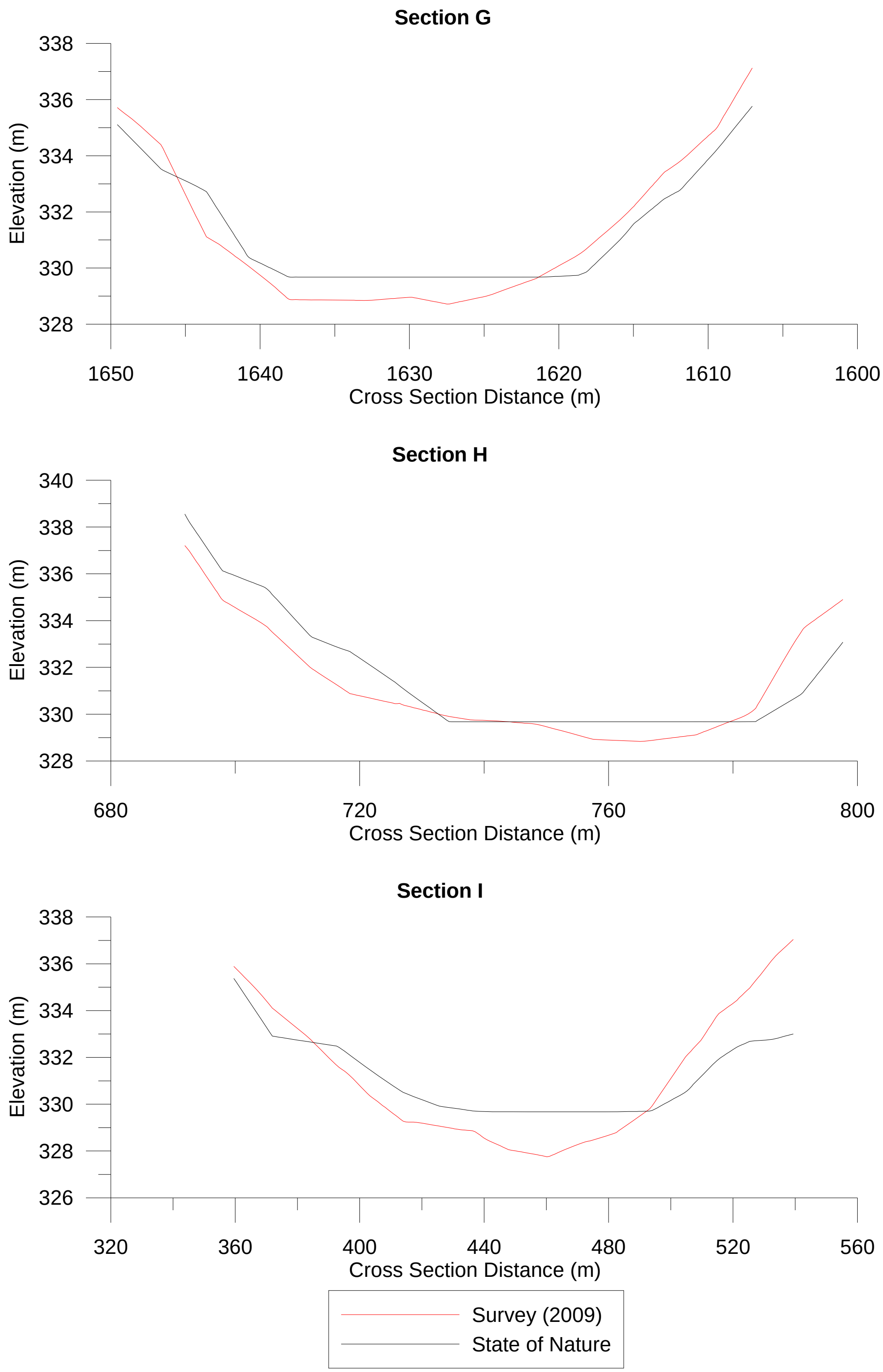

Figure D-4 - State of Nature Cross Section Comparison - G,H,I

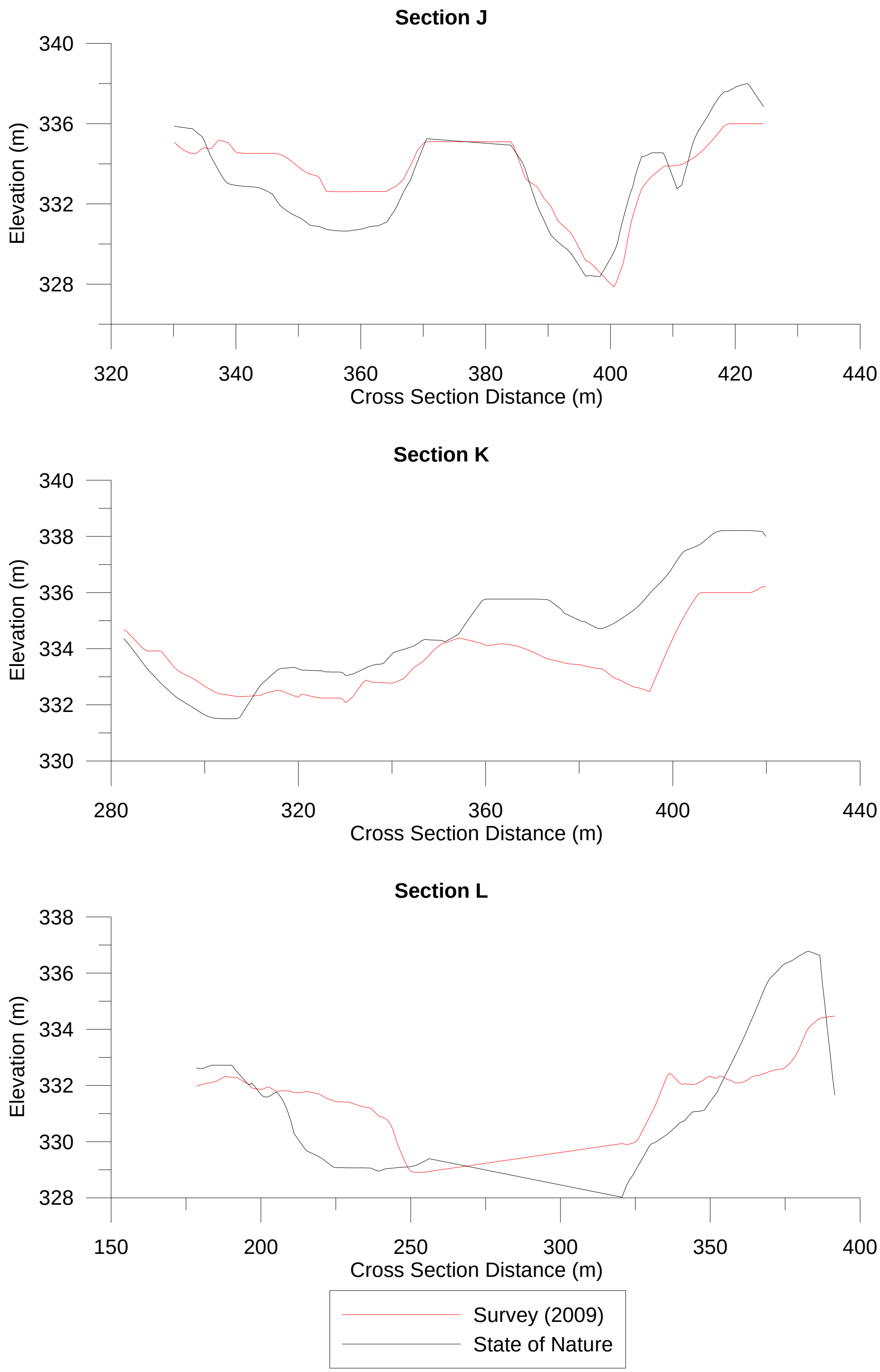

Figure D-5 - State of Nature Cross Section Comparison - J,K,L