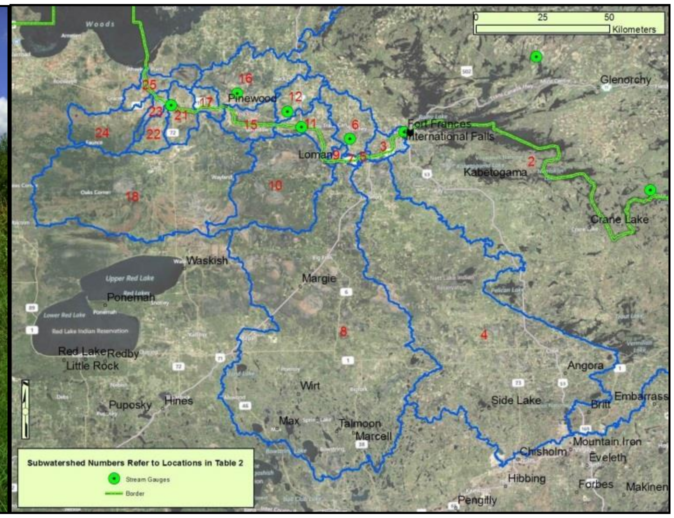
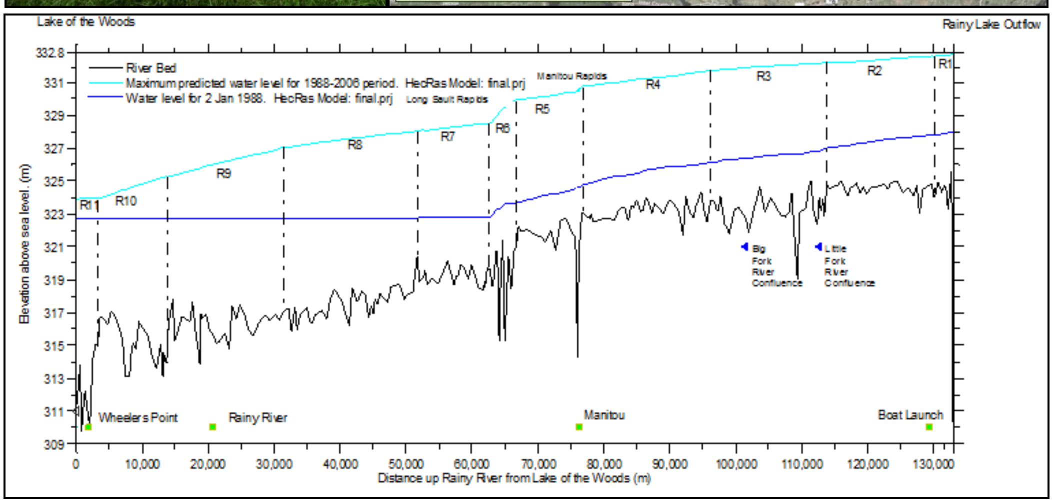
An Investigation of the Effects of the 2000 Rule Curve Change on the Rainy River Hydrologic and Hydraulic Regime.





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Prepared for:
International Joint Commission
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IJC Hydrology Report

for the project entitled:

Characterize the hydrology of the Rainy River in terms of levels and flows, tributary and local inflow, flow attenuation and alteration from pre-dam and pre-2000 Rule Curve hydrology.

April, 2014

In support of

The International Joint Commission (IJC) 2009 Plan of Study (POS) for the Evaluation of the 2000 Rule Curve Changes for Rainy and Namakan Lakes and Rainy River.

Prepared for

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EXECUTIVE SUMMARY

Background

The International Falls/Fort Frances Dam (IFD) has been in operation since 1909 and supports two hydroelectric facilities. Rule curves issued by the International Joint Commission are used to guide the operation of the dam and Namakan Reservoir upstream. The rule curves provide guidelines to maintain the upstream reservoir elevations between a minimum and maximum elevation depending on the date. Changes were made to the 1970 rule curves in the year 2000. The rule curves and operational changes at IFD influences the downstream flow regime and hydraulic habitat of Rainy River as does the backwater effect from Lake of the Woods (LOW) in the lower portion of the river. Dam building started in the late 1800's on Lake of the Woods and the current water level is approximately one meter higher on average than the naturally occurring water levels observed before dam construction. Methods were used to assess how the flow regime and related hydraulic conditions in the Rainy River have changed from their natural condition and before and after the rule curve change.

Objectives

The three main objectives of this study were to document any differences in flow regime between the pre- and post- 2000 rule curve periods for observed and State of Nature (SON) conditions, to investigate the potential causes of any observed differences, and to determine the effect of any changes in the duration and timing of water levels and by extension, habitat availability. The 2000 Namakan Lake rule curve permitted marginally higher water levels in Rainy Lake during April-May, and lower water levels in the August-November period. The post-2000 rule curve permits higher water levels in the lake in the December-June period and reduces the range of operation from 2.5 m to 1.5 m. Lower water levels are permitted in Namakan Lake in the July-November period. Thus, changes in the pattern of observed flows may be related to the rule curve change if they are observed in these two seasonal periods, and independent of any confounding influences related to natural trends in regional climate and/or fluctuations of reservoir water levels.

Methods

The inundation frequency and duration of a riverbed reflects a rivers' flow regime. In this report we assess alteration in the flow regime of Rainy River between pre- and post-rule curve periods to provide an indication of whether changes in inundation characteristics would be expected. Central to the assessment of streamflow alteration is the concept of using controls or controlled conditions as a reference against which the alteration is assessed. We use the Before-After-Control-Impact (BACI) design to assess the streamflow time series observed at the *impact* site *before* and *after* the operating change, which is expected to be influenced by the alteration to the system, against a *control* which is not affected by the change. Here we refer to the *control* as State of Nature (SON). We also use the Reference Condition Approach to determine the deviation of a hydrologic indicator variable from its expected natural range. The natural range is determined from the probability distribution for a hydrologic indicator variable derived from a reference time series (e.g. SON). We refer to three SON cases in this document.

1) Flows prorated from natural reference river for assessing change in hydrology at IFD.
2) Flows simulated using Flow Duration Curve (FDC) transference to IFD for assessing change in hydrology.
3) A pre- settlement simulation of hydraulic conditions in the Rainy River using a HEC-RAS model, SON flows simulated using FDC transference at IFD and tributaries along the river, and a SON water level time series simulated at LOW.

Hydrologic indicators used in the assessment included flow duration curves and flow metrics. Flow duration curves show the proportion of time a flow value is equaled or exceeded and, by incorporating the complete range of river flows, provides an informative summary of a flow regime. Flow metrics, such as the Indices of Hydrologic Alteration (IHA), quantify fundamental characteristic of the flow pattern including the magnitude, duration, timing, frequency, and rate of change of flows.

To evaluate if a change in hydrologic regime occurred at IFD we compared flows in the pre- to post-periods using a) decadal FDC's for each period, b) monthly FDC's for each period, and c) IHA flow metrics. To examine if the changes observed in these periods was within the range of natural variability, and thus not solely driven by the rule curve change, we compared observed flows to SON flows at IFD by management period. More specifically, three comparisons were made to investigate the following questions:

1) Are the observed FDS's for the period within the maximum and minimum range of prorated reference river SON FDCs?
2) Are the observed monthly FDC's more similar to the SON FDC's derived from the simulated natural flow regime for IFD in the pre- or post- period?
3) Are the observed flow metrics within the range of variability of flow metrics calculated using the simulated SON flow series? More specifically, is there a statistically significant difference in flow metric means between the pre- and post- periods in both the observed and SON flows?

Rainy River flow regime fluctuations below IFD were simulated over the period of interest using an existing unsteady flow hydraulic model (HEC-RAS). Modifications made to the IJC HEC-RAS model included: 1) Rediscretization of the HEC-RAS model and extraction of subwatershed characteristics using GIS; 2) Simulation of flows at nineteen ungauged subwatersheds (tributaries and interconfluent subwatersheds) for the period 1970-2010 for the HEC-RAS models (i.e. 'Observed' and 'State of Nature' flow cases) using flow duration curve transference; 3) An update of the LOW water level data for model validation (2006-2010) of the HEC-RAS 'Observed' model using inverse distance weighting of observed data; 4) Simulation of the State of Nature boundary conditions (i.e. hydrograph at IFD and water level hydrograph at LOW); 5) Running the updated, unsteady HEC-RAS 'Observed' model and validating the model using observed data from gauging stations between IFD and LOW; and 6) Running the updated, unsteady HEC-RAS model for the State of Nature scenario.

Using HEC-RAS output, we examined regime shifts in water levels, daily change in water levels, and wetted perimeter between rule curve periods, and under the SON case. A statistical analysis was conducted to evaluate which factors affected the shape of the monthly duration curves for the 1970 to 2000 period. To test the hypothesis that there were no changes in the hydraulic regime between management periods, the model was used to identify if significant differences in duration curve shapes between rule curve periods exist. To evaluate if the hydraulic regime differences were solely governed by rule curve changes, we then tested to see if these differences were significant if other factors that affect the hydraulic regime are included (e.g. climate, water levels in upstream reservoirs, and changes in rule curve between pre- and post- periods). We also use the statistical model to document how far downstream significant differences in duration curve shape persist for the pre- to post- period for observed and SON flows. Finally, we documented differences in wetted perimeter duration curves at eleven response reaches along the Rainy river to examine how hydraulic habitat changed between rule curve periods, within the context of the SON case.

Findings

Key findings of study as they relate to the project's objectives are summarized below and detailed in Section 6.1

Are there changes in the flow regime of Rainy River between the pre- and post- 2000 periods?

Post- to Pre- Rule curve period differences in observed discharge at IFD:

a) Period of record flow duration

A greater percentage of time in the post-2000 rule curve period was spent at very low and very high flows. Given the more extreme runoff conditions in the post-period, the post- FDC curve strongly reflected the rule curve release targets. Flows between the maximum capacity of the U.S. (240 m^3s^{-1}) and Canadian (354 m^3s^{-1}) hydroelectric facilities occurred with the same frequency between pre- and post- periods.

b) Monthly flow duration

The post-2000 monthly flow duration curves are more stepped in appearance, relative to the pre-2000 FDCs. In many months, more time was spent at the low flow release rate in the post-period. There was also more time spent at or above maximum turbine capacity implying higher volumes of water spilled in the post-period.

c) Flow metrics

Monthly median flows for April and June were outside the expected range of variability associated with the pre- period. In the post-rule curve period, the monthly median flows were lower in April and higher in June than expected from the pre period

Are these hydrologic trends associated with the change in rule curve ruling in 2000 or within the range of behaviour for natural rivers?

Observed to SON (Reference Rivers) differences in discharge at IFD

a) *Pre- period.* The observed flow exceedances for some flows at IFD was outside the range of flow variability for local, natutral reference rivers (i.e. SON) during the pre-rule curve period . During the 1970-2000 rule curve period, the Rainy River at IFD had lower extreme high flows, and higher extreme low flows, relative to the reference rivers. Discharges also occurred at a higher frequency for mid-bank to bankfull flows at IFD, relative to the reference rivers.

b) *Post- period.* In contrast, the observed flow exceedances at IFD was not outside the range of flow variability for local, natural reference rivers (i.e. SON) for the post-rule curve period. However, the Rainy River at IFD experienced flows being held at rule curve targets, unlike the reference rivers. The extreme low flows at IFD were maintained for a longer duration, relative to the reference river mean FDC, where lower flows were observed. Extreme high flows at IFD were lower relative to the unregulated rivers. This suggests that riparian flows are lower than reference rivers but some mitigation of drought occurs in Rainy River as a result of flow regulation.

Thus, the flow regime at IFD has an altered flow pattern in both the pre- and post- periods as expected. The flows at IFD were outside the range of variability of the natural rivers for the pre- period but not for the post- period. The uncertainties associated with the interpretation of this reference river type comparison are discussed in Section 6.1. These uncertainties led to further analysis using simulated flows at IFD (see below), and a statistical analysis of climatic and regulation effects (see Hydraulics section below).

Observed to SON (Simulated) differences in monthly flow duration at IFD

The relative influence of climate or regulation on changes in the monthly flow pattern represented in the FDC's was not clear from the FDC comparison between the observed and SON case. As previously observed, the post -2000 rule curve period was closer to the SON case, particularly for November through May and July. Under the post-2000 rule curve, agreement between altered FDC and State of Nature FDC also improved in May and June for high magnitude flows.

Observed to SON (Simulated) differences in flow metrics at IFD

To examine the hypothesis that the 2000 rule curve caused a shift in the flow regime we examined if a shift in the flow pattern could be detected in the year 2000 using Classification and Regression Trees (CART). Natural breaks in flow metrics occurred within the pre- and post- periods (e.g. 1975 1986, 1992, and 2002) but none were directly coincident with the year 2000. While not conclusive, this result does not support the hypothesis that the 2000 rule curve caused a shift in the flow regime; unless undetected lag effects occurred (discussed in Section 6.1). The changes in the flow pattern indicated by the CART analysis are consistent with anticipated effects from both the cessation of hydro-peaking in the U.S. facility, and elimination of weekend ponding in the Canadian facility in 2001.

Linear trends in the flow metrics for the entire period of observation (1970 to 2010) were documented. The following significant trends were detected in the observed flow series but not in the SON series: Increases in low pulse count and frequency of extreme low flows; and decreases in mean monthly flow in February and March, the three day minimum flow, low flows in February, March and April, and high peak flows. Most of these trends showed a consistent pattern throughout the pre- and post- period, without any change in year-to-year pattern to suggest that the trends are dependent on the rule curve change. A change in behaviour over the period of observation was observed in some variables, but again not coincident with the rule curve change in 2000 (e.g. the low pulse counts were much higher and variable between 1987 and 2002, and the monthly flows in April were higher and more variable after 1996). The change in pattern of these flow metrics likely reflects the intensification of hydro-peaking activities between the late 1980's and 2001, and the change in the AMO cycle after 1995. The comparison of pre- to post- distribution of flow regime metrics is not the best method to use for isolating causal linkages when the period specific distributions of a flow metric combines multiple confounding influences on the flow pattern that span both periods. Regardless, one would expect more evidence of a change in flow pattern in 2000 if the effects of the rule curve change were stronger than other confounding influences on runoff pattern.

Despite differences in mean values for the decades between 1970 and 2010, there was no significant difference (p=0.05) in mean monthly precipitation, snowfall or temperature between these decades. However, the mean precipitation and temperature were higher in 2000-2010 relative to the three previous decades. These positive trends in precipitation and temperature in the post- rule curve period are consistent with entering the positive phase of the Atlantic Multi-decadal Oscillation.

The post- rule curve period was too short to calculate reliable extreme value statistics. However, the most extreme discharge events occurred in the current positive phase of the Atlantic Multi-decadal Oscillation cycle (i.e. after 1995). There were only four years with discharges exceeding 1000 m^3/s at IFD during the period studied. These discharges in order of highest to lowest occurred in 2002, 2001, 2008 and 1996, respectively. The post-period also had a lower minimum discharge, relative to the pre- period. A more detailed statistical analysis was conducted on water level changes to help parse out the relative effects of climate and management (see below).

Are there changes in river bed inundation in the Rainy River between pre- and post- 2000 periods and are these hydraulic trends associated with the change in rule curve ruling in 2000 or other factors (e.g. climate)?

a) Water Levels

A statistical analysis of output from the revised HEC-RAS model showed significant differences in duration curves between the rule curve periods for both water level and daily water level difference. However, these differences were not significant if other factors were also considered such as climate, water levels in Rainy Lake and Namakan Reservoir or year of observation. We included a variable in the statistical model that was a measure of the difference in water levels permitted between the two rule curve periods. This term was not significant for any month. These results collectively support the assertion that the pre- and post- hydraulic conditions in the Rainy River are influenced by climate and reservoir water levels, however, there was no strong evidence to suggest that the post- rule curve flow pattern was governed solely by the rule curve change in 2000.

The serial discontinuity concept posits that the alteration caused by a discontinuity (e.g. dam) extends downstream until the effect can no longer be detected. We investigated if there were differences in water level and daily stage range between the pre- and post-period for four stations downstream of IFD. Significant differences in water levels and water level fluctuations between the pre- to post- period were detected for 110 km to greater than 130 km downstream of the dam depending on the month.

b) Wetted Perimeter

Pre- to Post-. There was a difference in wetted perimeter frequency duration curves between the pre- and post- rule curve periods along the Rainy River. The wetted perimeter increased in the post-period for floodplain and baseflows, relative to the pre- development period. However, the wetted perimeter decreased per given exceedance value in the post-period for all other sub-bankfull flows. The difference in wetted perimeter between the post- and pre- periods decreases with distance downstream, being minimal below the Rapid River (Reaches 9-11). This downstream trend can result from both the decreasing influence of releases from IFD, and increasing influence of both confluent tributaries and the backwater effect from LOW.

Pre- period. There was a difference in wetted perimeter frequency duration curves between the observed and State of Nature cases for the pre-rule curve periods along the Rainy River. The largest difference between the observed and State of Nature wetted perimeter duration curves for the pre-rule curve period occur in the lower river from Reach 7 to Lake of the Woods. The backwater effect of raising the water level in LOW by an average of 0.9 m at the turn of the century resulted in more frequent inundation of the State of Nature channel and floodplain. The change in river habitat between the State of Nature case and pre- rule curve period was most pronounced below the Long Sault Rapids. This change would shift the lower river to a more lentic state, relative to the SON case.

The other notable difference between the observed and State of Nature wetted perimeter duration curves for the pre-rule curve period occurs in the upper river between Reach 1 and Reach 6. There were two key differences: 1) The main difference is that the observed wetted perimeter is narrower more frequently, (i.e. exceeded between 75% and 100% of the time), relative to the State of Nature. As expected this effect diminishes with distance downstream, but is masked by the larger backwater effect after Reach 6. Thus, the regulation effect of IFD is to reduce the amount of useable habitat in the baseflow to mid-bankfull flow range; and 2) The wetted perimeter is also narrower for infrequent, riparian flows (i.e.

exceeded between 0.1% and 35% of the time), relative to the State of Nature. This suggests that a narrower band of floodplain is inundated for a given frequency of flow in the upper river.

Post- period. There was a difference in wetted perimeter frequency duration curves between the observed and State of Nature cases for the post-rule curve periods along the Rainy River. The differences between the observed and State of Nature wetted perimeter curves in the upper river were slightly larger in the post-rule curve period. The wetted perimeter during the extreme low flow exceedances (e.g. >95%) were slightly higher for the post-period SON comparison in both the upper and lower river, relative to the pre-period SON comparison. This result reflects the large runoff events that occurred during this period.

The alteration in wetted perimeter between the pre- to post- rule curve periods was small, relative to the present day to State of Nature wetted perimeter comparison, where wetted perimeters increased substantially in the backwater zone in the lower river from the historic increase in water levels in LOW.

The length backwater effect of LOW is seasonally variable and dependent on LOW water levels. At high LOW water levels, the backwater effect can extend upstream 110 + km. Lowering the LOW water levels to State of Nature conditions causes much less backwatering in the lower river, particularly downstream of the Long Sault Rapids. Relatively small changes in LOW water levels can change the hydraulic conditions over long distances of the lower Rainy River. This provides a potential management opportunity to meet habitat targets in the Rainy River, beyond flow regulation in the Namakan Reservoir and Rainly Lake.

Inferences related to the effects of the Namakan River reservoir rule curve resulting from our statistical analysis should be evaluated within the context of the study entitled “Develop a hydrologic reservoir routing model for Rainy Lake and the Namakan Reservoir to assess the hydrodynamic changes due to the 2000 Rule Curves.” The HEC-RAS model has been calibrated at two points that are not also boundary condition locations. For studies requiring more refined and spatially distributed river stage estimates, some further steps could be taken to increase confidence in the predictions being made between calibration locations. These model-related recommendations are provided in Section 5.4.

CONTENTS

List of Figures

This optimized parameter set was then used with a daily precipitation and temperature data for the 1970-2010 period to generate an State of Nature series. The Y axis range is fixed to facilitate comparisons between series generated by the different simulation methods shown Figs 3.1-6.

Figure 2.15. Simulated hydrographs using SpatPro. The simulation is Run 1 using the FDC transposition method.

Figure 2.16 Simulated hydrographs using SpatPro. The simulation is Run 1 using the proration method.

Figure 2.17 Fluctuating water levels on Lake of the Woods at Keewatin for the period 1914 to 2011.

Figure 2.18 Water levels at LOW for existing conditions (Observed) and for simulated State of Nature flows. The pre-dam mean is plotted as given by the early LOWCB study. The offset from the mean for the period 1913-1925 for max and min flows was transferred onto the pre-dam mean to provide guidance on approximate variability to expect the simulation to contain. The State of Nature simulation is outside that range but this is to be expected as it represents a 40 year period (i.e. vs 1913-1925).

Figure 2.19 Predicted and observed stage at Manitou rapids for a) the original HEC-RAS model and b) the revised model (i.e. original HEC-RAS model with revised unsteady flow file).

Figure 2.20 One-to-one plots showing predicted and observed stage at Manitou rapids for a) the original HEC-RAS model and b) the revised model (i.e. original HEC-RAS model with revised unsteady flow file). The Manning's *n* in the channel is 0.05 and 0.085 above the bank station elevations of 327.48 and 327.98 m. The lowest elevation in the channel cross section is 320.34 m.

Figure 2.21 Predicted and observed stage at the town of Rainy River for a) the original HEC-RAS model and b) the revised model (i.e. original HEC-RAS model with revised unsteady flow file).

Figure 2.22 One-to-one plots showing predicted and observed stage the Town of Rainy River for a) the original HEC-RAS model and b) the revised model (i.e. original HEC-RAS model with revised unsteady flow file). The Manning's *n* in the channel is 0.035 and 0.085 above the bank station elevations of 321.87 and 323.20 m. The lowest elevation in the channel cross section is 315.68 m. The floodplain roughness appears to be too high for stages greater than 323.55 m.

Figure 3.1 Runoff of the Rainy River (Fort Frances & Manitou Rapids) and three Reference 1 rivers (Turtle River, Namakan River, English River) for the period 1905-2010.

Figure 3.2 Runoff of the Rainy River (Fort Frances & Manitou Rapids) and three Reference 1 rivers for the period 1970 to 2010. There appears to be a high degree of correspondence of the event peaks between the three sites.

Figure 3.3 Significant negative trends in observed flows at Fort Frances/International falls for the 1970-2010 period for a) February monthly flows, b) March monthly flows, and c) three day minimum.

Figure 3.4 Significant trends in observed flows at Fort Frances/International Falls for the 1970-2010 period for the six flow metrics from Table 3.3 with significant trends. Note that changes in the pattern of

List of Tables

pre-dam period (1905-1908) and post-dam reference period (1970-2010). The 1970-2010 parameter set reflects elements of the water balance for the current, altered condition at Fort Frances.

List of Appendices

Supporting Information and Products

PROGRAMS

#	Program Name	Description
1	*SpatPro*	Predicts hydrographs at ungauged stations or patches flows at gauging stations
2	*HourlyInterpolation*	Interpolates hourly data from daily data
3	*IDW_Daily*	Inverse distance weighting of climate data
4	*Evaluate_POR_Restricted*	Evaluates the fit of HEC_RAS validation runs
5	*Rainy_River_Hydrozone_Daily*	Plots duration curves by month for the pre- and post-period for water level
6	*WaterLevelFluct*	Plots duration curves by month for the pre- and post-period for the daily difference in water levels

SPATIAL DATA PRODUCTS

Path: C:\Rainy_R_Spatial_Data

#	File Name	Description
1	anprecip_utm	US Climate Stations
2	Bathymetric_Data	USGS bathymetric data - merged
3	Bathymetry_USGS_RR	USGS bathymetric data
4	Canadian_Stations_Clip	Canadian climate stations
5	Centroids	Watershed centroids
6	CXCutlines	HEC-RAS cross sections
7	dem_rr	Merged US and Canadian DEM
8	EC_Climate_Stations	Environment Canada climate stations
9	lakes_merged_Intersect	Lakes
10	Precip_Stns	Precipitation stations
11	Quaternary_Map	Quaternary geology map – merged US & Cdn
12	rainy_wtrshd	Watershed divide upstream of IFD
13	Ref_Gauges_Corrected	Reference station gauge locations
14	Sites_new	Pour point sites
15	soils	Soils map - merged US & Cdn
16	Soils_Intersect	Soils map - merged US & Cdn – Clipped to study area
17	streamord	Stream order derived from dem_rr
18	surf_geology	Surficial Geology
19	toporr	Digital elevation model – floating point format
20	Watersheds_All	Watersheds for redisctrtized HEC_RAS model and reference basins.
21	WS_Join12	Intersection of HEC-RAS cross section and 2006 bathymetric survey data.

HEC-RAS FILES

Path: C:\Rainy_R_HEC_RAS

#	Project Name	Description
1	final.prj	Original HEC-RAS file with seasonal roughness of 1.14.
2	FinalMRevised.prj	Final.prj converted to metric units and revised with new unsteady flow file

Model runs (i.e. Plans) contained in FinalMRevised.prj :

Observed 1990-2010 runs

1) 1970_1990_Seasonal roughness 1.14
2) 1990_2010_Seasonal roughness 1.14

State of Nature 1990-2010 runs

3) 1970_1990_Seasonal roughness 1.14 SNat2
4) 1991_2010_Seasonal roughness 1.14 SNat2

SECTION 1. INTRODUCTION AND BACKGROUND

This report summarizes the work for the project "Characterize the hydrology of the Rainy River in terms of levels and flows, tributary and local inflow, flow attenuation and alteration from pre-dam and pre-2000 Rule Curve hydrology" as set out by the schedule contained in the IJC-OMNR MOU (19 Dec 2011). The overall objective of the study is to determine differences in the hydrologic and hydraulic properties of the Rainy River flow regime between the 1970-2000 Rule Curve flow regime, the post-2000 Rule Curve flow regime, and the natural (pre-dam) flow regime (i.e. 'State of Nature'). Of particular interest are changes to the water level regime and habitat availability associated with the Rule Curve revision relative to the other two reference hydroperiods.

The dam at International Falls/Fort Frances Dam (IFD) has been in operation since 1909 (Figure 1.1). Two hydroelectric facilities operate at the IFD. The maximum turbine capacity at IFD is 354 m^3/s (113.3 m^3/s Canadian, 240.7 m^3/s U.S.). A rule curve issued by the International Joint Commission is used to guide operation of the dam and hydroelectric facilities to maintain the upstream reservoir elevation between a minimum and maximum elevation depending on the date (Figure 1.2). Currently, the instantaneous outflow rate from IFD must be reduced to 100 m^3/s if Rainy Lake water levels are lower than the minimum elevation of the curve. The instantaneous outflow rate must be further reduced to 65.1 m^3/s if Rainy Lake water levels fall below the drought line (IJC, 2001; O'Shea, 2006).

Differences between the Rainy Lake rule curves implemented in 1970 and 2000 are illustrated in Figure 1.2 for two years with discharge extremes. Dam operators are directed to keep the water levels of the lake between the upper and lower bounds of the rule curves. Although the two rule curves are very similar, in the post-2000 rule curve permits higher water levels in April and May and lower water levels from August to November. Thus, flow alteration metrics specific to these two periods may be significantly different between the pre- and post-2000 reference periods, if the appropriate weather conditions permitted operation within the rule curve envelopes.

In addition to the rule curve changes there have been changes in the frequency and pattern of hydro-peaking. However, the temporal resolution of daily average flow is not sufficient to fully characterize the hydroelectric peaking pattern in the time series. For example, O'Shea (2006) reports that during a 15-week hydro-peaking period in 2001 when weekend ponding was occurring, the fluctuation about the daily mean at the Manitou Gauge, located 55 km downstream of IFD, during the weekdays averaged 29 m^3/s with a 147 m^3/s fluctuation over the weekend. However, the daily flow series only captures weekend ponding activity where outflow rates are decreased to store water for the power generation during peak times during the next week. Hydro-peaking activities at IFD, as inferred from hourly data records, are summarized by O'Shea (2006):

- Only a few periods of peaking occurred during the 1970's and 1980's and the early 1990's;
- The frequency of peaking increased after 1993; however,
- The U.S. side of the IFD stopped peaking in 2001; and
- The Canadian side still peaked but stopped weekend ponding.

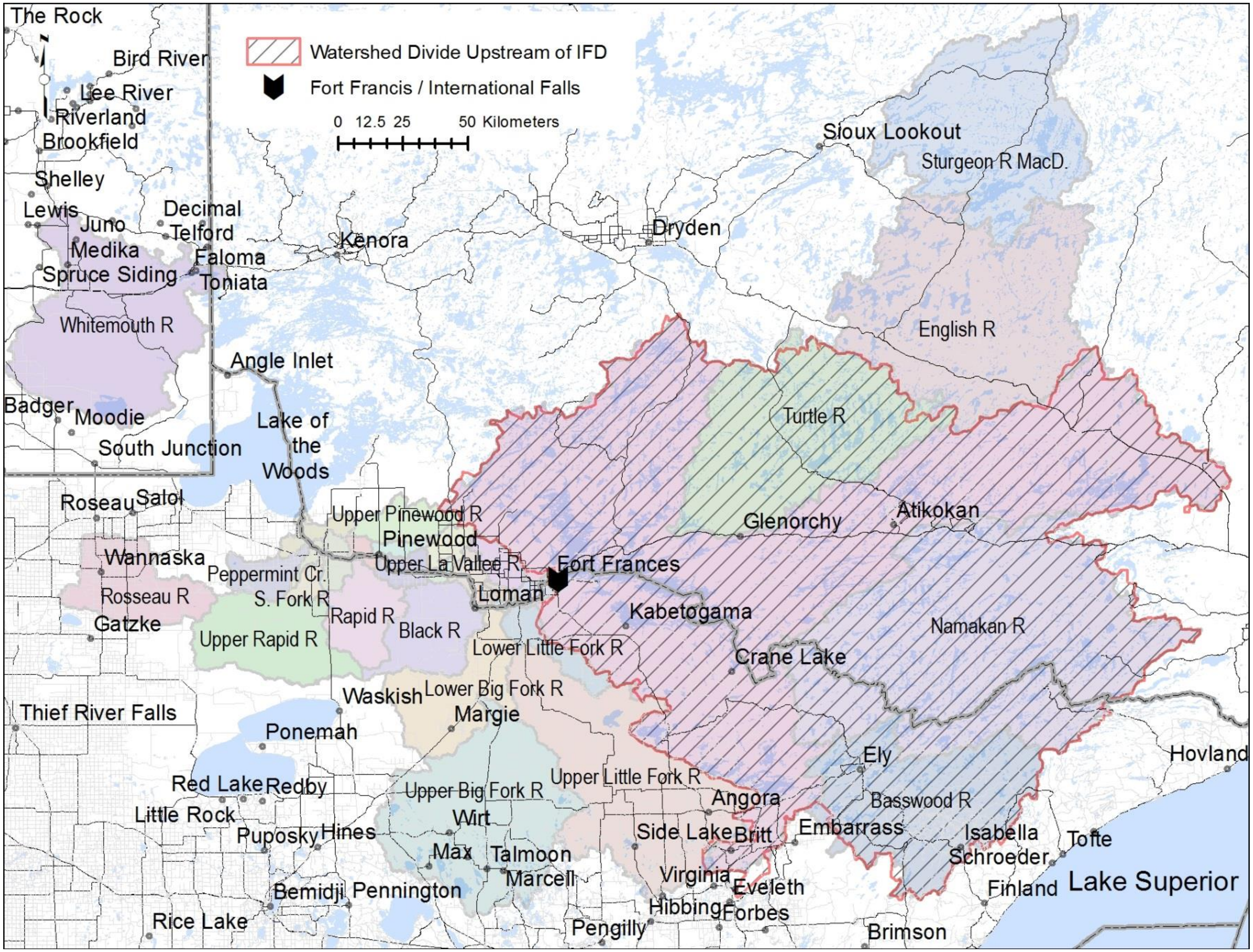


Figure 1.1 Study area showing the location of the International Falls/Fort Frances dam (IFD) and upstream watershed.

The hourly discharge data for the period since the O'Shea report has not been analyzed for the occurrence of hydroelectric peaking and ponding activity.

The water levels in Rainy Lake and Rainy River may also be influenced by flow regulation in Namakan Reservoir. The rule curves for the Namakan Reservoir are showin in (Figure 1.3). Under the 1970 rule curve, Namakan Reservoir had a maximum winter draw down of 2.04 m and water levels peaked by the end of June. Under the 2000 rule curve ruling, the winter drawdown was reduced to 1.05 metres, with peak water levels reached by the end of May. These prescribed changes in the usage of active storage of Namakan Reservoir have the potential to alter the rate at which flow events translate through the Rainy River system.

The water levels in Rainy River upstream of LOW are also governed by LOW water levels. The presence of LOW can cause water levels to backwater for 10's km upstream, relative to there being no impoundment there. If flow is obstructed by an object (e.g. Dam) or flow constriction (e.g. Narrow bedrock water fall) then the water surface increases behind the obstruction to build up enough potential energy to flow over/through the object/constriction. Consequently, the water surface profile ceases being parallel to the bed causing the water surface slope to decrease on the upstream side of the object. This type of water surface profile is called a backwater curve. The river is not ponded in the backwater zone, but the flow depths are elevated, relative to there being no flow obstruction downstream. Thus, it is not readily apparent in the field from the look of the river if one is in the backwater zone because the zone extends upstream of any slack water behind the obstruction. Regardless, the hydraulic properties of the river are altered in the backwater zone, being most pronounced closest to the obstruction. The lower Rainy River appears inundated at low flow which may be due in part to turn of the century dam construction on the LOW system, resulting in an average increase in LOW water levels of three feet. A first order approximation of the upstream extent of backwatering on the Rainy River based on river slope and bankfull depth is 75+ km (Section 5.3.4). Thus, the Rainy River flow regime is potentially influenced by not just climate related changes in runoff, or flow regulation from IFD, but the upstream influence of flow regulation in LOW. In this report we provide more insight into the relative importance of these factors in governing the behavior of the Rainy River hydrosystem to help provide guidance for the river's management.

We investigated the following questions:

1) Are there significant differences in the flow regime of Rainy River between the pre- and post-2000 periods?

2) Are any observed differences in the flow regime greater than natural variability of streamflow observed over the same period.

3) What is the degree of hydrologic alteration between the pre- and post- 2000 periods and the natural reference condition at Rainy River.

4) Are there significant differences in water level regimes and by extension, wetted perimeter duration, for discrete river segments in the Rainy River between the pre- and post- 2000 periods?

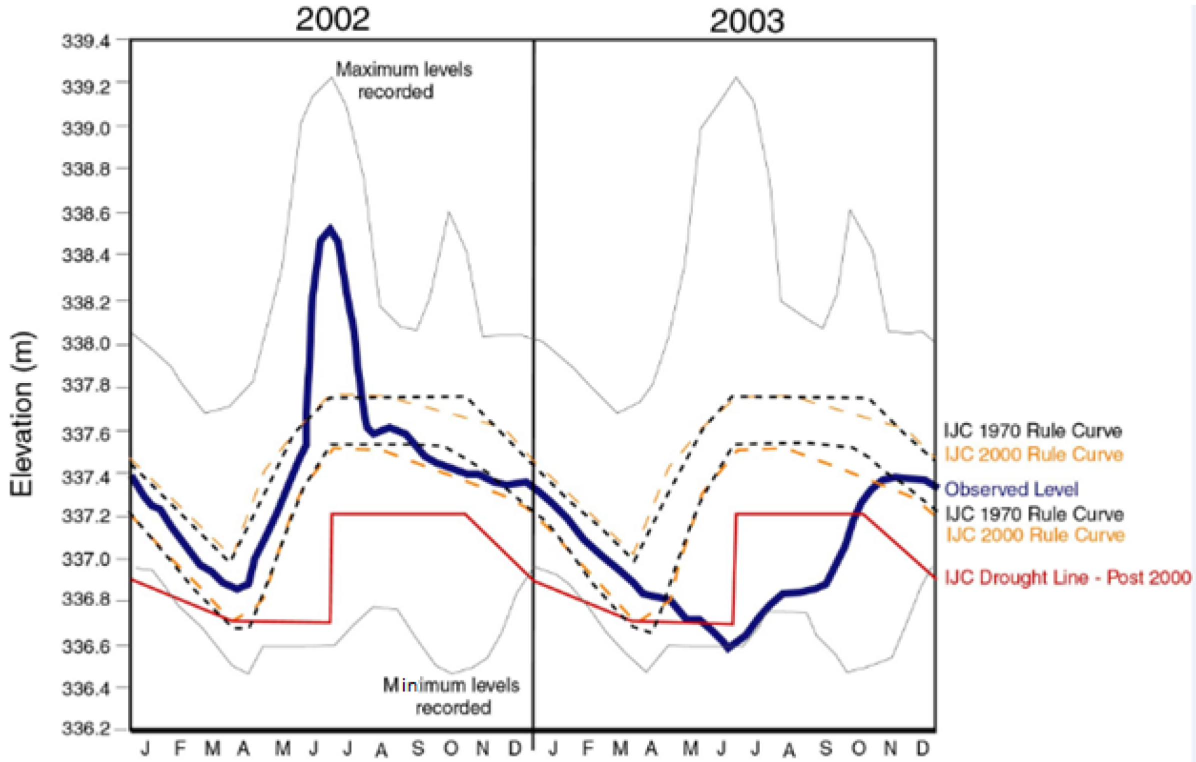


Figure 1.2 Rainy Lake Rule Curves implemented in 1970 and 2000 and two years of discharge extremes.

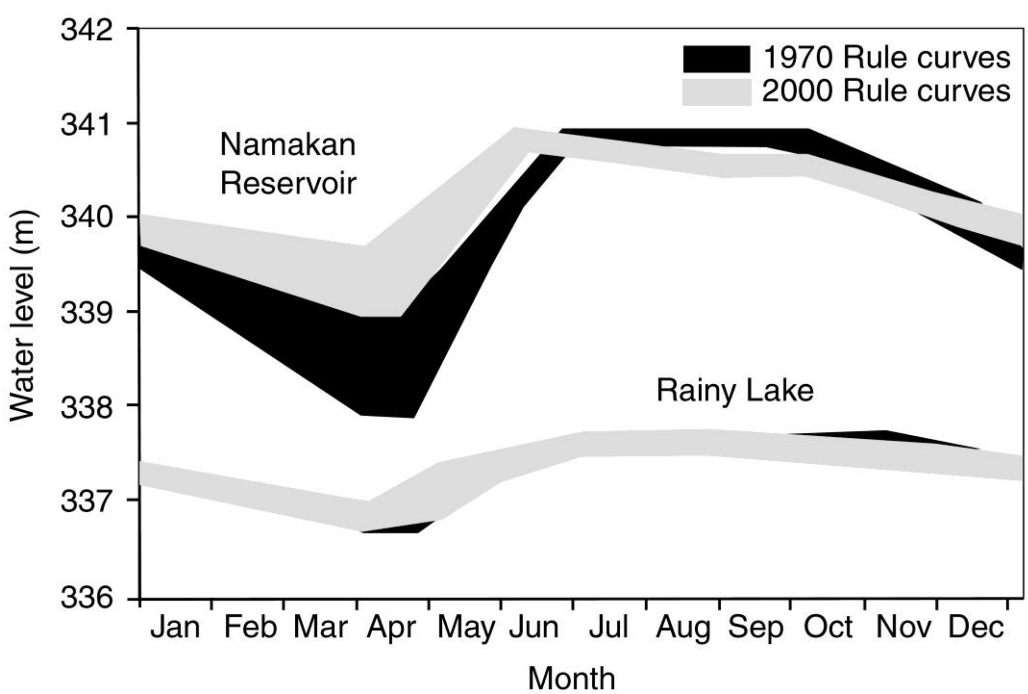


Figure 1.3 Differences between 1970 and 2000 rule curves for Rainy Lake and Namakan Reservoir. Modified from McEwen, and Butler (2010).

5) Are there differences in wetted perimeter duration, for 11 river response segments in the Rainy River between the observed and the State of Nature flow regime for the pre- and post- 2000 periods?

Further detail about the study area and Rainy River watershed follow.

1.2 Overview

The inundation frequency and duration of a riverbed reflects a rivers' flow regime. In this report we assess alteration in the flow regime of Rainy River between pre- and post-rule curve periods to provide an indication of whether changes in inundation characteristics would be expected. Central to the assessment of streamflow alteration is the concept of using controls or controlled conditions as a reference against which the alteration is assessed. The natural flow regime is often used to satisfy this reference. This could include its use in a Reference Condition Approach (RCA) or in a Before-After-Control-Impact (BACI) experimental design (Downes et al 2002). The former is used to determine the deviation of a hydrologic indicator variable from its expected natural range. The natural range is determined from the probability distribution for a hydrologic indicator variable derived from historical natural streamflow time series either available for the site, simulated for the site, or from nearby basins that are hydrologically similar to the impact basin. The simulated time series can be estimated using proration (Jenkinson, 2009), spatial interpolation (Hughes and Smakhtin, 1996; Smakhtin *et al.*, 1997; Smakhtin, 1999), or modeling (Samuel et al., 2010; Samuel et al., 2011a; Samuel et al., 2011b). The probability distribution can be drawn from a single streamflow time series or from streamflow time series from multiple reference basins.

In the BACI experimental design, the *control* is used to detect changes related to specific stimuli at an *impact* site, such as changes to a dam's operating regime. The streamflow time series observed at the *impact* site *before* and *after* the operating change is expected to be influenced by the alteration to the system while the *control* is not affected by the change. The relative states of a hydrologic indicator variable for the paired sites between the two periods is compared to determine whether the change is significant or not (i.e. greater than the natural variability observed over the same period). Thus, while the BACI experimental design allows us to test whether the change in a hydrologic indicator variable can be attributed to a management action, the RCA approach is used to determine if a hydrologic indicator variable is within it's expected natural range or the magnitude of deviation from this natural reference condition. Both approaches have been used in this study to elucidate changes to the Rainy River flow and water level regimes. Natural flowing rivers in the study area (i.e. reference basins) were used as controls to discern whether any observed changes in the Rainy River flow regime were the result of the rule curve change or other factors as well as to simulate a natural flow regime at IFD to establish a natural reference condition. In this report we scale local, unregulated river hydrographs to IFD to examine departure of the annual flow duration curve of the observed case, from the State of Nature case (Section 3.2.2). These State of Nature flows represent a 'State of Nature' (SON) flow regime. We also evaluate more detailed methods to synthesize a State of Nature daily flow series and investigate the degree of hydrologic alteration between the reference condition, 1970-2000 flow regime, and the 2000-present flow regime. Using the refined State of Nature series, we calculated metrics that reflect flow regime characteristics, and assessed changes in these metrics both throughout the reference period (1970-2000), and in the pre- and post-2000 periods. We also use State of Nature series to simulate a pre-regulation flow regime between

IFD and LOW on the Rainy River. This State of Nature hydraulic model run was used as a benchmark to contextualize changes in wetted perimeter in eleven response reaches for the pre- and post- rule curve periods (Section 5.3).

In Section 5.0 we assess alterations in water level and wetted perimeter regime in Rainy River below IFD. Changes in water levels were investigated using an existing hydraulic model (HEC-RAS) that was further refined by updating hydrology data to include the 2006-2010 period and improving the estimates of tributary and lateral inflows. The HEC-RAS model was validated at two locations with the revised flow file. The validated model output was used to show differences in the duration of a) water levels, b) wetted perimeter and c) inter-daily water level range between the pre-to post-2000 period for selected cross sections. A statistical analysis was conducted to investigate if there were significant differences if water level regime between the pre- and post- rule curve periods and the potential causes of these changes (e.g. climate, flow management).

The primary objectives of the hydraulic modeling were to:

1) Update the hydrology data in the HEC-RAS model to include the 2006-2010 period and to simulate data using multiple reference stations and spatial interpolation;

2) Validate the HEC-RAS model with the revised flow file;

3) Use the validated model output, to graphically show differences in the duration of a) water levels and b) inter-daily water level range between the pre-to post-2000 period for selected cross sections; and

4) Use the validated model output, to conduct a statistical analysis to investigate the following questions.

    - Are there significant differences between duration curves (water level, daily wetted perimeter, and water level difference) between the pre- and post- rule curve periods?

    - Are these between period differences in river regime still significant if we account for variations in a) monthly climate (precipitation, snowfall, snow depth, and temperature), b) water level durations in Rainy Lake and Namakan Reservoir, and c) differences in the upper and lower bounds of the rule curves between the periods?

    - Are there differences between wetted perimeter duration curves between the observed flows and simulated State of Nature flows for each rule curve period?

Objectives 1 and 2 are addressed in Section 2.0. Objectives 3 and 4 are documented in Sections 4.0 and 5.0

SECTION 2. MODELLING RAINY RIVER HYDROLOGIC AND HYDRAULIC REGIMES

This Section describes the methods used to update the hydraulic model of the Rainy River. The process of updating the hydraulic model, and analysis of management related changes to Rainy River hydrology, required flows to be simulated for both ungauged, confluent tributaries along the river, and for the State of Nature case at IFD and LOW. In this report we refer to 'Observed' flows in contrast to simulated State of Nature flows. Observed flows refer to archival discharge data from hydrometric stations. The Observed flow series used in subsequent analyses are summarized in Tables 2.5 and 2.12.

2.1 Hydraulic Modelling

Fluctuations in the Rainy River flow regime below IFD over the period of interest were examined using an unsteady flow hydraulic model (HEC-RAS). Modifications and additions made to the original HEC-RAS model included:

1) Updating the hydrology data in the HEC-RAS model to include the 2006-2010 period.
2) Simulation of discharge series at ungauged sites.
3) Simulation of discharge series for the State of Nature condition at IFD and LOW.
4) Validation of the HEC-RAS model for existing, observed conditions with the revised flow file.
5) Simulation of changes in hydraulic regime for the State of Nature condition.
6) Using the hydraulic model output to graphically show differences in the duration of a) water levels, b) inter-daily water level range and c) wetted perimeter between the pre-to post-2000 period, and between the altered state and State of Nature.

The hydrologic data, simulated hydrographs and validated HEC-RAS model output were used to investigate the following questions:

- Are there significant differences between duration curves (water level and daily water level difference) between the pre- and post- rule curve periods (Section 3.)?
- Are these between period differences in river regime still significant if we account for variations in a) monthly climate (precipitation, snowfall, snow depth, and temperature), b) water level durations in Rainy Lake and Namakan Reservoir, and c) differences in the upper and lower bounds of the rule curves between the periods (Section 4.)?
- How has the flow regime changed along the Rainy River between IFD and LOW (Section 5.)?

The following is a brief overview of the steps taken to validate the HEC-RAS model:

1) An original unsteady HEC-RAS model (2011) for Rainy River was obtained and used as the basis for the modelling.
2) The HEC-RAS model was rediscretize and subwatershed areas and watershed characteristics extracted using a GIS.
3) Flows were simulated at the nineteen ungauged subwatersheds (tributaries and interconfluent subwatersheds) for the period 1970-2010 for the 'Observed' and 'State of Nature' HEC-RAS models. Daily time series were converted to hourly time series for input into HEC-DSS using a program developed for this case study (*HourlyInterpolation*).
4) LOW water level data was updated for model validation (2006-2010) of the 'Observed' HEC-RAS model.
5) State of Nature boundary conditions were simulated (i.e. hydrograph at IFD and water level hydrograph at LOW).
6) The updated, unsteady HEC-RAS 'Observed' model was validated using observed data from gauging stations between IFD and LOW.
7) The updated, unsteady HEC-RAS model was run for the State of Nature scenario.
8) Water level regime statistics for the pre- and post-2000 rule curve periods were extracted and sytnthesised from the validated model.

2.2 HEC-RAS Model setup and validation

The existing HEC-RAS model (final.prj, 1988-2006 – Seasonal roughness 1.14) was run for the period of record considered in the seasonal roughness study (1988-2006). The unsteady flow data used in the original model (final.u03) are in the HEC-DSS database management system format and include:

1) An input flow hydrograph at Fort Frances;

2) Nine lateral inflow hydrographs at the ungauged confluent tributaries;

3) Three uniform lateral inflow hydrographs for the inter-confluent area adjacent to the river; and

4) Water levels at Lake of the Woods.

A primary objective was to update the hydrology data to include the 2006-2010 period and to simulate flows using multiple reference stations and spatial interpolation. We revised the model by generating a new unsteady flow file (Section 2.4.2). The lateral inflow hydrographs are hourly discharge series that have a discrete input location within the model. The lateral inflow hydrographs distribute an hourly hydrograph equally along a segment of river of specified length. The intended use of the HEC-RAS model is to investigate changes in hydraulic habitat along the length of the Rainy River. Consequently, it is important for the model to reflect changes in downstream lateral inputs.

Over the 133 km stretch of the Rainy River, the drainage basin area increases from 38,600 km^2 at Fort Frances to 54,500 km^2 at Lake of the Woods. Figure 2.1 shows the increase in drainage basin area with distance downstream of Fort Frances and the position of major confluent tributaries. The most significant increases in drainage basin area occur where the Rainy River receives discharge from the Big- and Little-Fork Rivers, and the Rapid River. Simulated flow series are required at the nine tributaries located downstream of Fort Frances (Table 2.1). Six of the nine tributaries have some archival discharge data and gaps in these discharge records have been identified in Table 2.1. Methods used to address data gaps are also provided in Table 2.1 (e.g. patch, extended, scale to confluence).

The three inter-confluent areas considered in the original HEC-RAS model (Upper, Middle and Lower River) were further divided into nine inter-confluent areas to better reflect the water level response segments, and variability in physiography and network structure along the river (Figures 2.2 & 2.3). More specifically, we broke the study reach down into 11 different response segments based on the long profiles output from the existing model (Figure 2.2), observed water level fluctuations in hourly data at four locations (Figures 5.1-2), and differences in river morphology and confluent tributary locations (Section 2.3.4). Each response segment appears to have a slightly different water level fluctuation regime.

Figure 2.3 show the new subwatershed discretization of the Rainy River reach between International Falls and Lake of the Woods. Table 2.2 shows the HEC-RAS cross sections river station reference (i.e. chainage in feet) for gauge locations and reach centers.

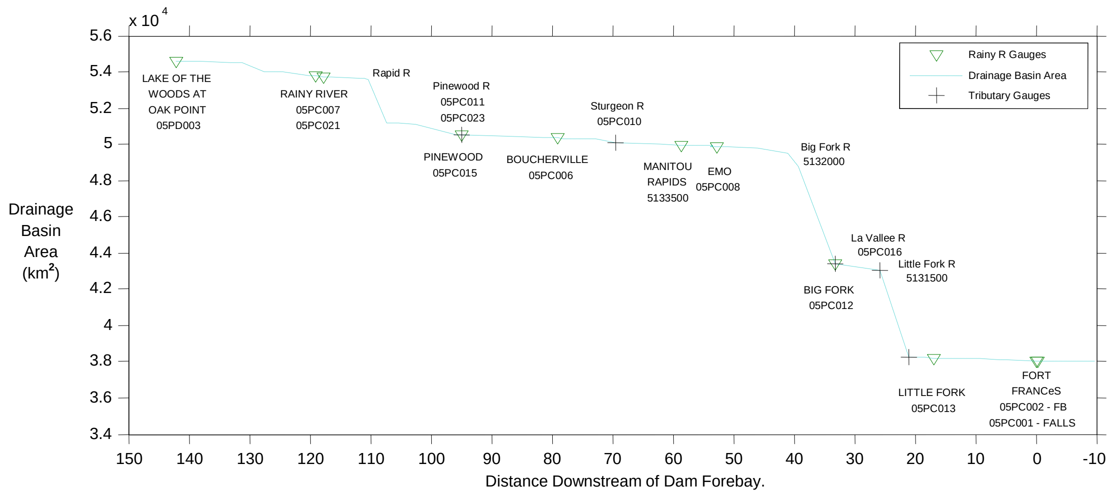


Figure 2.1 Increase in drainage basin area between Fort Frances and Lake of the Woods.

Table 2.1 Flow simulation nodes downstream of Fort Frances, International Falls.

	Rainy River Tributary	Upstream Gauge Station	Gauge Number	Data Gaps between 1970-2010	Action Required	Comment
1	Little Fork River Confluence	Little Fork River at Little Fork, MN	05131500	No	Scale	*Fine Grained Glaciolacustrine*
2	Big Fork River Confluence	Big Fork River at Big Falls, MN	05132000	70-82,91-97	Patch and scale	*Holocene Peat, Lake Modified Till, Ground Moraine*
3	Black River Confluence	Na	Na	Na	Simulate using Reference	*Holocene Peat, Lake Modified Till*
4	Sturgeon River Confluence	Sturgeon River near Barwick	05PC010	70-86 ice;86-10 missing	Patch, Extend, Scale	*Fine Grained Glaciolacustrine*
5	Pinewood River Confluence	Pinewood River near Pinewood, at Hwy No. 617	05PC011/05PC023	70-98 patchy due to ice; 98-07 missing	Patch and Scale	*Fine Grained Glaciolacustrine, Organic Deposits*
6	Rapid River Confluence	Rapid River near Baudette, ON	05134200	85-07 missing	Patch and Scale	*Lake Modified Till, Holocene Peat,*
7	South Fork Baudette	Na	Na	Na	Simulate using Reference	*Lake Modified Till, Glaciolacustrine,, Holocene Peat,*
8	La Vallee R.	La Vallee River near Devlin	05PC016	86-10 missing; 70-86 record has ice condition data gaps	Patch and Scale	*Fine Grained Glaciolacustrine*
9	Winter Rd/Peppermint Cr	Na	Na	Na	Simulate using Reference	*Lake Modified Till, Glaciolacustrine,, Holocene Peat,*

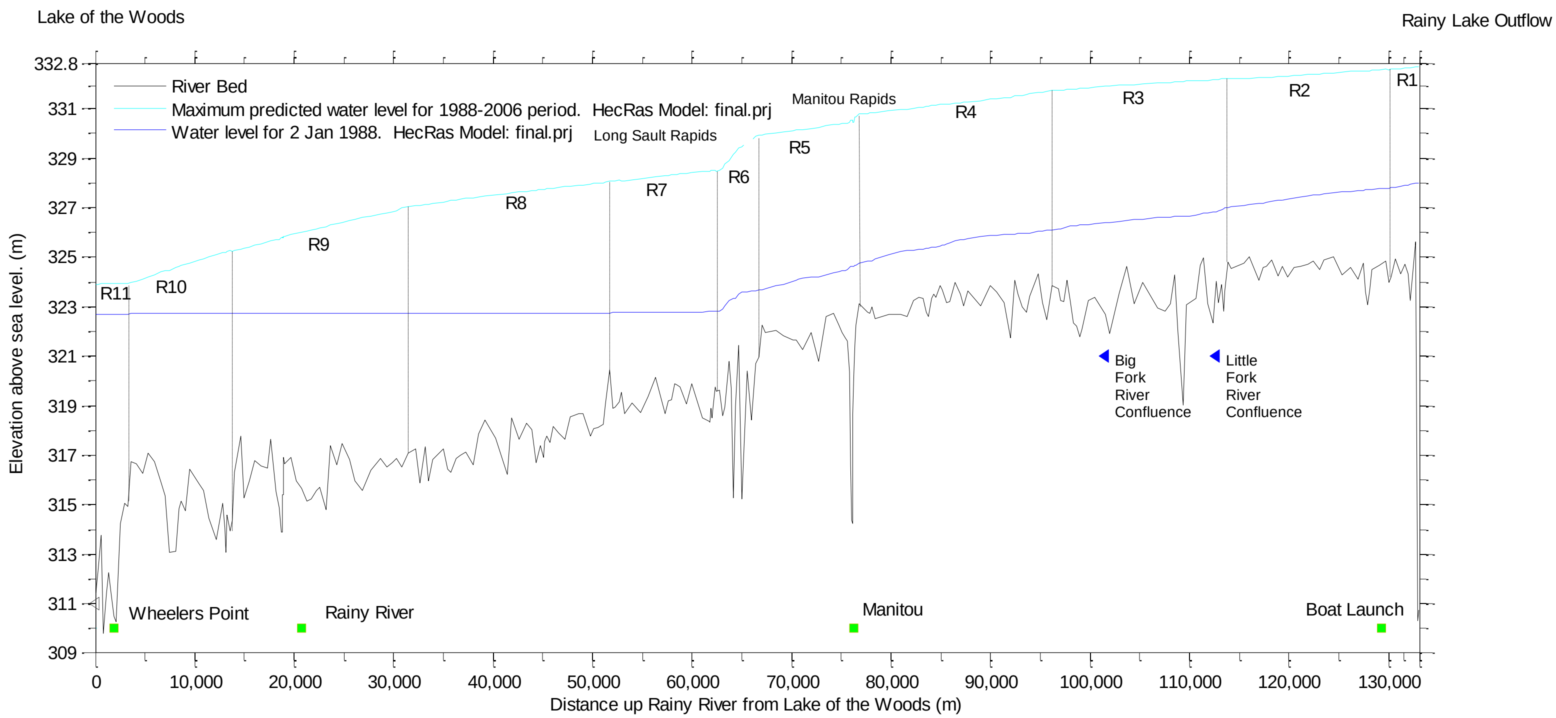


Figure 2.2 Long profile of the Rainy River from the dam at Fort Frances/International Falls to Lake of the Woods. The water surface slope for a high and low flow are shown as modeled by the 2011 Unsteady HEC-RAS model. Note the location of the gauge stations at the base of the plot. We have divided the river into eleven reaches based on breaks in water surface slope and bed morphology.

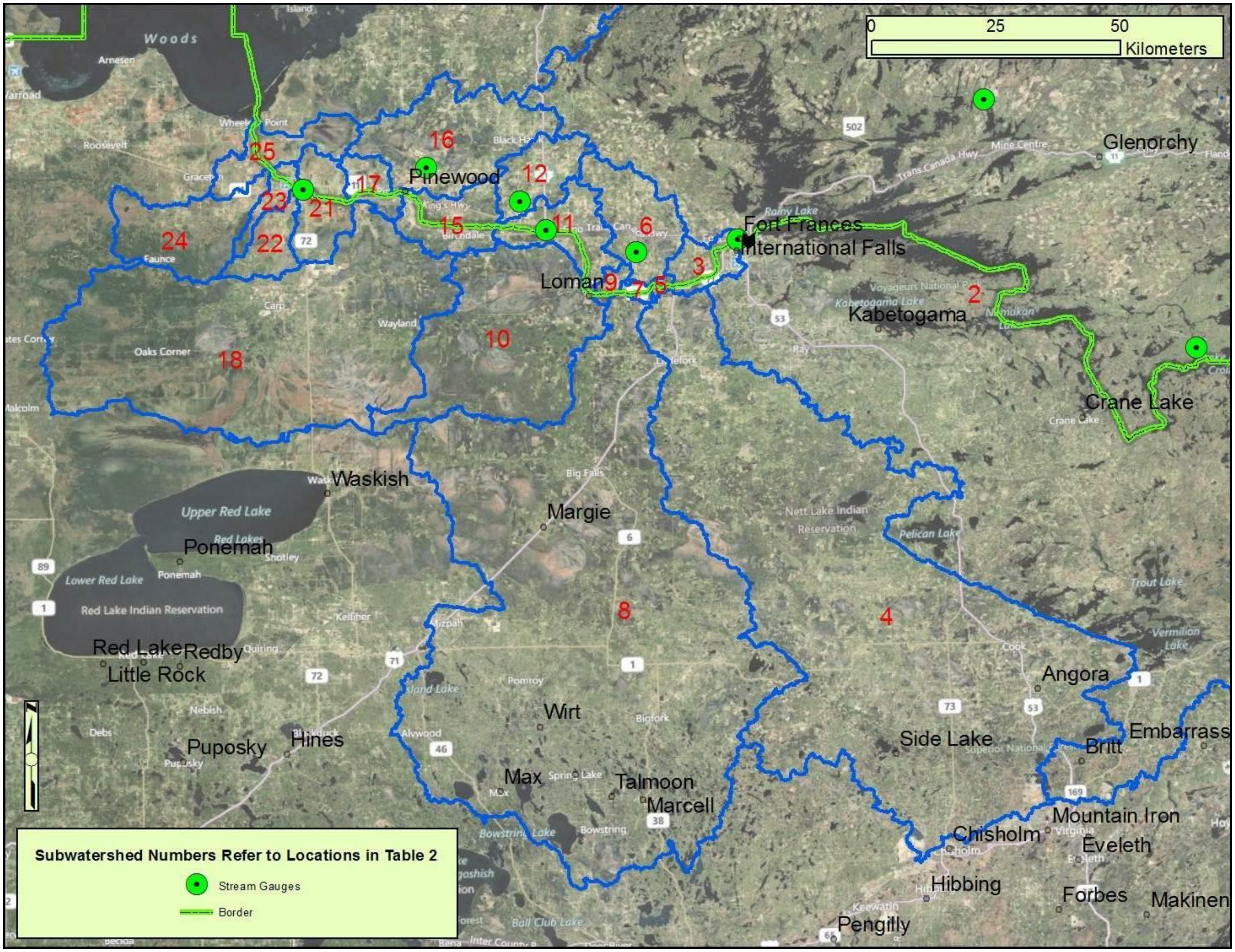


Figure 2.3 New subwatershed discretization of the Rainy River hydraulic model.

Table 2.2 HEC-RAS cross sections for gauge locations and reach.

Location	Distance upstream from Lake of the Woods (ft.)
Fort Frances Tailrace	436630.50
Reach 1	432814.20
Reach 2	401820.40
Reach 3	345234.60
Reach 4	283570.00
Reach 5	236099.60
Manitou Rapids	214813.30
Reach 6	213183.60
Reach 7	189120.00
Reach 8	136053.00
Reach 9	74068.12
Rainy River	68108.36
Reach 10	27652.46
Reach 11	5149.69
Lake of the Woods	18.94

2.3 Simulating Flow Series Hydrographs

Several methods were considered to simulate natural flow regimes for ungauged basins downstream of IFD for input into HEC-RAS, and to provide the reference control and reference condition time series at IFD:

1. Spatial Interpolation (Hughes and Smakhtin, 1996; Smakhtin *et al.*, 1997; Smakhtin, 1999) using the five source sites identified in Section 2. (i.e. Namakan R, English R, Turtle R, Basswood R. Sturgeon R);
2. Proration using the five source sites identified in Section 2.;
3. MAC-HBV hydrologic model (Samuel et al., 2010; Samuel et al., 2011a; Samuel et al., 2011b); and
4. A mass balance reverse reservoir routing model to simulate State of Nature at IFD.

2.3.1 Methods of simulating hydrographs at ungauged sites

2.3.1.1 Spatial Interpolation – FDC Transposition

The flow duration curve (FDC) transposition method uses available observed streamflow data from one or more proximal and hydrologically similar gauging sites (i.e. 'source sites') to transpose a hydrograph series to an ungauged site ('destination site). FDCs show the proportion of time a flow value is equalled or exceeded and, by incorporating the complete range of river flows, provides the most informative summary of a flow regime (Searcy, 1959; Vogel and Fennessey, 1995). Shu and Ouarda (2012) found that the FDC transposition methods outperformed the area ratio method, in terms of Nash, root mean squared error and Bias, for their 109 Quebec study river stations. The methodology employed in this study follows that of Hughes and Smakhtin (1996), Smakhtin et al. (1997), Smakhtin (1999), and Smakthin and Masse (2000) with the following exceptions:

1) Discharge was standardized using drainage basin area rather than an index flood (mean annual flow). This was done to avoid introducing errors when estimating the mean annual flow at the destination site.
2) The weighting scheme for combining estimates from multiple source sites was based on the degree of correlation between the shapes of the destination and source FDCs.
3) Instead of 17 percentage point locations on the FDCs we used 105 to more fully specify the curve's shape.
4) FDC shape of the destination site can be specified using a gauge within the destination watershed, with FDCs calculated from a non-concurrent time period. Castellarian et al (2004) demonstrate how FDC specification using a short period of record (e.g. 5 years) can provide a better estimate of the destination FDC shape, relative to statistical approaches of regionalization.

In a separate analysis, we estimated the FDC shape at the destination site using multivariate models of watershed characteristics related to hydrologic response. However, the results were not reliable for summer months when active storage within the basins is at a maximum. Consequently, we employed the original method of destination site FDC specification, by selecting a hydrologically similar reference basin and scaling the monthly FDCs to the destination site.

The FDC transposition algorithm follows these steps:

1) Calculate the monthly flow duration curves for each month of the period of record for the source site(s) using standardized discharge.
2) Select a reference site to represent the destination site FDCs. The hydrologic response of the reference site should be similar to that of the destination site, as assessed in Section 2.3.4. This is done to ensure that the shape of the destination site FDC assumed by using the reference site, is as close to the actual shape of an FDC for that destination site (i.e. if discharge data were available at the ungauged destination site to validate the assumption).
3) Calculate the monthly flow duration curves for each month of the period of record for the destination site using standardized discharge.
4) For the first day of the period of interest, locate the FDC of the first source site for the appropriate month and read off the corresponding percentage exceedance point value. Locate the destination FDC for the same month and the same percentage exceedance point value as observed on the source FDC. Read off the standardized discharge value for that exceedance point and record it for that day. Repeat this procedure for all days in the period of record.
5) Repeat the transposition process for the other source sites.
6) Combine all source site estimates into one time series using a weighting scheme. More specifically, regress the standardized flow duration curve of the destination site against the standardized flow duration curve for the source site. Record the correlation coefficient. Repeat these steps for the other source sites. Calculate the weighting multiplier by dividing the source site correlation coefficient by the sum of the source site coefficients. Multiply this value by the source site's estimated time series. Repeat for each source site. Add the resulting vectors to get a weighted estimate of daily standardized discharge for the period of record.
7) Multiply the standardized time series by the drainage basin area of the destination site to convert the time series into a hydrograph of daily discharge in units of m^3/s.

This algorithm was implemented in a MATLAB script called *SpatPro.m*. We experimented with different weighting schemes including the slope and intercept of the FDC curves but the correlation coefficient yielded the most accurate results. The graphical FDC transposition method is illustrated in Figure 2.5 for a case where the hydrographs and curves are expressed in m^3/s (i.e. the discharge standardization is implicit).

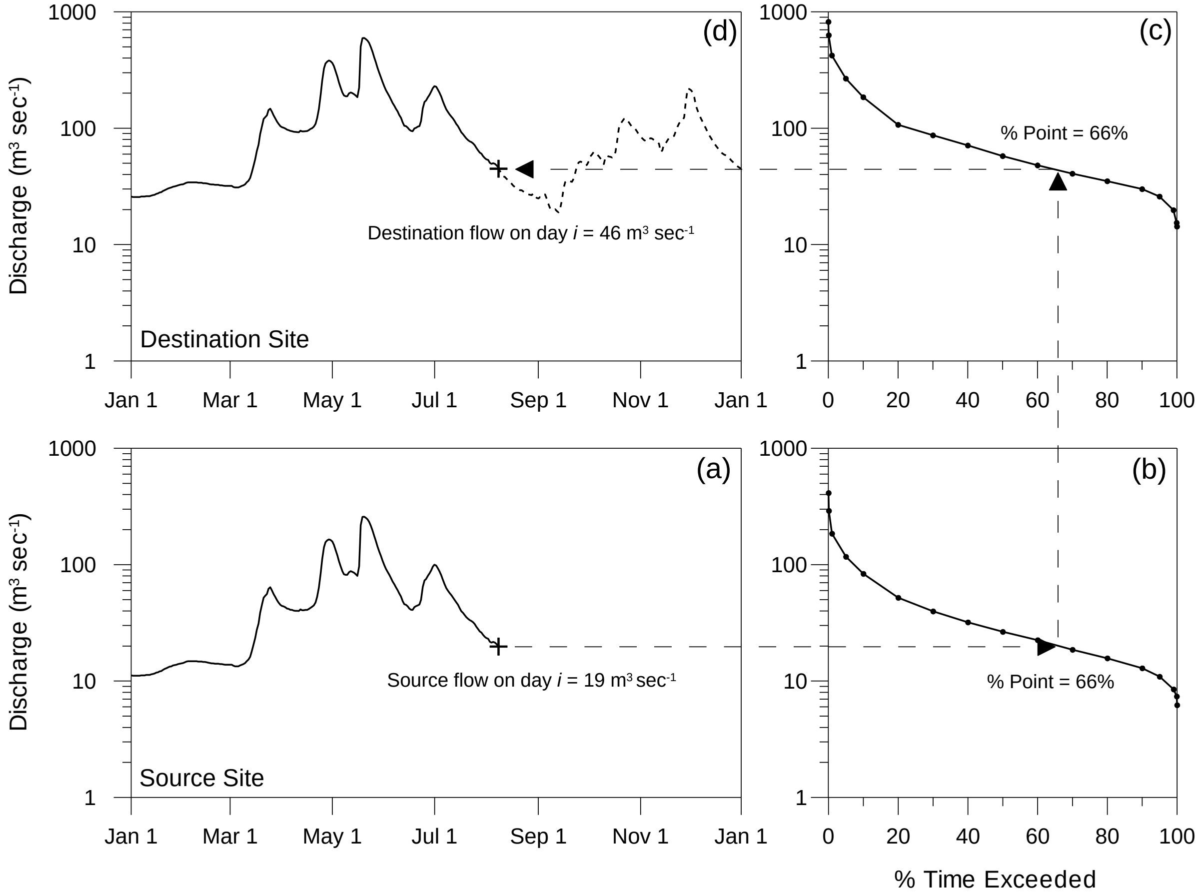


Figure 2.5 Streamflow generation procedure using (a) an observed hydrograph and (b) position of a daily mean flow on its FDC to (c) find the discharge value associated with the same percentage point on the destination site FDC to (d) create the simulated hydrograph for the destination site (Source: Metcalfe et. al., 2005a).

2.3.1.2 Proration – Area Ratio Method

Proration using the area ratio method is based on a general assumption frequently made in hydrology that stream discharge and drainage area scale linearly or in a near linear fashion (Dunne and Leopold, 1978; Galster et al., 2006; Galster, 2007). The drainage area ratio method is given by Equation (2.1):

$$Q_u = Q_g \left(\frac{A_u}{A_g}\right)^m \tag{2.1}$$

where, Q refers to flow rates, A is the drainage basin area and the subscripts u and g stand for gauged and ungauged sites (Jenkinson, 2009). The exponent *m* is a calibration factor to account for non-linearities. Typically *m* is assumed to have a value of one due to a lack of validation data. A MATLAB script was written to implement spatial interpolation (*SpatPro.m*).

This method is best applied at sites with drainage areas > 100 km^2 and where there is not a significant difference (orders of magnitude) between drainage basin areas of the two sites. Uncertainty in prorated streamflow estimates increases with increasing differences in basin characteristics between the gauged and ungauged sites. In addition to drainage area, many basin characteristics affect a rivers flow regime including basin physiography, stream order, channel morphometics, geology, landcover and land use, in addition to the proximity to the ungauged basin (Maidment, 1993). The suitability of transferring streamflow data across drainage basins increases where common characteristics can be identified (Moin and Shaw, 1986a, 1986b; Acres International Inc., 1994; OMOE, 1995; OMNR, 2000; OMOE, 2008).

In this study information had to be transferred from small gauged sites to destination locations along the Rainy River with much larger drainage basin areas. Consequently, we tested to see if adjustments had to be made during proration for the difference in drainage basin scale (i.e. Is the scaling parameter unity in this case?) and storage characteristics (i.e. percent lake area). The scaling parameter of Equation (2.1) was calculated for twenty four gauges proximal to the study area using the Namakan River as the source gauge (Table 2.3). Gauges were included to have drainage basin areas larger than the Rainy River at IFD to assess if the smaller Namakan River data can be scaled to the larger IFD location.

The scaling parameter in the drainage area ratio method was within 5% of unity for Canadian Shield drainage basins between 458 km^2 and 50000 km^2. Drainage basins that drained outwash plain areas had scaling coefficients that ranged from 0.72-0.79. The Manitou Rapids drainage area contains both Shield and Outwash areas and has an intermediate scaling parameter of 0.83. There was no significant effect of drainage basin area (R^2=0.03, p=0.57, n=24) and percent lake area (R^2=0.07, p=12, n=24) on the scaling parameter. These finding support the assertion that the hydrologic response varies between outwash catchments and shield basins. The findings also support using a scaling parameter near unity for transferring discharge data from smaller Canadian Shield reference basins to the Rainy River at IFD for a State of Nature simulation.

2.3.1.3 Rainfall-Runoff Model - MAC-HBV

The Hydrologiska Byråns Vattenbalansavdelning (HBV) model, originally developed by SMHI (Swedish Meteorological and Hydrological Institute) in the early 70´s to assist hydropower operations (Bergström, 1976, 1992), is a conceptual rainfall-runoff model that quantifies hydrological processes at the catchment scale. The aim was to create a hydrological model with reasonable demands on computer facilities and calibration data. As such, data input requirements are limited to mean daily temperature and total precipitation and values for a limited number of model parameters. Although originally designed for hydrological forecasting in calibrated basins, applications have expanded to include filling gaps in time series, simulation of streamflow at ungauged sites, design flood calculations and water quality modelling. A version of HBV optimised for conditions in Canada has been developed by the National Research Council's Canadian Hydraulics Centre (https://www.nrc-cnrc.gc.ca/eng/ibp/chc/software/kenue/green-kenue.html) and another version optimised for conditions in Ontario (MAC- HBV), particularly low flows, has been developed by McMaster University (Samuel et al., 2010; Samuel et al., 2011a; Samuel et al., 2011b)(http://people.trentu.ca/rmetcalfe/MACHBV.html). Other information can be obtained from SMHI (http://www.smhi.se/forskning/forskningsomraden/hydrologi/hbv-1.1566).

Table 2.3 List of gauges to investigate how the scaling exponent varies with drainage basin scale and lake area. The scaling parameter of Equation (2.1) was calculated for all twenty four gauges proximal to the study area using the Namakan River as the source gauge (i.e. m = 1). Gauges were included to have drainage basin areas larger than the Rainy River at IFD.

Gauge	Gauge No.	Area (km^2)	Lake %	*m*
Sturgeon River at McDougall Mills	05QA004	4442	21.1	0.97
Whitemouth River near Whitemouth	05PH003	4034	2.6	0.72
English River at Umfreville Outflow	05QA002	6131	21.2	0.96
Turtle River near Mine Centre	05PB014	4752	18.5	0.98
Pinewood River near Pinewood	05PC011	458	0.1	0.95
Sturgeon River Near Barwick	05PC010	168	0.0	0.79
La Vallee River near Devlin	05PC016	246	0.1	0.94
Roseau River below South Fork near Malung	5104500	1302	0.0	0.74
Rapid River near Baudette	5134200	1647	0.0	0.97
Basswood River near Winton	05PA012	3710	7.8	0.95
Little Fork River at Littlefork	5131500	4357	2.3	0.98
Big Fork River at Big Falls	5132000	3921	5.2	0.95
Namakan R at outlet of Lac la Croix	5PA006	13234	24.7	1.00
Rainy River at International Falls	05PC019	38252	27.8	0.98
Missinaibi River Below Waboose River	04LM001	22990	3.1	0.98
Ekwan River Below North Washagami River	04EA001	10400	9.6	0.97
Otoskwin River Below Badesdawa Lake	04FA001	9010	12.1	0.98
Attawapiskat River Below Muketei River	04FC001	36000	9.1	0.97
Attawapiskat River Below Attawapiskat Lake	04FB001	24200	15.5	0.96
Ogoki River Above Whiteclay Lake	04GB004	11200	18.7	0.98
Winisk River Below Asheweig River Tributary	04DC001	50000	14.2	0.97
Windigo River Above Muscrat Dam Lake	04CB001	10800	15.5	0.99
Rainy River at Manitou Rapids	05PC018/5133500	50200	27.8	0.83

MAC-HBV was selected for use because it was developed for modeling flows at ungagued sites using a province wide data set for Ontario (Samuel *et al*., 2010). At the core of MAC-HBV is a lumped rainfall-runoff model which follows the concept of the HBV model (Bergström, 1976). The structure of the model is similar to that used by Merz and Blöschl (2004) but it also includes a modified routing routine following Siebert (1999). The automated calibration process of MAC-HBV requires daily temperature and precipitation values for the period of record. Consequently, a MATLAB script was written to generate a daily temperature and precipitation series over a basin centroid using inverse distance weighting, and data from 34 climate stations (Figure 2.6) distributed across the study area (*IDW_Daily.m*). The MAC-HBV (Version 1, 2010) software was used to simulate the flow series for the following model runs, designed to test the accuracy of different model parameterization methods:

1. MAC-HBV hydrologic model (Samuel *et al*., 2010; Samuel *et al*., 2011a; Samuel *et al*., 2011b) was used to calculate HBV parameters for each of the five source sites identified in Section 2.3.4. This was done using Brent's parabolic interpolation method of optimizing HBV rainfall-runoff

model fit statistics, given a calibration data set of daily precipitation, temperature, and runoff for each gauged reference site. The reference site parameter set was averaged and used in the rainfall-runoff model to generate a State of Nature flow series using rainfall and temperature data for Rainy River (1970-2010).

2. MAC-HBV, Inverse Distance Weighted (IDW) regionalization method. The IDW approach weights HBV parameter values, considering a set of the 90 gauged basins considered in MAC-HBV, based on the spatial distance between the basin centroids of the source site and reference sites. A similarity threshold of 0.3 was used to select hydrologically similar catchments.
3. MAC-HBV, and coupled IDW and physical similarity (IDW-PS) approach. The IDW-PS uses information on the catchment attributes to create a physically similar sub-set of gauged basins that is then used in the IDW method for the ungauged basin. A similarity threshold of 0.3 was used to select hydrologically similar catchments. The full suite of Rainy River basin characteristics was used.
4. MAC-HBV calibrated to observed runoff at Fort Frances/International falls, and daily precipitation and temperature at the basin centroid for the pre-dam period (i.e. 1905-1908).

2.3.1.4 Back-calculating State of Nature inflows at IFD

We investigated the use of a reverse reservoir routing (RRR) model to estimate a natural inflow hydrograph to the reservoir based on the recorded reservoir outflow and headwater elevations, and stage storage curves for the State of Nature case. The IFD reservoir outflow is estimated from gate operations and power releases. The headwater elevations are measured directly. We did not use reverse reservoir routing to simulate State of Nature inflow hydrograph at IFD because the current project focused on the use of daily discharge data. The accuracy of the reverse reservoir method is compromised when not using outflow and headwater level data of hourly or smaller time increments (D'Oria et. al., 2012, Dooge and Bruen, 2005).

2.3.4 Reference watershed selection and flow duration curves.

Potential reference rivers to provide baseline conditions for unregulated rivers and to simulate flows at IFD and points downstream using FDC transposition were identified using the following sources:

1) An unpublished report by the Watershed Science Centre, Trent University and OMNR (WSC, unpublished) that included a list of all potential natural reference rivers in Ontario;
2) St. George (2007) Streamflow in the Winnipeg River basin: Trends extremes and climate linkages; and,
3) Rainy River Hydraulic Model Rainy-Namakan Basin – Draft Report.

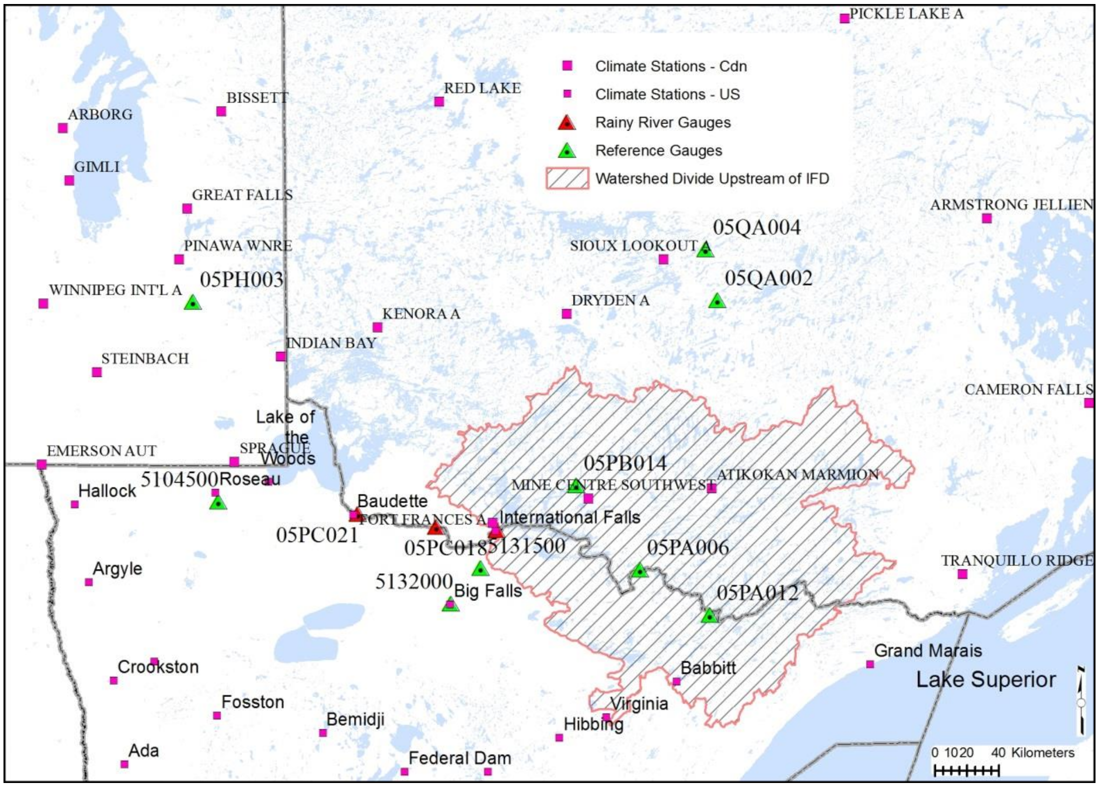


Figure 2.6 Rainy River drainage basin upstream of Fort Frances. The posted stream gauges include those on the Rainy River (see Table 2.4) and the refined set of candidate reference gauge stations (see Table 2.5). Climate stations located in the area are also shown.

The list of potential reference stream gauges was refined by selecting sites that satisfied the following criteria:

1) Possess a similar basin physiography to the basins for which flows have to be simulated;
2) Have a drainage basin area at least 1000 km^2 and preferably greater than 4000 km^2;
3) Do not have large gaps in the historical streamflow record;
4) Are located within 400 km of the basins of interest;
5) Possess a similar climatic regime to the basins of interest; and,
6) Have a similar hydrologic response to the basins that require flow simulations.

Stream gauges that met these criteria are shown in Figure 2.6 and summarized in Tables 2.4 and 2.5. Figure 2.6 also shows the location of climate stations from which data were collected for the period of record.

Similarity of hydrologic response was characterised for each station by calculating the flow duration curves using the Streamflow Analysis and Assessment Software (SAAS) v2.1.1. To facilitate comparisons between the stream gauges, discharge values were standardized by the drainage basin area and converted into runoff units (mm/day). Flow duration curves were generated for the periods 1970-1999 (pre-2000 rule curve), and 2000-2010 (post-2000 rule curve). For the Fort Frances gauge, a flow duration curve was also calculated for the brief pre-dam period of record (i.e. 1906-1909). This period was included as a point of reference. This early period is not directly comparable to the pre- and post-2000 rule curve periods without controlling for its brief duration, infrequent sampling interval and differences in climate.

Table 2.4 Rainy River discharge gauges.

Station Number	Station Name	Area km^2	Record Start Date	Record End Date	Gaps	Latitude	Longitude	Additional Info
05PC019	Rainy River at Fort Frances	38600	1905	2010	No	48°36'30"	93°24'12"	Calculated discharge
05PC018/ 5133500	Rainy River at Manitou Rapids	50200	1928	2010	No	48°38'4"	93°54'48"	19.22% lake area
05PC021	Rainy River at Rainy River	53800	1992	2010	No	48°43'0"	94°34'3"	Level Only

Table 2.5 Reference basin gauges for simulating State of Nature flows at IFD and concurrent unregulated flows at Rainy River tributaries.

Station Number	Station Name	Area km^2	Record Start Date	Record End Date	'70-'10 Data Gaps	Latitude	Longitude	Additional Info	Reference Case
05QA002	English River at Umfreville, ON	6230	1921	2010 (2012)	No	49°52'24"	91°27'35"	Lake area = 21.19% Western Great Lakes Forest;Central Canadian Shield Forest	1
05PB014	Turtle River near Mine Centre, ON	4870	1914	2010 (2012)	79,80,82, 83	48°51'0"	92°43'25"	Lake area = 18.46% Western Great Lakes Forest	1
05PA006	Namakan River at outlet of Lac la Croix, ON	13400	1921	2010 (2012)	No	48°22'57"	92°10'34"	Lake area = 24.68% Western Great Lakes Forest	1
05QA004	Sturgeon River at McDougall Mills, ON	4450	1961	2010 (2012)	No	50°10'2"	91°32'26"	229 km; Tv, Tb, GP, fL; Central Canadian Shield Forest, Mid Western Canadian Shield Forest	1
05PA012	Basswood River near Winton, ON	4510	1924	2010 (2012)	No	48°4'57"	91°39'4"	171 km- Western Great Lakes Forest	1
05132000	Big Fork River at Big Falls, MN	3833	1909	2010 (2012)	No	48°11'45"	93°48'25"	Fine Grained Glaciolacustrine & Organics; Western Great Lakes Forest	2
05131500	Little Fork River at Littlefork, MN	4351	1909	2010 (2012)	No	48°23'45"	93°32'57"	Fine Grained Glaciolacustrine; Western Great Lakes Forest	2
05PH003	Whitemouth River near Whitemouth, MB	3750	1942	2010 (2012)	No	49°56'19"	95°57'24"	Whole Basin – Organics 194 km-; Western Great Lakes Forest	3
05104500	Roseau River below South Fork near Malung, MN	1114	1946	2010 (2012)	No	48°47'41"	95°44'32"	Used in first HEC-RAS study as reference Gauge.;Western Great Lakes Forest; Northern tall grasslands	3

Flow duration curves for Fort Frances and the nine candidate reference rivers illustrate the variability in flow regimes amongst the basins. Gauges with a similar hydrologic response were subjectively grouped into three different response types (Figure 2.7), distinguished by the amount of lake storage, drainage pattern, basin relief, quaternary deposits and geographic location. Locations of the reference gauges are shown in Figure 2.8 on a shaded relief map of the 15 second Shuttle Radar Topography Mission data and rivers associated with each response type are also identified in Table 2.5.

Reference 1 type rivers (Figure 2.7) have a damped hydrologic response and are characteristic of the Canadian Shield. These basins have abundant water storage in lakes and wetlands, and an angular drainage pattern, reflecting the shallow till deposits that drape fractured bedrock. At the other extreme, Reference 3 type rivers (Figure 2.7) have a more varied hydrologic response. These basins are smaller and are located in areas of fine-grained clastic and organic/peat deposits to the west of Fort Frances. Intermediate to these two response cases are the Reference 2 type rivers (e.g. Big and Little Fork Rivers), also located to the West of Fort Frances. These rivers have some lake storage in their headwaters, are larger in size but also flow through fine grained glaciolacustrine sediments and peat deposits before entering Rainy River.

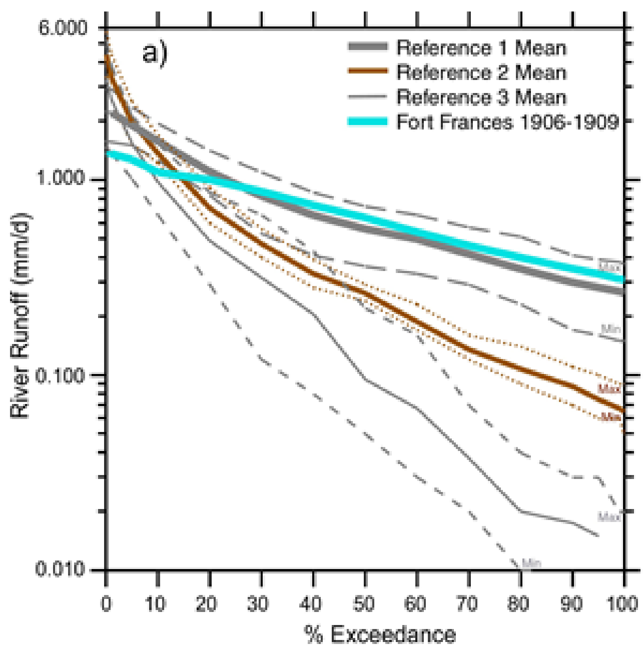


Figure 2.7 Flow duration curves for Fort Frances during the pre-dam period, and three types of reference rivers for the pre- and post-2000 rule curve periods.

The reference rivers were used to simulate a natural flow regime for Rainy River at Fort Frances using spatial interpolation (Hughes and Smakhtin, 1996; Smakhtin et al., 1997; Smakhtin, 1999; Smakthin and Masse, 2000) for the 1970-2010 period. They were also used for simulating the tributary inflows for the HEC-RAS modelling. Simulations typically used five reference rivers with the most hydrologically similar reference rivers weighted the highest in final flow series. The Reference 1 rivers were strongly weighted when simulating a flow series at Fort Frances. The Reference 2 rivers were strongly weighted when simulating a flow series for rivers confluent to the Rainy River, downstream of Fort Frances. Reference 3 rivers received strong weighting when hydrographs were simulated for the smaller tributaries located closer to Lake of the Woods. The reference rivers used in all simulated hydrographs are documented in Section 2.4.2, Table 2.12.

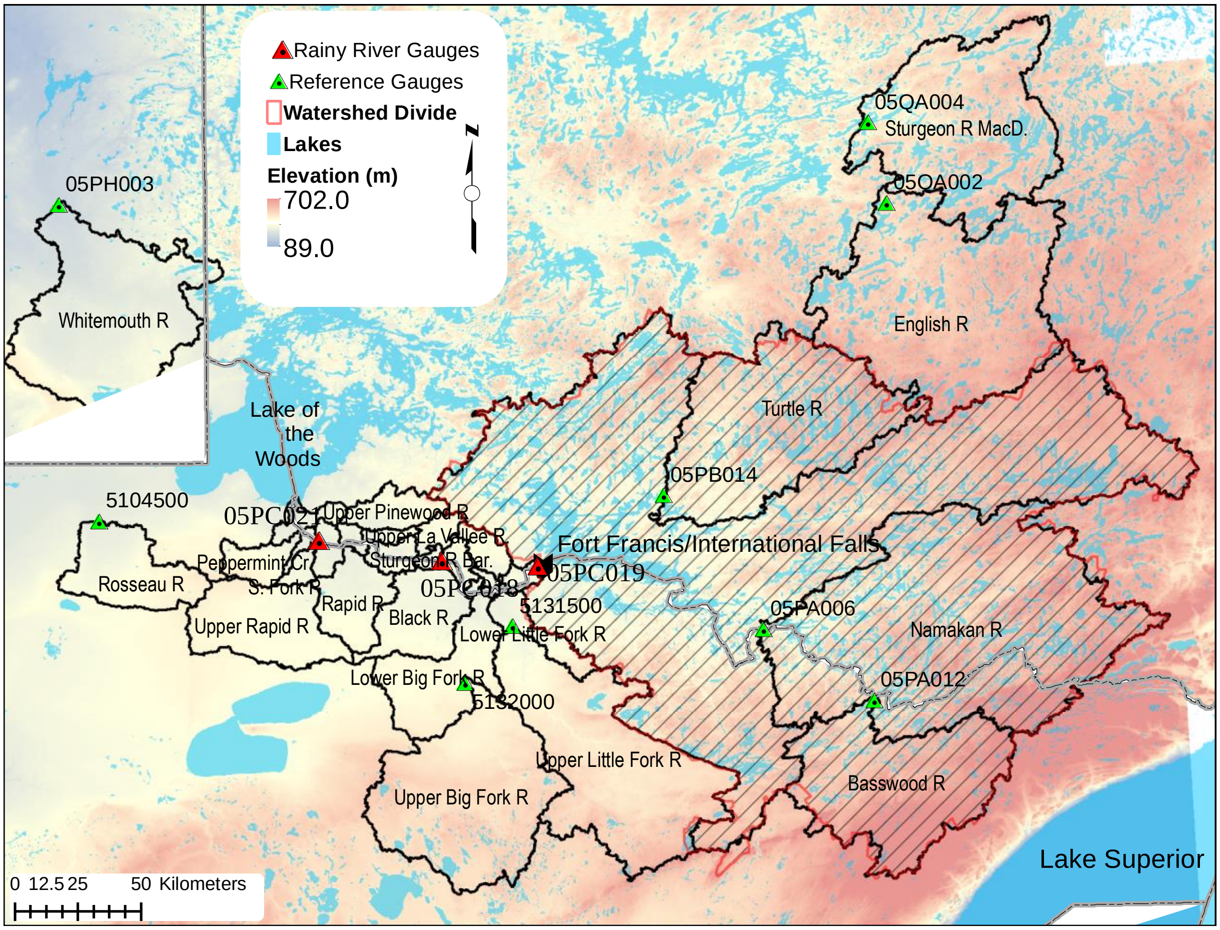


Figure 2.8 Rainy River and reference river basin topography and lake density. The shaded 'Watershed Divide' area drains to IFD. The red outline of the Watershed Divide was done previous to this study, at a coarser resolution, and consequently does not directly match up with the updated, black watershed boundaries. The English, Sturgeon, Whitemouth and Rosseau Rivers do not drain to the Rainy River, unlike the remaining unshaded watersheds between IFD and LOW.

2.3.5 Hydrologic Model Selection and Validation

We investigated the performance of the models outlined in Section 2.3.1 to select a method for simulating flows for the HEC-RAS model runs. The details provided below in Sections 2.3.5.1 and 2.3.5.2 suggest that the FDC transposition methods narrowly outperform the other methods.

2.3.5.1 Simulation of flows at IFD for 1970-2010

We first simulated flows for the Rainy River at Fort Frances using three methods:

Method 1 - FDC Transposition;
Method 2 - Proration; and
Method 3 - MAC-HBV with four different parameterizations (3a-3d).

The SpatPro model parameterization is given in Table 2.6 (Run 11). The 'Run' refers to the model run using SpatPro. By toggling Run 11 in *Spatpro*, the parameters shown in Table 2.6 (i.e. drainage area at IFD & source sites used in the FDC transposition) are automatically entered into *SpatPro*, for simulating flows at IFD. The validated MAC-HBV parameters are given in Tables 2.7-2.9.

The six simulated series are shown in Figures 2.9 to 2.14. In each figure, the observed flows at Fort Frances are also shown for reference. There should not be a direct match between the observed and State of Nature flows, but the annual flow volumes and general hydrograph shape should be similar. To quantify some of the differences between the simulations, we compared the simulated series to the observed flow series and calculated regression slope, intercept, adjusted R^2, Inter-class Correlation Coefficient and Nash-Sutcliffe efficiency coefficient (Nash–Sutcliffe, 1970) (Table 2.10). The R^2_{adj} indicates the degree of correlation between the observed and simulated series. Higher interclass correlation coefficients (*ICC*) indicate higher similarity between the observed and simulated flows (Shrout and Fleiss, 1979). The Nash-Sutcliffe (Nash-S) efficiency coefficient has a value of 1 when there is a perfect agreement between the two series. Lower efficiency coefficients indicate poorer agreement. Negative values suggest that the mean of the observed series is a better predictor of daily observed values, relative to the daily values of the simulation.

Since the discharge in the observed series is altered and the simulated hydrographs represent the State of Nature, the regression intercept is not expected to be zero, and the slope is not expected to be 1:1. The summary of comparative metrics provides a quantitative gauge to compare differences between the six flow simulation techniques. The top three simulation methods in terms of maximizing the correlation, similarity and efficiency coefficient to the observed series are (Table 2.10):

- Spatial Interpolation (Method 1),
- Proration (Method 2), and
- MAC-HBV-Inverse distance weighting (Method 3b).

The MAC-HBV performs well for baseflow but appears to over-predict peak flows for Methods 3a, 3b and 3c (Figures 2.11-2.13, respectively). Not surprisingly, the simulation using Method 3d, the pre-dam simulation which reflects early 1900's watershed land use conditions and water storage conditions, is the most dissimilar from current, observed conditions at IFD. The Method 3d simulation result should be interpreted with caution as it is based on a very short calibration period, and the flow data were not always observed on a daily basis during this early period. While the overall hydrograph pattern differs from the observed series as expected, the annual flow volumes are very similar.

Table 2.6 Validation SpatPro run details for simulation Methods 1 and 2.

Run #	Destination Site	Area (km^2)	Start Time	End Time	Destination FDC *	Source FDC	Source Site 1	Wt	Source Site 2	Wt	Source Site 3	Wt	Source Site 4	Wt	Source Site 5	Wt
11	Rainy River Fort Frances - 1970-2010	38601	1-Jan-70	31-Dec-10	1	Namakan R	English R Umf.	0.20	Namakan R	0.21	Basswood R	0.20	Turtle R Patched	0.19	Sturgeon R MacD	0.20
1	Wanapitei River	3720.3	1-Jan-06	31-Dec-09	1	Sturgeon R Glen Afton	Sturgeon R Glen Afton	0.80	Vermillion R Val Caron	0.20						
2	Turtle River	4870	1-Jan-70	31-Dec-10	1	English R Umf	English R Umf.	0.26	Namakan R	0.25	Sturgeon R MacD	0.25	Basswood R	0.24		
3	Big Fork	3833	1-Jan-70	31-Dec-10	1	Little Fork R	Little Fork R	0.52	Whitemouth R	0.48						
4	Namakan River	13400	1-Jan-70	31-Dec-10	1	Basswood R	English R Umf.	0.25	Basswood R	0.27	Turtle R Patched	0.24	Sturgeon R MacD	0.24		
5	Rainy River Fort Frances 1908	38600	1-Jan-70	31-Dec-10	1	English R Waib.	English R Waib.	0.39	Winnipeg R	0.32	St. Marys R	0.30				

*FDC Selection Method - 1) FDC calculated from a nearby source site can be prorated to the destination site with data from the POR. 2) FDC calculated from a nearby source site can be prorated to the destination site with data that does not directly correspond with the POR.

Table 2.7 HBV parameter sets for flow simulation Method 3a. MAC-HBV optimized parameter sets for the five hydrologically similar reference basins identified in Section 3.2. The calibration and validation data are daily runoff at each gauge and daily precipitation, and temperature at the reference basin centroid. The calibration/validation period is 1970-2010.

			Namakan River		**Turtle River**		**English River**		**Sturgeon River**		**Basswood River**	
Routine	**Parameter**	**units**	**Calibration**	**Validation**	**Calibration**	**Validation**	**Calibration**	**Validation**	**Calibration**	**Validation**	**Calibration**	**Validation**
Snow	tr	^{0}C	-1.43	0.00	1.68	-1.10	-1.10	2.50	-1.30	1.67	-1.43	0.10
	scf	-	0.98	0.99	0.86	0.99	0.80	0.98	1.07	1.33	1.07	1.02
	ddf	mm/(day^{0}C)	0.49	1.01	0.57	1.70	0.28	0.57	0.29	0.62	0.70	1.37
Soil Moisture	athorn	-	0.13	0.18	0.13	0.17	0.13	0.15	0.15	0.16	0.13	0.19
	fc	mm	351.80	311.56	297.97	369.96	269.53	322.18	277.28	623.05	256.15	296.47
Response	clp	mm/mm	0.90	0.66	0.87	0.54	0.84	0.84	0.81	0.79	0.87	0.67
	beta	-	10.00	4.88	10.00	6.22	10.00	10.00	10.00	4.25	10.00	5.21
	k0	days	1.00	15.00	1.00	15.00	1.00	15.00	1.00	14.90	1.00	12.15
	lsuz	mm	98.50	99.99	87.95	99.98	87.03	99.98	86.44	99.62	92.08	89.10
	k1	days	35.71	37.30	31.90	26.75	36.74	39.76	35.51	38.83	23.96	24.79
	cperc	mm/day	0.64	0.75	0.68	1.26	0.67	1.71	1.06	1.45	0.54	0.65
	k2	days	367.94	830.82	716.04	382.08	640.91	496.37	360.10	425.88	314.02	995.80
Routing	maxbas	days	20.00	19.00	5.00	4.70	12.97	7.00	6.00	5.00	18.86	18.00
	rcr	-	0.96	0.96	0.99	1.02	0.99	1.02	0.99	1.01	0.96	0.96
	alpha1	-	1.27	1.27	1.27	1.26	1.27	1.25	1.26	1.26	1.25	1.26

tr = An upper threshold temperature, to distinguish between rainfall & snowfall ; sfc = Snowfall correction factor ; ddf = Degree day factor ; athorn = A constant for Thornthwaite's equation ; fc = Maximum soil box water content ; clp = (limit for potential evaporation) divided by (maximum soil box water content) ; beta = A non-linear parameter controlling runoff generation ; k0 = Flow recession coefficient at an upper soil reservoir ; lsuz = A threshold value used to control response routing on an upper soil reservoir ; k1 = Flow recession coefficient at an upper soil reservoir ; cperc = A constant percolation rate parameter ; k2 = Flow recession coefficient at an lower soil reservoir ; maxbas = A triangular weighting function for modeling a channel routing routine ; rcr = Rainfall correction factor ; alpha1 = An exponent in relation between outflow and storage of lower reservoir.

Table 2.8 HBV parameter sets for flow simulation Methods 3b and 3c. MAC-HBV parameters estimated using inverse distance weighting of parameters from the MAC-HBV set of reference stations. The basin similarity parameter had to be relaxed from 0.6 to 0.3. The basin characteristics considered in the (IDW-PW) included the centroid of the Rainy River basin upstream of Fort Frances, drainage area, mean elevation, mean slope, percent lake, percent forest, percent glacial till, percent glaciofluvial deposits, percent rock, percent rapid drainage class, percent root depth > 150 cm.

Routine	Parameter	units	Inverse Distance Weighting of Parameters (IDW)	IDW and Basin Characteristics (IDW-PW)
Snow	tr	^{0}C	-0.01	1.65
	scf	-	0.69	0.83
	ddf	mm/(day^{0}C)	1.41	1.44
Soil Moisture	athorn	-	0.19	0.15
	fc	mm	326.19	405.89
Response	clp	mm/mm	0.86	0.87
	beta	-	4.93	5.64
	k0	days	5.70	11.09
	lsuz	mm	48.28	37.26
	k1	days	32.19	26.90
	cperc	mm/day	0.63	0.40
	k2	days	149.39	112.57
Routing	maxbas	days	6.74	4.28
	rcr	-	0.96	0.87
	alpha1	-	1.00	0.99

See Table 2.7 for parameter descriptions.

Table 2.9 HBV parameter sets for flow simulation Method 3d. MAC-HBV optimized parameters for Fort Frances generated using daily data for precipitation, temperature and runoff for the pre-dam period (1905-1908) and post-dam reference period (1970-2010). The 1970-2010 parameter set reflects elements of the water balance for the current, altered condition at Fort Frances.

			1905-1908		1970-2010	
Routine	Parameter	units	Calibration	Validation	Calibration	Validation
Snow	tr	^{0}C	2.50	2.43	-1.24	-1.30
	scf	-	1.60	1.60	0.53	0.81
	ddf	mm/(day^{0}C)	0.26	0.23	2.00	1.90
Soil Moisture	athorn	-	0.17	0.16	0.12	0.19
	fc	mm	725.32	780.95	479.26	350.84
Response	clp	mm/mm	0.67	0.27	0.90	0.67
	beta	-	3.19	2.48	10.00	4.44
	k0	days	1.00	1.00	1.00	1.00
	lsuz	mm	5.74	2.37	65.91	93.68
	k1	days	99.96	99.99	29.38	36.39
	cperc	mm/day	6.00	6.00	0.80	0.90
	k2	days	601.19	612.66	792.09	930.92
Routing	maxbas	days	20.00	19.78	15.00	13.00
	rcr	-	1.00	1.05	0.96	0.97
	alpha1	-	1.26	1.24	1.25	1.27

See Table 2.7 for parameter descriptions.

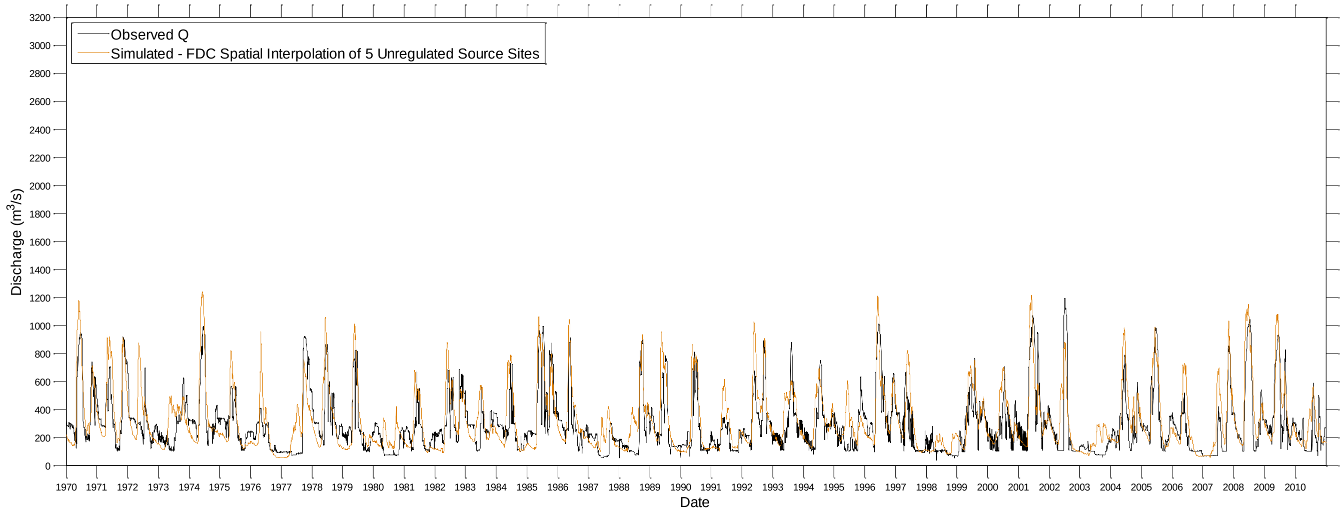


Figure 2.9 Observed and simulated (Method 1) discharge series at Rainy River at Fort Frances/International Falls for the period 1970-2010 (Run 11). The simulation method is the flow duration curve based spatial interpolation (Hughes and Smakhtin, 1996) using 5 reference source gauges. The Y axis range is fixed to facilitate comparisons between series generated by the different simulation methods shown Figures 2.9 to 2.14.

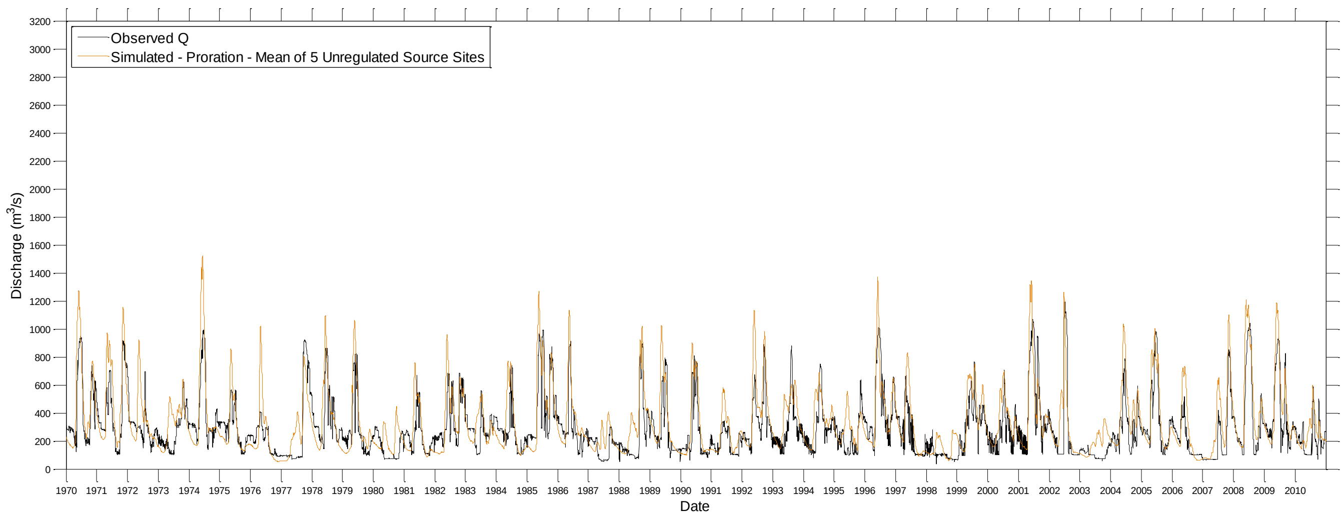


Figure 2.10 Observed and simulated (Method 2) discharge series at Rainy River at Fort Frances/International Falls for the period 1970-2010 (Run 11). The simulation method is proration of 5 reference source gauges. The average of the five gauges is shown. The Y axis range is fixed to facilitate comparisons between series generated by the different simulation methods shown Figures 2.9 to 2.14.

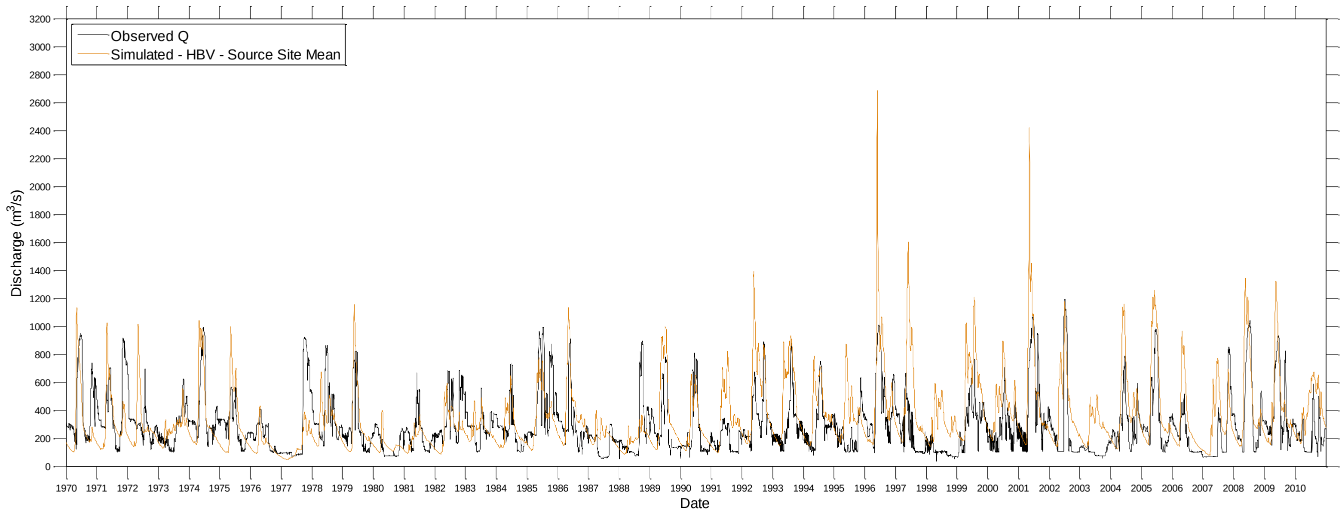


Figure 2.11 Observed and simulated (Method 3a) discharge series at Rainy River at Fort Frances/International Falls for the period 1970-2010. MAC-HBV was used to estimate parameters at the 5 reference source gauges using time series of daily precipitation, temperature and runoff. This optimized parameter set was averaged and used with a daily precipitation and temperature data to generate a State of Nature series for the period. The Y axis range is fixed to facilitate comparisons between series generated by the different simulation methods shown Figures 2.9 to 2.14.

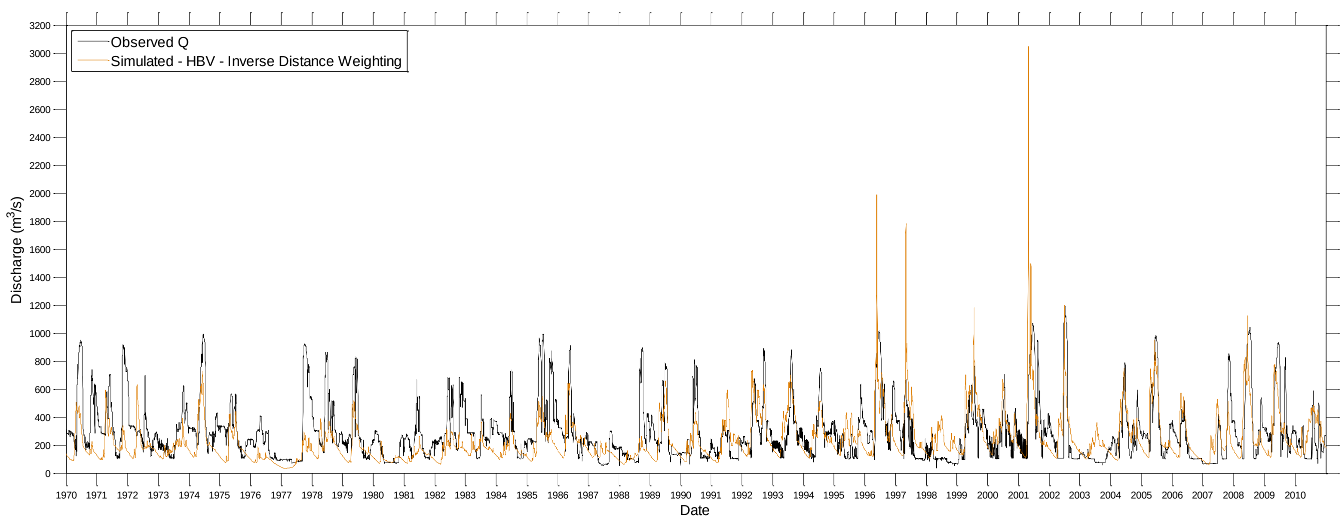


Figure 2.12 Observed and simulated (Method 3b) discharge series at Rainy River at Fort Frances/International Falls for the period 1970-2010. MAC-HBV was used to estimate model parameters using inverse distance weighting of unaltered gauging station parameters. This parameter set was used with a daily precipitation and temperature data to generate an unaltered series for the period. The Y axis range is fixed to facilitate comparisons between series generated by the different simulation methods shown Figures 2.9 to 2.14.

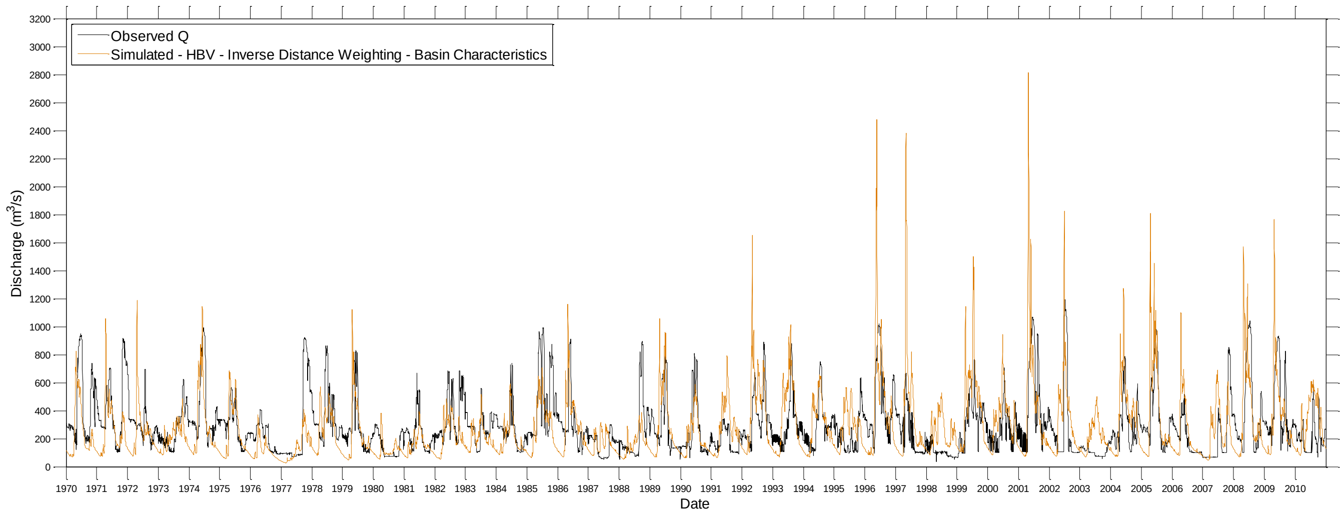


Figure 2.13 Observed and simulated (Method 3c) discharge series at Rainy River at Fort Frances/International Falls for the period 1970-2010. MAC-HBV was used to estimate model parameters using inverse distance weighting of unaltered gauging station parameters. Basin similarity was also considered in selection of the parameter set. This parameter set was used with a daily precipitation and temperature data to generate a State of Nature series for the period. The Y axis range is fixed to facilitate comparisons between series generated by the different simulation methods shown Figures 2.9 to 2.14.

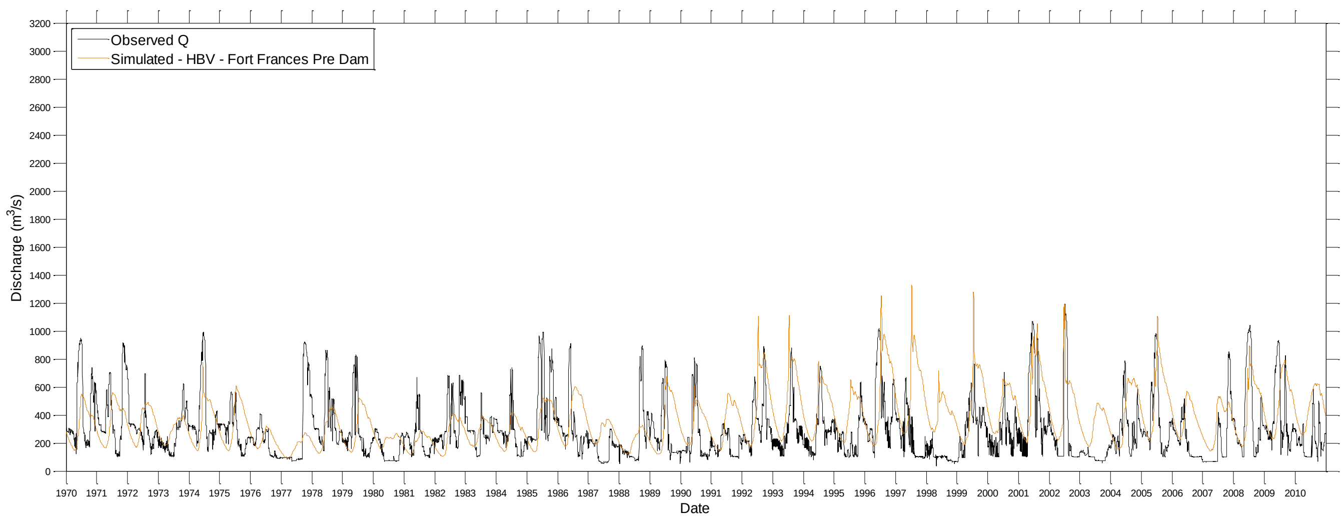


Figure 2.14 Observed and Simulated (Method 3d) discharge series at Rainy River at Fort Frances/International Falls for the period 1970-2010. MAC-HBV was used to estimate parameters at Fort Frances for the pre-dam 1905-1908 period using time series of daily precipitation, temperature and runoff. This optimized parameter set was then used with a daily precipitation and temperature data for the 1970-2010 period to generate a State of Nature series. The Y axis range is fixed to facilitate comparisons between series generated by the different simulation methods shown Figures 2.9 to 2.14.

Table 2.10 Summary statistics characterizing differences between the observed (altered) discharge time series and each of the six simulated (State of Nature) discharge time series for Rainy River at Fort Frances/International Falls, 1979-2010.

Method	Flow series estimation method description	*Intercept*	*Slope*	*SEE*	R^2_{adj}	*ICC*	*Nash-S*
1	Spatial Interpolation - FDC based - 5 source site weighted average	56	0.72	124	0.64	0.89	0.52
2	Proration - 5 source site average	55	0.69	122	0.65	0.89	0.46
3a	HBV - 5 source site parameter averages	127	0.47	168	0.34	0.72	-0.15
3b	HBV - Inverse Distance Weighting (IDW) of parameters	133	0.67	172	0.30	0.70	0.15
3c	HBV - IDW and weighting by similarity of basin characteristics	173	0.43	180	0.24	0.65	-0.19
3d	HBV - Rainy River at Fort Frances pre-dam calibration (1905-1908)	177	0.30	198	0.08	0.43	-0.49

ICC = interclass correlation coefficients, Nash-S = Nash-Sutcliffe efficiency coefficient

2.3.5.2 Simulation of flows at test basins

We simulated flows at five test basins (Table 2.6, Runs 1-5) to compare the efficiency of the FDC Transposition and Proration methods. An example of the SpatPro output for Run 1 is provided in Figures 2.15 and 2.16. For each run a hydrograph series was generated for gauges where observed flows were available. The fit between the observed and predicted flows for the five model runs are provided in Table 2.11. These model fit statistics suggest both methods are reasonably accurate and give similar results.

1) Both FDC transposition and proration methods yielded Nash Sutcliffe values > 0.57. The median Nash Sutcliffle Efficiency values for FDC Transposition and proration are 0.62 and 0.65, respectively. The median Nash Sutcliffe Efficiency values for HBV models applied to cold regions is 0.64, and ranges from 0.31 to 0.93 (Parajka et al 2013), significantly better than the MAC-HBV results (Table 2.10), but comparable to the results of FDC Transposition and Proration.
2) The two methods were scored in terms of how many metrics scored better than the other metric (1=better fit, 0=worse fit) for model Runs 1-5 and Run 11. Each method scored 19 points but the FDC Transposition method provided a better fit when considering the IFD runs.

Table 2.11 Summary statistics characterizing differences between the observed (altered) discharge time series and each of the six simulated (State of Nature) discharge time series for Rainy River at Fort Frances/International Falls, 1979-2010.

SpatPro	Site	Method	y-intercept	slope	SEE	AdjR2	ICC	NashS
Run 1	Wanapitei River Validation	FDC Transposition	-0.4	1.00	2.17	1.00	1.00	1.00
		Proration	4.3	0.93	5.06	0.98	1.00	0.98
Run 2	Turtle River	FDC Transposition	-1.4	0.89	2.16	0.61	0.87	0.57
		Proration	2.4	0.90	21.16	0.63	0.88	0.62
Run 3	Big Fork	FDC Transposition	3.7	0.71	14.24	0.79	0.93	0.64
		Proration	3.5	0.93	12.92	0.83	0.95	0.82
Run 4	Namakan River	FDC Transposition	28.2	0.72	47.65	0.70	0.90	0.59
		Proration	10.5	0.85	46.53	0.71	0.91	0.68
Run 5	Rainy River Fort Frances 1908	FDC Transposition	-150.6	1.41	57.78	0.84	0.91	0.75
		Proration	-347.1	1.96	59.26	0.83	0.82	0.59

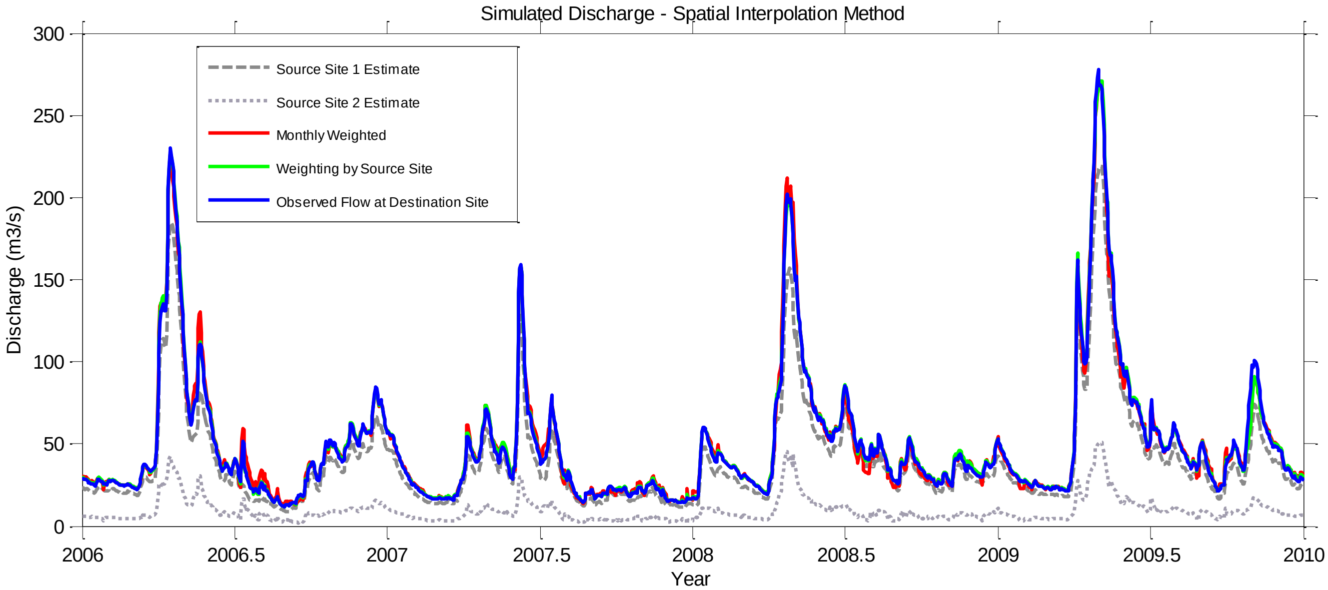


Figure 2.15. Simulated hydrographs using SpatPro. The simulation is Run 1 using the FDC transposition method.

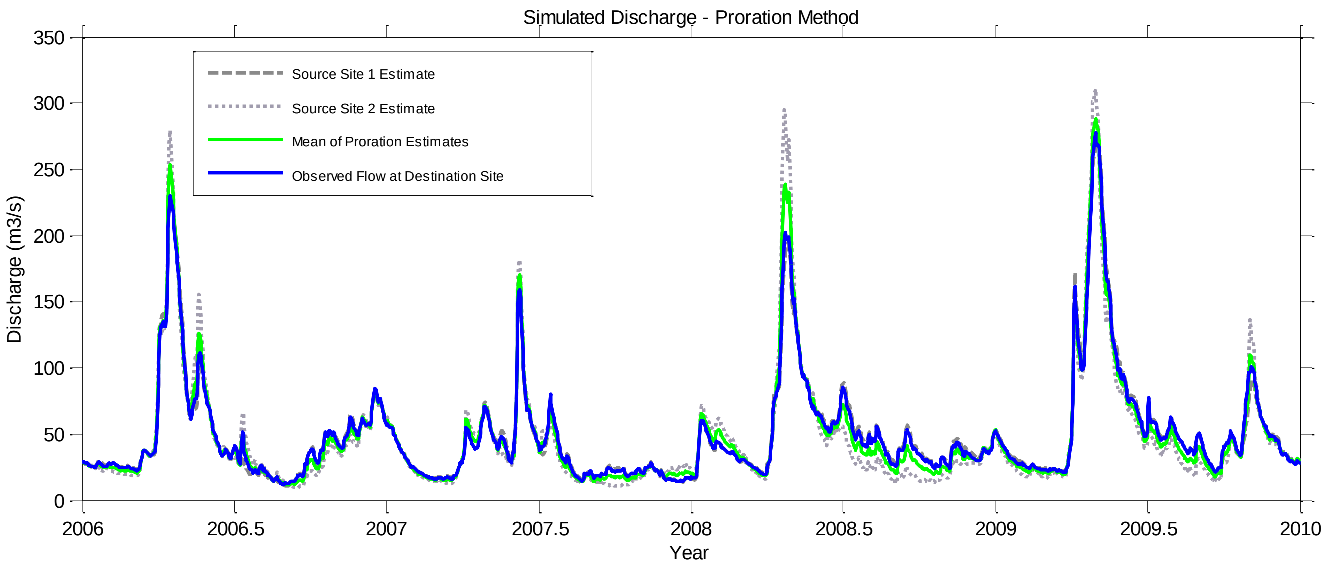


Figure 2.16 Simulated hydrographs using SpatPro. The simulation is Run 1 using the proration method.

2.3.6 Hydrologic Model Simulation Runs

SpatPro was used to simulate daily flows using FDC Transposition at the nineteen ungauged subwatersheds shown in Figure 2.4 for the period 1970-2010. The SpatPro simulation runs and input assumptions are provided in Table 2.12.

Table 2.12 Hydrologic model simulation runs.

Run #	Destination Site	Area (km^2)	Start Time	End Time	Destination FDC *	Source FDC	Source Site 1	Wt	Source Site 2	Wt	Source Site 3	Wt	Source Site 4	Wt	Source Site 5	Wt
11	Rainy River Fort Frances - 1970-2010	38601	1-Jan-70	31-Dec-10	1	Namakan R	English R Umf.	0.20	Namakan R	0.21	Basswood R	0.20	Turtle R Patched	0.19	Sturgeon R MacD	0.20
16	Rainy River Manitou Rapids	50200	1-Jan-70	31-Dec-10	1	English R Umf.	English R Umf.	0.20	Namakan R	0.20	Basswood R	0.20	Little Fork R	0.20	Big Fork R Patched	0.20
17	Rainy River Lake of the Woods	54598	1-Jan-70	31-Dec-10	1	English R Umf.	English R Umf.	0.24	Namakan R	0.22	Basswood R	0.22	Big Fork R Patched	0.15	Little Fork R	0.17
18	Confluence - Little Fork	4799	1-Jan-70	31-Dec-10	1	Little Fork R	Big Fork R	0.22	Little Fork R	0.23	Whitemouth	0.21	Roseau R	0.19	Namakan R	0.15
19	Confluence - La Vallee R	298	1-Jan-70	31-Dec-10	2	La Vallee River	Big Fork R	0.23	Little Fork R	0.24	Whitemouth	0.20	Roseau R	0.23	Namakan R	0.10
20	Confluence - Big Fork R	5384	1-Jan-70	31-Dec-10	1	Big Fork R	Big Fork R	0.24	Little Fork R	0.23	Whitemouth	0.22	Roseau R	0.19	Namakan R	0.12
21	Confluence - Black R	1063	1-Jan-70	31-Dec-10	1	Big Fork R	Big Fork R	0.24	Little Fork R	0.23	Whitemouth	0.22	Roseau R	0.19	Namakan R	0.12
22	Confluence - Sturgeon R	218	1-Jan-70	31-Dec-10	2	Sturgeon River Barwick	Big Fork R	0.24	Little Fork R	0.25	Whitemouth	0.21	Roseau R	0.23	Namakan R	0.08
23	Confluence - Pinewood R	570	1-Jan-70	31-Dec-10	2	Pinewood River	Big Fork R	0.20	Little Fork R	0.22	Whitemouth	0.21	Roseau R	0.22	Namakan R	0.15
24	Confluence - Rapid	2506	1-Jan-70	31-Dec-10	2	Rapid River	Big Fork R	0.22	Little Fork R	0.23	Whitemouth	0.21	Roseau R	0.21	Namakan R	0.13
25	Confluence - South Fork Baudette	134	1-Jan-70	31-Dec-10	1	Big Fork R	Big Fork R	0.24	Little Fork R	0.23	Whitemouth	0.22	Roseau R	0.19	Namakan R	0.12
26	Confluence - Peppermint Cr	380	1-Jan-70	31-Dec-10	1	Big Fork R	Big Fork R	0.24	Little Fork R	0.23	Whitemouth	0.22	Roseau R	0.19	Namakan R	0.12
27	Lateral - International Falls to Little Fork R	120	1-Jan-70	31-Dec-10	1	Big Fork R	Big Fork R	0.24	Little Fork R	0.23	Whitemouth	0.22	Roseau R	0.19	Namakan R	0.12
28	Lateral - Little Fork R to La Vallee R Con.	14	1-Jan-70	31-Dec-10	1	Big Fork R	Big Fork R	0.24	Little Fork R	0.23	Whitemouth	0.22	Roseau R	0.19	Namakan R	0.12
29	Lateral - Black River to Manitou Rapids	183	1-Jan-70	31-Dec-10	1	Big Fork R	Big Fork R	0.24	Little Fork R	0.23	Whitemouth	0.22	Roseau R	0.19	Namakan R	0.12
30	Lateral - Rapid River to South Fork	211	1-Jan-70	31-Dec-10	1	Big Fork R	Big Fork R	0.24	Little Fork R	0.23	Whitemouth	0.22	Roseau R	0.19	Namakan R	0.12
31	Lateral - South Fork Con. to Peppermint Con.	70	1-Jan-70	31-Dec-10	1	Big Fork R	Big Fork R	0.24	Little Fork R	0.23	Whitemouth	0.22	Roseau R	0.19	Namakan R	0.12
32	Lateral - Sturgeon R Con. to Pinewood R Con.	218	1-Jan-70	31-Dec-10	1	Big Fork R	Big Fork R	0.24	Little Fork R	0.23	Whitemouth	0.22	Roseau R	0.19	Namakan R	0.12
33	Lateral - Manitou Rapids & Sturgeon R	63	1-Jan-70	31-Dec-10	1	Big Fork R	Big Fork R	0.24	Little Fork R	0.23	Whitemouth	0.22	Roseau R	0.19	Namakan R	0.12
34	Lateral - Pinewood R Confl. to Rapid R Confl.	91	1-Jan-70	31-Dec-10	1	Big Fork R	Big Fork R	0.24	Little Fork R	0.23	Whitemouth	0.22	Roseau R	0.19	Namakan R	0.12
35	Lateral - Peppermint Cr to Outlet at LOW	211	1-Jan-70	31-Dec-10	1	Big Fork R	Big Fork R	0.24	Little Fork R	0.23	Whitemouth	0.22	Roseau R	0.19	Namakan R	0.12

*FDC Selection Method - 1) FDC calculated from a nearby source site can be prorated to the destination site with data from the POR. 2) FDC calculated from a nearby source site can be prorated to the destination site with data that does not directly correspond with the POR.

2.4 Simulating Hydraulic Conditions in Rainy River between IFD and LOW

2.4.1 Hydraulic Model Setup

The following modifications were made to the original HEC-RAS model:

1) Save final.prj project as FinalM.prj
2) Convert project units of FinalM.prj from US Customary to SI(Metric) units
3) Changed aerial photo positional coordinates from US Customary to SI(Metric) units. This required the following steps: Open RainyRiver_FSAi.jgw files in notepad and convert measurement in feet to metres. Save. -> Add/Edit background pictures for the schematic.-> Open jpeg files.
4) Save project. Save Project as ProjectM_Revised.prj
5) Updated the flow series as given in Table 2.14.
6) Ran the model for the 1970-2000 period.
7) Divided the model into two time periods (1970-1989, 1990-2010) to enable HEC-RAS output functions to work properly.
8) Added a hot start at the beginning of each model to minimize errors associated with the 'wind up period'. This involved entering starting water levels at all internal cross sections.
9) The hydrograph output locations shown in Table 2.2 were specified.

2.4.2 Hydraulic Model Simulation Runs

Two model runs were conducted to represent the observed river conditions and State of Nature conditions. The boundary conditions for each model run are provided in Table 2.13.

Table 2.13 HEC-RAS model runs and boundary conditions.

Model Run	Upstream Boundary	Downstream Boundary
Observed	Observed daily discharge at IFD interpolated to hourly flows.	Hourly water level series
State of Nature	Simulated State of Nature discharge at IFD using spatial interpolation (SpatPro Run 11). Interpolated from daily to hourly.	Simulated State of Nature at LOW using spatial interpolation (SpatPro Run 17). Discharge converted to normal water level using Normal_Depth.m, a MATLAB script written to calculate normal depth of flow in a compound channel containing a bankfull channel and floodplain. The script follows the methods of A. Osman Akan (2006), calculating normal depth for overbank flows. The simulation was conducted on River Station 18 and required extending the cross section beyond the limits of the original HEC-RAS model using the DEM.

2.4.3 Estimating water levels at Lake of the Woods.

The HEC-RAS model requires boundary conditions to be set at Lake of the Woods. The boundary condition can be defined either by a time series of water levels or by a rating curve. Observed water level data was used to model existing conditions but a water level series for the State of Nature case does not exist. While a water balance model exists for simulating State of Nature flows in LOW, it was not used in this study because of the uncertainty associated with the State of Nature rating curve and the relatively coarse spatial discretization of the model. Additional work would be required to further refine the water balance model for this particular application. Alternatively, we estimated the natural range of State of Nature water levels from historical accounts and then simulated a water level series from a State of Nature hydrograph. Background on the State of Nature water levels and simulation methods follow.

The morphology of the lower Rainy River and extent of inundation at baseflow suggests that water levels are higher now than during the formation of the rivers banks and floodplain. The former floodplain is now partially inundated at baseflow at the river mouth. Historical accounts and data for the 1892 to 1915 period collected by the LOWCB suggest that water levels increased after regulation by an average of 0.9 metres (i.e. at 322.088 m). Regulation commenced with construction of a Rollerway dam in 1888 to raise water levels for navigation and facilitating the transport of lumber. In 1898, the Norman Dam was constructed, replacing the hydraulic function of the roller dam. A power house was constructed in 1926 which may also have changed water levels. Antidotal evidence from the 1880's suggests that the State of Nature water levels on LOW were more variable (0.6 to 2.13 m), relative to the post-regulation period. Certainly, water levels in LOW have become more predictable during the period of regulation as shown in the Figure 2.17 below (i.e. 2.62 m range prior to 1941 vs. 1.5 m range after 1970).

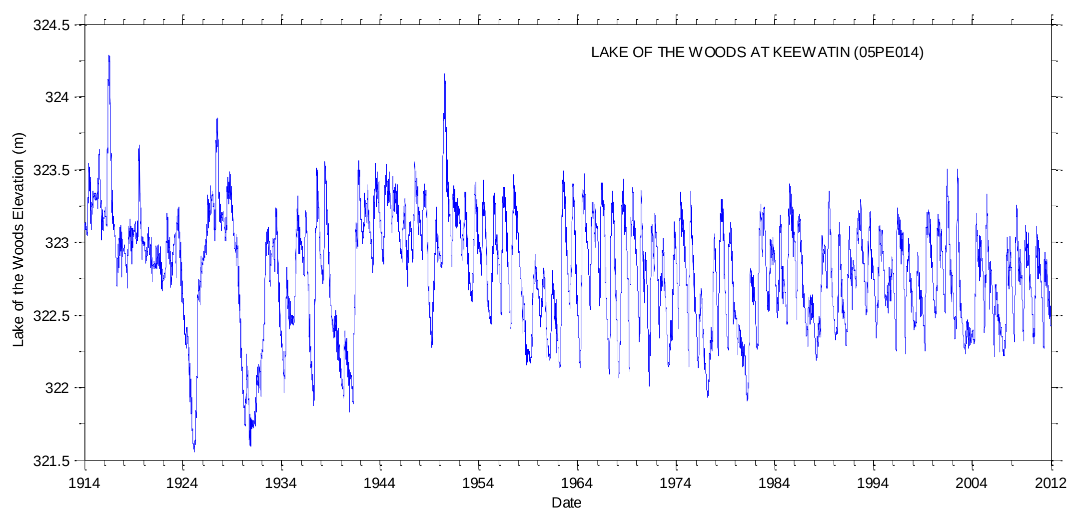


Figure 2.17 Fluctuating water levels on Lake of the Woods at Keewatin for the period 1914 to 2011.

The State of Nature water level curve for Rainy River at Lake of the Woods was calculated using the following method:

1) Simulate the State of Nature discharge series for the 1979-2010 series using SpatPro, Run 17. This model run uses FDC Transposition to generate a flow hydrograph at LOW using the assumptions listed in Table 2.12.
2) Calculate the flow depth from the discharge series (Run 17) as detailed in the script Normal_Depth.m. This script calculates the normal flow depth in a compound channel consisting of a bankfull channel and floodplain following the method outlined in A Osman Akan (2006). The cross section data used are for HEC-RAS River Station 18. The floodplain data points were extended using the DEM data detailed earlier. Additional input data include the channel slope (0.0001 m/m), the channel manning's n value (0.035) and floodplain manning's n value (0.085).
3) Simply running Normal_Depth.m for the existing channel geometry does not account for any backwater effects from Lake of the Woods. That calculation assumes that LOW does not exist and results in an average water level approximately 2 metres below the current average lake level. We know that the average lake level was only 0.91 m below the lake levels observed in 1915. Consequently, the State of Nature case was simulated by increasing the channel invert (i.e. The bottom of the cross section), rerunning the Normal_Depth.m script, calculating the new average water level and comparing it to the State of Nature Water level (322.0883 m) and repeating the above steps until the simulated water level average matched the State of Nature mean water level. The resulting channel invert was 317.60 m. The resulting simulated State of Nature series is shown in Figure 2.18. While the backwater effects are not explicitly accounted for by this method, the resulting series has the same mean water level as measured by LWCB in an early study, has the same range of values and pattern as reported earlier and observed in the 1914-1926 run of river, pre-regulation case. Confidence in the methods was further supported by raising the channel invert to simulate present day conditions, which provided a near perfect match in flow pattern.
4) HEC-RAS requires hourly data so the daily flows were linearly interpolated using a program developed for this case study (*HourlyInterpolation*). The hourly flow and level data was imported into the HEC-DSS database management system. A list of files is provided in Table 2.14.

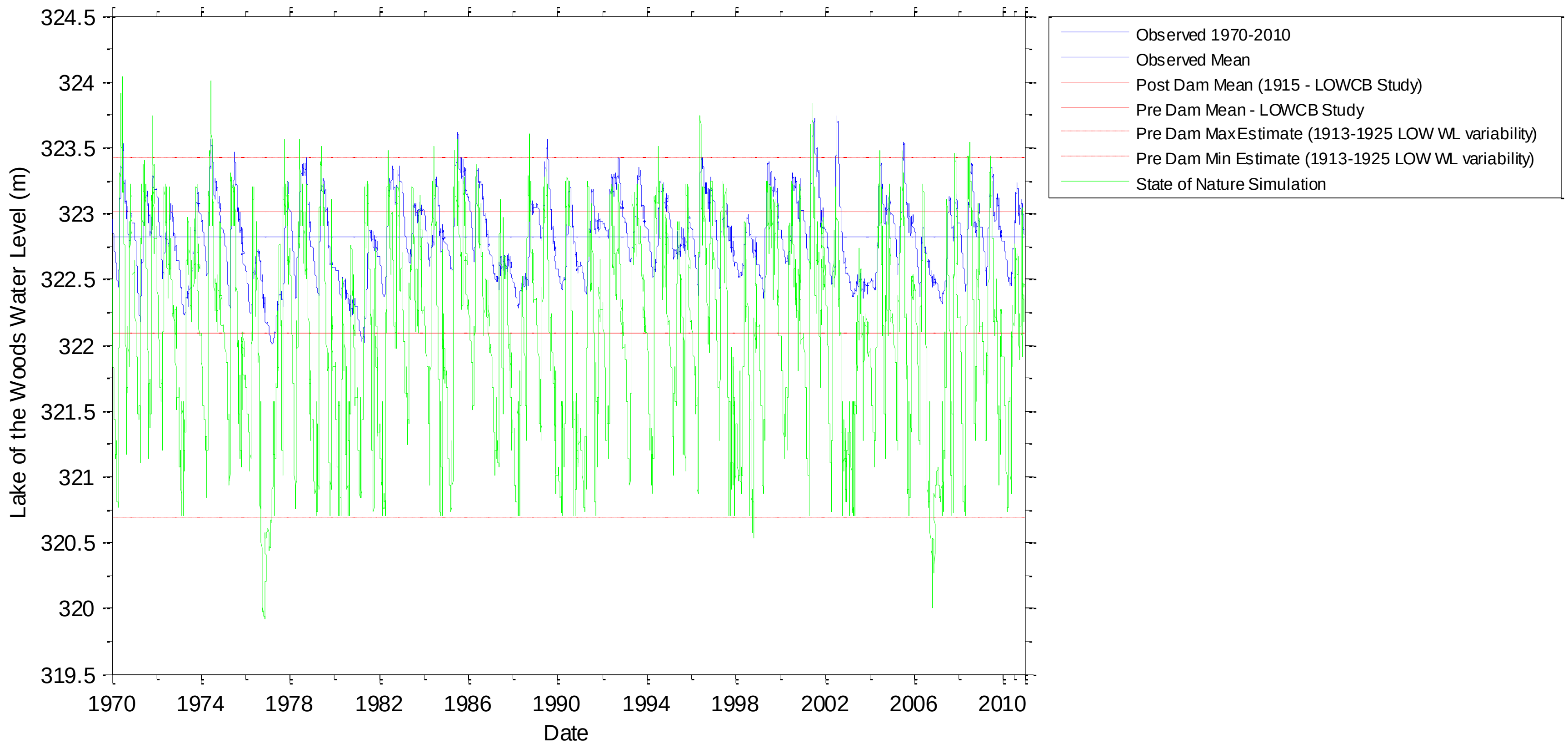


Figure 2.18 Water levels at LOW for existing conditions (Observed) and for simulated State of Nature flows. The pre-dam mean is plotted as given by the early LOWCB study. The offset from the mean for the period 1913-1925 for max and min flows was transferred onto the pre-dam mean to provide guidance on approximate variability to expect the simulation to contain. The State of Nature simulation is outside that range but this is to be expected as it represents a 40 year period (i.e. vs 1913-1925).

Table 2.14 Summary of flow data files for the updated HEC-RAS model of Rainy River. The items labeled ‘Part A’ through ‘Part F’ are the file pathway naming conventions for the HEC-DSS database management system.

#	Part A	Part B*	Part C	Part D	Part E	Part F	Comment 1**	Comment 2	Comment 3
1	RAINY_RIVER	FORT_FRANCIS_436630.5	FLOW	01JAN1970	1HOUR	HYDAT	05PC019	Flow Hydrograph	Observed
2	RAINY_RIVER	FORT_FRANCIS_436630.5	FLOW	01JAN1970	1HOUR	SPATPRO_RUN11_SPAT	Output_Run11	U/S Boundary Condition - Flow Hydrograph	State of Natue - Simulated
3	RAINY_RIVER_LATERAL_1	DS_TO_LITTLE_FORK_R	FLOW	01JAN1970	1HOUR	SPATPRO_RUN27_SPAT	Output_Run27	Uniform Lateral Inflow	Simulated
4	LITTLE_FORK	LITTLE_FORK_CONF_371566.7	FLOW	01JAN1970	1HOUR	SPATPRO_RUN18_SPAT	Output_Run18	Lateral Inflow Hydrograph	Simulated
5	RAINY_RIVER_LATERAL_2	DS_TO_LA_VALLEE_R	FLOW	01JAN1970	1HOUR	SPATPRO_RUN28_SPAT	Output_Run28	Uniform Lateral Inflow	Simulated
6	LA_VALLEE_R	LA_VALLEE_R_CONF_355920	FLOW	01JAN1970	1HOUR	SPATPRO_RUN19_SPAT	Output_Run19	Lateral Inflow Hydrograph	Simulated
7	RAINY_RIVER_LATERAL_3	DS_TO_BIG_FORK_R	FLOW	01JAN1970	1HOUR	SPATPRO_RUN29_SPAT	Output_Run29	Uniform Lateral Inflow	Simulated
8	BIG_FORK_R	BIG_FORK_CONF_332994.3	FLOW	01JAN1970	1HOUR	SPATPRO_RUN20_SPAT	Output_Run20	Lateral Inflow Hydrograph	Simulated
9	RAINY_RIVER_LATERAL_4	DS_TO_BLACK_R	FLOW	01JAN1970	1HOUR	SPATPRO_RUN30_SPAT	Output_Run30	Uniform Lateral Inflow	Simulated
10	BLACK_R	BLACK_R_CONF_313884.1	FLOW	01JAN1970	1HOUR	SPATPRO_RUN21_SPAT	Output_Run21	Lateral Inflow Hydrograph	Simulated
11	RAINY_RIVER_LATERAL_5	DS_TO_STURGEON_R	FLOW	01JAN1970	1HOUR	SPATPRO_RUN31_SPAT	Output_Run31	Uniform Lateral Inflow	Simulated
12	STURGEON_R	STURGEON_R_CONF_216407.2	FLOW	01JAN1970	1HOUR	SPATPRO_RUN22_SPAT	Output_Run22	Lateral Inflow Hydrograph	Simulated
13	RAINY_RIVER	MANITOU_RAPIDS_21481313	FLOW	01JAN1970	1HOUR	USGS	05PC018/5133500	Validation Site	Observed
14	RAINY_RIVER	MANITOU_RAPIDS_21481313	ELEV	01JAN1970	1HOUR	USGS- NAVD	05PC018/5133500	Validation Site	Observed
15	RAINY_RIVER_LATERAL_6	DS_TO_PINEWOOD_R	FLOW	01JAN1970	1HOUR	SPATPRO_RUN32_SPAT	Output_Run32	Uniform Lateral Inflow	Simulated
16	PINEWOOD_R	PINEWOOD_R_CONF_136053	FLOW	01JAN1970	1HOUR	SPATPRO_RUN23_SPAT	Output_Run23	Lateral Inflow Hydrograph	Simulated
17	RAINY_RIVER_LATERAL_7	DS_TO_RAPID_R	FLOW	01JAN1970	1HOUR	SPATPRO_RUN33_SPAT	Output_Run33	Uniform Lateral Inflow	Simulated
18	RAPID_R	RAPID_R_CONF_100964.8	FLOW	01JAN1970	1HOUR	SPATPRO_RUN24_SPAT	Output_Run24	Lateral Inflow Hydrograph	Simulated
19	RAINY_RIVER	RAINY_RIVER_68108.36	FLOW	01JAN1970	1HOUR	NAVD-IHS	05PC021	Validation Site	Observed
20	RAINY_RIVER	RAINY_RIVER_68108.36	ELEV	01JAN1970	1HOUR	WSC-NAVD	05PC021	Validation Site	Observed
21	RAINY_RIVER_OUTLET	LAKE_OF_WOODS	ELEV	01JAN1970	1HOUR	SPATPRO_17_SON	Output_Run17 to W/L	D/S Boundary Condition	State of Nature – Simulated
22	RAINY_RIVER_LATERAL_8	DS_TO_SF_BAUDETTE	FLOW	01JAN1970	1HOUR	SPATPRO_RUN34_SPAT	Output_Run34	Uniform Lateral Inflow	Simulated
23	SF_BAUDETTE	SF_BAUDETTE_CONF_61903.77	FLOW	01JAN1970	1HOUR	SPATPRO_RUN25_SPAT	Output_Run25	Lateral Inflow Hydrograph	Simulated
24	RAINY_RIVER_LATERAL_9	DS_TO_WINTER_PEPPERMINT	FLOW	01JAN1970	1HOUR	SPATPRO_RUN35_SPAT	Output_Run35	Uniform Lateral Inflow	Simulated
25	WINTER_PEPPERMINT	WINTER_PEPPERMINT_CONF_37330.33	FLOW	01JAN1970	1HOUR	SPATPRO_RUN26_SPAT	Output_Run26	Lateral Inflow Hydrograph	Simulated
26	LAKE_OF_THE_WOODS	LAKE_18.94075	ELEV	01JAN1970	1HOUR	WSC-NAVD	05PD003	05PD003	Observed

*Number refers to river station in HEC-RAS model (ft.)
**C:/RR_Matlab/SpatPro_Output/

2.4.4 Hydraulic Model Validation

The updated unsteady HEC-RAS model was validated using both observed data and a program developed for this case study (*Evaluate*). The validation period was for the years 2002 to 2006, to overlap the period of interest in the original HEC-RAS model.

We include model fit information for the original model and the updated model. The purpose of providing these two cases is to verify that the updated model containing a more detailed unsteady flow file has not changed the model performance enough to evoke the need for a study to recalibrate the model. Such a study could collect the data necessary to evaluate if a better model fit, in either case, is the result of an overcompensation error (e.g. tuning a manning's n to compensate for a lack of flow volume) or a physical process.

Unfortunately, the benefits of increasing the number of flow nodes between IFD and LOW cannot be addressed here because there are only two independent gauges where long term water level data are available (i.e. Rainy River and Manitou Rapids). However if one discounts other potential sources of model system behaviour, the new model fit should improve with distance downstream if the timing of flows from the confluent tributaries is expressed in more detail in the model.

2.4.4.1 Validation for the Rainy River at Manitou Rapids

For Manitou Rapids, the predicted stage hydrographs for the original model (Figure 2.19a) and flow revised model (Figure 2.19b) are quite similar to the observed water levels. Both model run results were similar to each other but the revised model tended to: a) predict some of the largest peaks more accurately (Figure 2.20b, Water levels exceeding 329 m) and b) predict mid-range stages less accurately. Figure 2.20 shows the one-to-one plot of predicted versus observed values for the Manitou Rapids simulations. The accuracy of the prediction increases as the slope approaches a value of one, and the intercept approaches a value of zero.

Model fit statistics are provided in Table 2.15 for Manitou Rapids. The fit statistics suggest that there is only a small difference in accuracy between the original model and revised model. Some metrics suggest that the fit is marginally better for the revised model (e.g. y intercept and slope). For example, the regression slope of the predicted versus observed water levels is slightly closer to one suggesting a marginal improvement in model fit. The y intercept is also closer to zero suggesting a slightly better model fit. Other fit statistics suggest the fit is slightly poorer for the revised model (e.g. correlation coefficient and Nash Sutcliffe). The degree of correlation increases as the adjusted correlation coefficient (R_{Adj}^2) approaches a value of one. However, a high correlation coefficient can be misleading as the predicted and observed values can be highly correlated but be significantly offset from the one-to-one line. Consequently, the Nash Sutcliffe value was included to provide a measure of similarity of fit. The closer the Nash Sutcliffe index is to one, the more similar the fit between predicted and observed values. If the Nash Sutcliffe index is less than 0.5 then an average value would predict the observed water level better than the HEC-RAS model. The Nash Sutcliffe values are high for both model runs. However, the original model had slightly higher values for most months. The Nash Sutcliffe values were lowest during months when the following processes occur: freeze up (Nov-Dec), break up (Feb-March), and convective

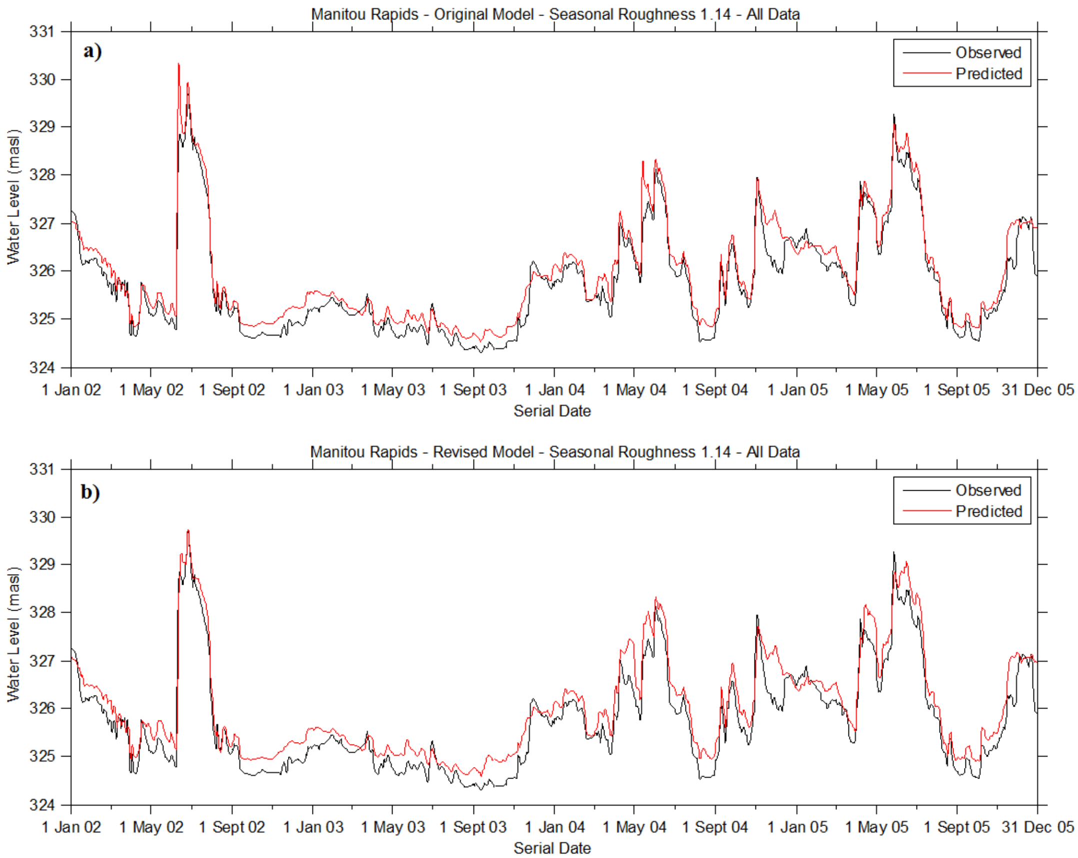


Figure 2.19 Predicted and observed stage at Manitou rapids for a) the original HEC-RAS model and b) the revised model (i.e. original HEC-RAS model with revised unsteady flow file).

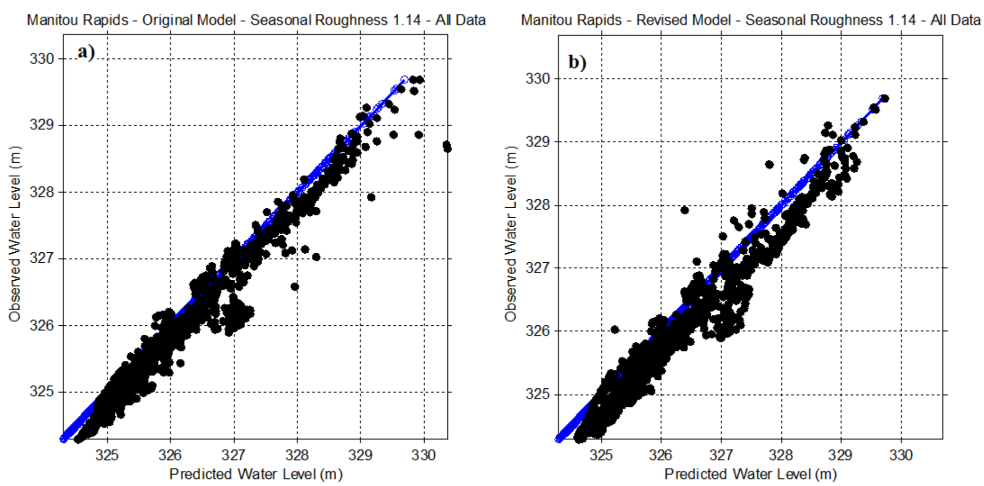


Figure 2.20 One-to-one plots showing predicted and observed stage at Manitou rapids for a) the original HEC-RAS model and b) the revised model (i.e. original HEC-RAS model with revised unsteady flow file). The Manning's *n* in the channel is 0.05 and 0.085 above the bank station elevations of 327.48 and 327.98 m. The lowest elevation in the channel cross section is 320.34 m.

Table 2.15 Model fit statistics for predicted versus observed river stage at the Manitou Rapids for the original HEC-RAS model, and the revised model (i.e. original HEC-RAS model with revised unsteady flow file).

Data	Original y-intcpt	slope	R_{Adj}^2	SEE	NashS	Revised y-intcpt	slope	R_{Adj}^2	SEE	NashS
All Months	8.0	0.97	0.97	0.20	0.92	6.9	0.98	0.95	0.23	0.88
January	-70.6	1.22	0.91	0.18	0.83	-67.1	1.21	0.90	0.19	0.81
February	47.2	0.85	0.97	0.07	0.72	41.1	0.87	0.97	0.07	0.63
March	74.2	0.77	0.70	0.18	0.38	72.8	0.78	0.70	0.18	0.26
April	-1.5	1.00	0.99	0.11	0.96	33.2	0.90	0.95	0.24	0.82
May	5.0	0.98	0.97	0.21	0.93	-12.7	1.04	0.98	0.18	0.88
June	15.0	0.95	0.98	0.23	0.95	5.5	0.98	0.97	0.29	0.94
July	6.5	0.98	0.99	0.12	0.98	17.3	0.95	0.99	0.14	0.94
August	-38.7	1.12	0.97	0.08	0.77	-18.8	1.06	0.89	0.15	0.59
September	-17.3	1.05	0.99	0.05	0.87	-18.1	1.05	0.98	0.10	0.71
October	-45.0	1.14	0.99	0.05	0.83	-33.1	1.10	0.95	0.12	0.46
November	37.1	0.89	0.90	0.28	0.68	28.9	0.91	0.87	0.32	0.59
December	8.9	0.97	0.79	0.34	0.68	17.0	0.95	0.77	0.35	0.63

storm fronts (fall). Ice forms at Manitou Rapids before 12 Nov or persists past 16th March only 10% of the time. Median freeze up and break up dates are 13 Dec and 11 Feb, respectively.

Some model runs were executed to examine the sensitivity of the model to variations in the seasonal roughness values, and in the Manning's *n* roughness values. The Nash Sutcliffe value for the revised model case increases from 0.88 to 0.94 when the Manning's *n* was varied with depth using the Limerinos (1970) equation.

2.4.4.2 Validation for the Rainy River at the Town of Rainy River

The predicted stage hydrograph for the original model mimics the pattern of the observed stage hydrograph (Figure 2.21a). However, the predicted stage hydrograph is consistently higher than observed (Figure 2.21a). The predicted stage hydrograph for the revised model (Figure 2.21b) more closely represents the observed stage hydrograph (Figure 2.21b). The model fit statistics for the original and revised model are very similar with the exception of the Nash Sutcliffe values, which reflect the higher degree of similarity between the revised model stages and observed stages shown in Figure 2.22. Again, the fit was poorest during the break up period (March) and winter period as indicated by low Nash Sutcliffe index values (Table 2.16). However, the Nash Sutcliffe values were high in the fall, unlike those for Manitou Rapids.

The floodplain roughness appears to be too high for stages greater than 323.55 m (Figure 2.22b). This may indicate a reduction of roughness with flow depth on the floodplain typical for inundation of a young tree case (Soong and Hoffman, 2002 – see Young trees case - Equation (31)).

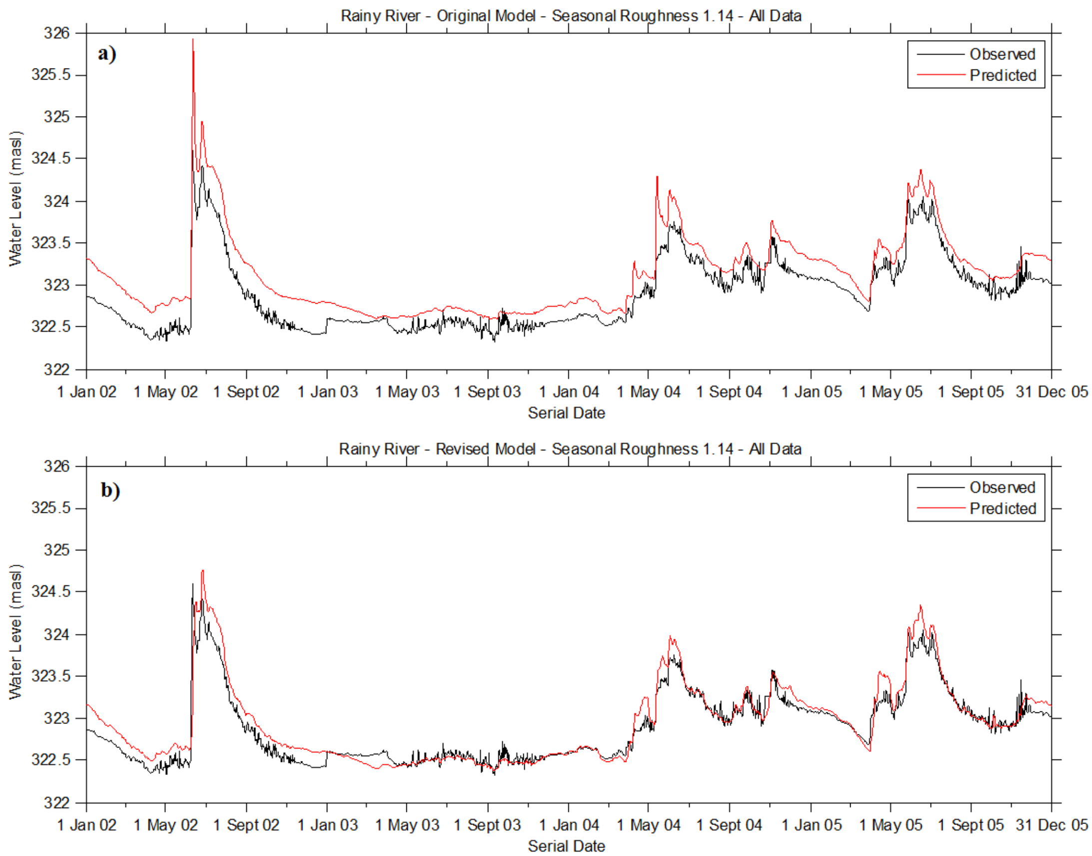


Figure 2.21 Predicted and observed stage at the town of Rainy River for a) the original HEC-RAS model and b) the revised model (i.e. original HEC-RAS model with revised unsteady flow file).

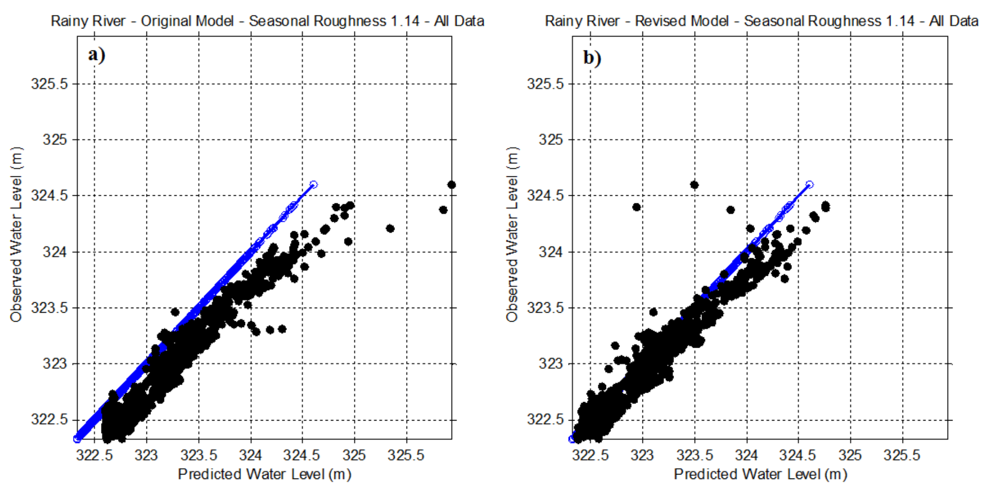


Figure 2.22 One-to-one plots showing predicted and observed stage the Town of Rainy River for a) the original HEC-RAS model and b) the revised model (i.e. original HEC-RAS model with revised unsteady flow file). The Manning's *n* in the channel is 0.035 and 0.085 above the bank station elevations of 321.87 and 323.20 m. The lowest elevation in the channel cross section is 315.68 m. The floodplain roughness appears to be too high for stages greater than 323.55 m.

Table 2.16 Model fit statistics for predicted versus observed river stage at the Town of Rainy River for the original HEC-RAS model, and the revised model (i.e. original HEC-RAS model with revised unsteady flow file).

	Original					Revised				
Data	y-intcpt	slope	R_{Adj}^2	SEE	NashS	y-intcpt	slope	R_{Adj}^2	SEE	NashS
All Months	41.5	0.87	0.94	0.11	0.60	46.3	0.86	0.93	0.12	0.88
January	81.2	0.75	0.85	0.07	-0.93	89.1	0.72	0.83	0.08	0.57
February	79.6	0.75	0.83	0.07	-0.85	85.9	0.73	0.82	0.07	0.68
March	132.6	0.59	0.46	0.09	-1.73	144.0	0.55	0.45	0.09	0.11
April	11.6	0.96	0.91	0.10	0.39	82.3	0.74	0.87	0.11	0.66
May	37.9	0.88	0.91	0.13	0.53	26.9	0.92	0.96	0.09	0.90
June	59.8	0.81	0.95	0.15	0.65	54.8	0.83	0.89	0.22	0.82
July	49.2	0.85	0.98	0.08	0.72	63.9	0.80	0.98	0.07	0.89
August	48.0	0.85	0.91	0.09	0.33	51.1	0.84	0.92	0.08	0.88
September	39.6	0.88	0.85	0.10	0.08	44.0	0.86	0.87	0.09	0.83
October	-34.7	1.11	0.84	0.11	0.30	-21.0	1.07	0.86	0.10	0.86
November	11.3	0.96	0.92	0.11	0.44	19.1	0.94	0.92	0.10	0.88
December	0.9	1.00	0.95	0.07	0.14	15.5	0.95	0.95	0.07	0.84

2.4.4.3 Conclusions

The original HEC-RAS model parameterization was relatively robust to the changes made in the hydrology file. The new model fit is reasonable and does not warrant a total recalibration of the model for this study. Potential refinements to the model to further improve the fit were identified and reccomendations for future studies are provided in Section 6.3.

SECTION 3. CHANGES IN THE HYDROLOGIC REGIME AT IFD

3.1 Historical trends in discharge variability

Discharge data for Fort Frances are show in Figure 3.1 for the period between 1905 and 2010 while discharge for the 1970-2010 period is shown in Figure 3.2. St. George (2007) demonstrated how long term flow patterns in the Winnipeg River system can be driven by oscillations in Ocean temperatures. The Atlantic Multi-decadal Oscillation (AMO) index is also shown in Figure 3.1. A positive AMO value indicates that Atlantic Ocean temperatures are warmer than average. Fluctuations in the Atlantic and Pacific Oscillation cycles affect the annual frequency and intensity of cyclonic storms and snow pack build up in the study area. The discharge records show periods with more extreme events, that are approximately 30-40 years in duration, interspersed with more moderated hydrologic periods. These cycles roughly correspond with oscillations in ocean temperatures. This nonstationarity in climate and runoff response signals must be accounted for when comparing hydrologic periods. Unfortunately, the post- and pre- periods are not bounded within either a negative or positive AMO cycle to help standardize post- and pre- period comparisons. The pre-period covers both approximately 75% of a negative AMO cycle, and the start of the positive AMO cycle. The post- period only encompasses approximately 25% of the positive AMO cycle. These results suggest that the pre-2000 rule curve period should be divided into three decades when detecting differences in discharge and climate to account for nonstationarity. We later address this nonstationarity using classification and regression trees in Section 3.2.1 and using multivariate adaptive regression splines in Section 3.3.

The most extreme discharge events occurred in the current positive phase of the AMO (i.e. after 1995). There were only four years with discharges exceeding 1000 m^3/s at IFD. These discharges in order of highest to lowest occurred in 2002, 2001, 2008 and 1996, respectively. The post-period also had a lower minimum discharge, relative to the pre-period (Table 3.1). The mean annual discharge was also lower in the post-period suggesting a lower overall water yield in this period despite the presence of more extreme flood events.

Table 3.1 Summary statistics of discharge for the pre- and post- rule curve periods.

Period	Min Q Observed (m^3/s)	Mean Q Observed (m^3/s)	Max Q Observed (m^3/s)
Pre-	50.3	297.4	992
Post-	35.3	280.76	1190

3.2 Temporal Changes in Indices of Hydrologic Alteration

The Indices of Hydrologic Alteration (IHA) software package (IHA version 7.1) developed by the Nature Conservancy (Richter et al., 1996) was used to calculate 33 IHA parameters and 34 Environmental Flow Component (EFC) parameters using the observed and simulated flow series. The five different groups of IHAs are: 1) magnitude of monthly water conditions (mean monthly flows); 2) magnitude and duration of annual extreme water conditions; 3) timing of annual extreme water conditions; 4) frequency and duration

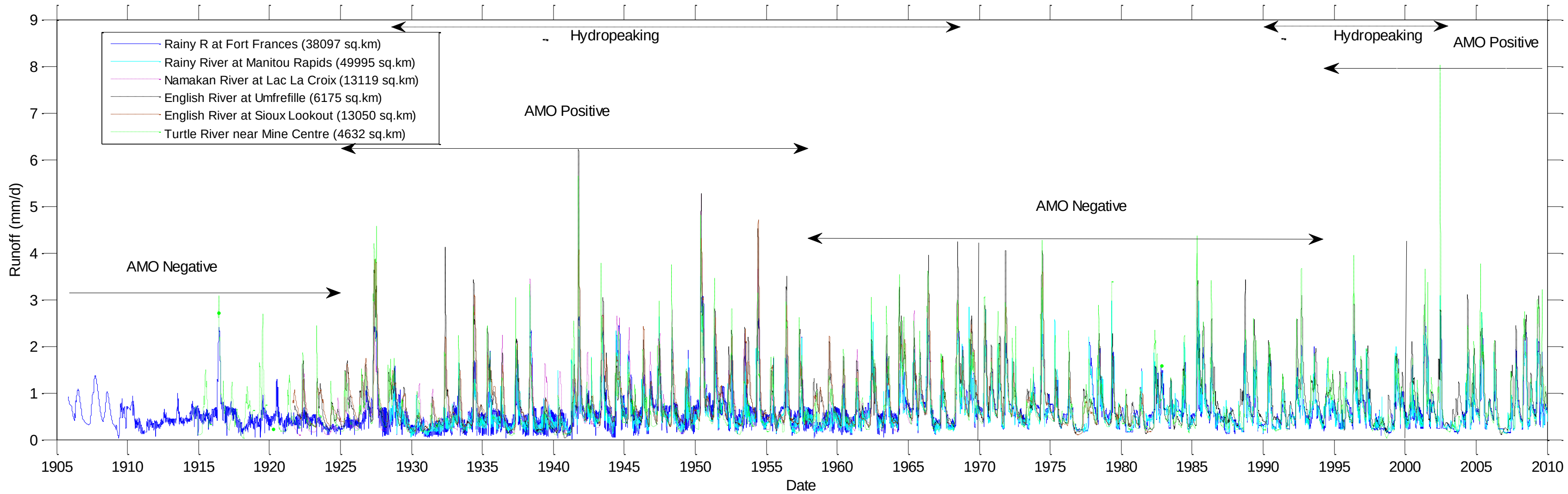


Figure 3.1 Runoff of the Rainy River (Fort Frances & Manitou Rapids) and three Reference 1 rivers (Turtle River, Namakan River, English River) for the period 1905-2010.

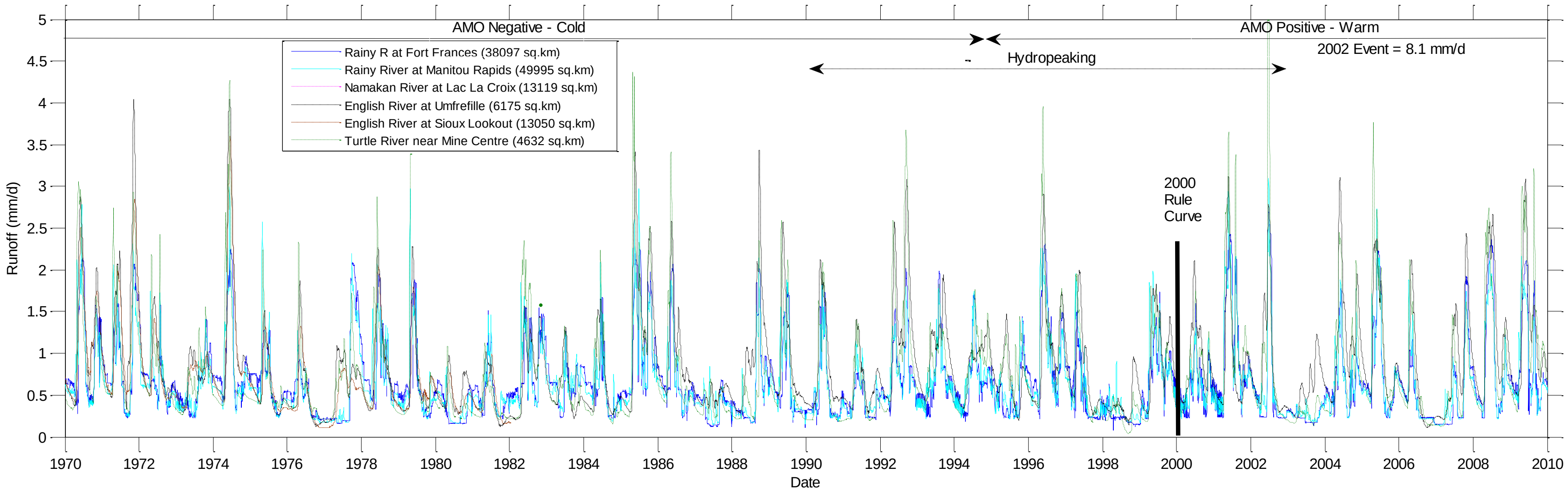


Figure 3.2 Runoff of the Rainy River (Fort Frances & Manitou Rapids) and three Reference 1 rivers for the period 1970 to 2010. There appears to be a high degree of correspondence of the event peaks between the three sites

of high and low pulses; and 5) the rate and frequency of water condition changes. The five different types of EFCs are: 1) low flows; 2) extreme low flows; 3) high flow pulses; 4) small floods; and 5) large floods.

The IHA software also implements the Range of Variability Approach (RVA) described in Richter et al. (1997) for the IHA parameter set. The RVA analysis uses the "pre-development" natural variation of IHA parameter values as a reference for defining the extent to which natural flow regimes have been altered. Application of the RVA method for our pre- to post-2000 data is problematic because: 1) Steps or trends in hydrologic variables do not always occur at the reference point of interest (e.g. 2000 rule curve change) (Sun & Feng, 2012), and 2) At least 20 years of data are required in both the pre- to post-periods (here only a decade is available in the post-2000 period). Even longer observation periods are required for the comparison of extreme event related metrics (Nature Conservancy, 2009). Consequently, we supplemented the RVA analysis with methods that are less sensitive to sample size. Specifically, we analyzed long term changes in IHA parameter values using linear regression for the entire 40 year period (Section 3.3.1). We then used classification and regression trees to investigate if dates for flow regime shifts can be detected to see if these threshold dates are coincident with the year 2000 (Section 3.3.2). These exploratory analyses provided context for the RVA analysis of the pre- to post-2000 period provided in Section 3.4.

3.2.1 Identifying trends in hydrologic alteration metrics using linear regression.

3.2.1.1 Methods- IHA

To evaluate the long term temporal trends in flow regime metrics, the IHA software was used to compute linear regressions of the dependent variable (each IHA index) versus the independent variable (year). The regression slope indicates if the IHA index is decreasing (negative slope) or increasing (positive slope) with time. The *p* value indicates the degree of statistical significance. We report trends that were statistically significant at p=0.05. Unfortunately, the Durbin-Watson statistic is not provided in the IHA software to evaluate the degree of autocorrelation in the residuals resulting from nonstationarity. Consequently, the *p* values may be optimistic in cases where non-stationarity exists in the data.

3.2.1.2 Results - IHA

Table 3.2 shows linear trends in IHA (Group 1 & 2) flow metrics over the 1970 to 2010 period at IFD for the observed series, and simulated State of Nature series. State of Nature series are shown for simulation methods one, two and six (Section 3.2). Only the significant trends are reported. For the observed IFD series, there is a long term linear decrease in *mean monthly flows* in February and March, and in the *three day minimum flows*. These negative trends were not detected in the State of Nature flows that reflect current basin characteristics (Methods 1 & 2). Figure 3.3 shows the significant negative trends for February monthly flows, March monthly flows, and three day minimum flows. There are three distinct periods evident for the *three day minimum flows* between the years 1987 and 1997.

The long term linear trends in IHA (Groups 3 to 5) flow metrics are shown in Table 3.3. For the observed IFD series there was a long term increase in the *low pulse count* and *extreme low frequency*. There was a decrease in the *low flows* for February, March and April, and for the *high flow peak* metric. No long term

Table 3.2 Linear temporal trends in IHA Group 1& 2 metrics for the 1970 – 2010 period. The regression slopes of flow metric versus time are reported below if the trend was significant at *p*<=0.05.

	Observed (Slope)	**Method 1 (Slope)**	**Method 2 (Slope)**	**Method 3d (Slope)**
Group 1 - Magnitude of monthly water conditions (mean monthly flows)				
January	-	-	-	3.5
February	-2.3	-	-	2.8
March	-2.5	-	-	2.4
April	-	-	-	2.8
May	-	-	-	4.7
June	-	-	-	9.8
July	-	-	-	9.6
August	-	-	-	8.3
September	-	-	-	7.7
October	-	-	-	7.1
November	-	-	-	6.1
December	-	-	-	4.6
Group 2 - Magnitude and duration of annual extreme water conditions				
1-day minimum	-	-	-	2.5
3-day minimum	-0.8	-	-	2.5
7-day minimum	-	-	-	2.5
30-day minimum	-	-	-	2.6
90-day minimum	-	-	-	2.7
1-day maximum	-	-	-	16.3
3-day maximum	-	-	-	16.0
7-day maximum	-	-	-	15.2
30-day maximum	-	-	-	11.6
90-day maximum	-	-	-	9.6
Number of zero days	-	-	-	-
Base flow index	-	-	-	-

trends were found in the State of Nature flow simulations that reflect current basin (but unaltered) conditions (Methods 1 & 2). The metrics with significant long term trends are show in Figure 3.4. Again, a nonlinear, threshold-type pattern is evident for some IHA metrics for the period (e.g. *low pulse count*, *monthly flows for April*). The date of change is not generally coincident with the 2000 rule curve amendment.

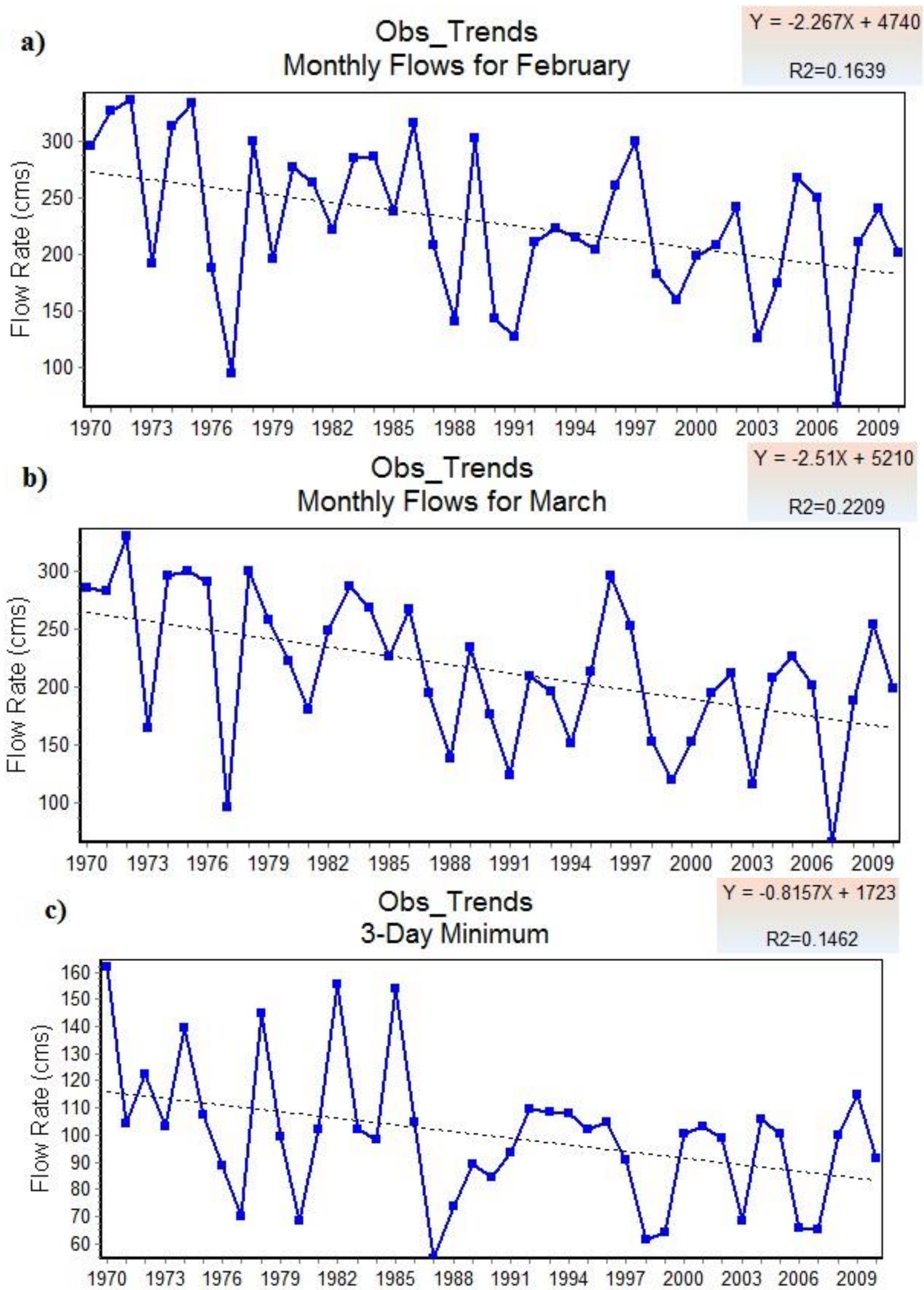


Figure 3.3 Significant negative trends in observed flows at Fort Frances/International falls for the 1970-2010 period for a) February monthly flows, b) March monthly flows, and c) three day minimum.

Table 3.3 Trends in IHA Group 3 - 5 metrics over the 1970 – 2010 period. The regression slopes of flow metric versus time are provided below if the trend was significant at *p*<=0.05.

	Observed (Slope)	Method 1 (Slope)	Method 2 (Slope)	Method 3d (Slope)
Group 3 - Timing of annual extreme water conditions				
Date of minimum	-	-	-	-
Date of maximum	-	-	-	-
Group 4 - Frequency and duration of high and low pulses				
Low pulse count	0.1	-	-	-
Low pulse duration	-	-	-	-2.6
High pulse count	-	-	-	-
High pulse duration	-	-	-	2.6
Group 5 - Rate and frequency of water condition changes				
Rise rate	-	-	-	-
Fall rate	-	-	-	0.0
Number of reversals	-	-	-	-
Environmental Flow Components				
1. Low Flows				
January Low Flow	-	-	-	2.9
February Low Flow	-2.2	-	-	2.0
March Low Flow	-2.5	-	-	1.6
April Low Flow	-2.0	-	-	1.8
May Low Flow	-	-	-	3.5
June Low Flow	-	-	-	4.2
July Low Flow	-	-	-	-
August Low Flow	-	-	-	-
September Low Flow	-	-	-	-
October Low Flow	-	-	-	-
November Low Flow	-	-	-	-
December Low Flow	-	-	-	3.8
2. Extreme Low Flows				
Extreme low peak	-	-	-	-
Extreme low duration	-	-	-	-
Extreme low timing	-	-	-	-
Extreme low freq.	0.2	-	-	0.0
3. High Flows				
High flow peak	-3.8	-	-	-
High flow duration	-	-	-	-
High flow timing	-	-	-	-1.7
High flow frequency	-	-	-	-
High flow rise rate	-	-	-	-
High flow fall rate	-	-	-	-
4. Small Flood				
Small Flood peak	-	-	-	-
Small Flood duration	-	-	-	-
Small Flood timing	-	-	-	-
Small Flood freq.	-	-	-	0.0
Small Flood rise rate	-	-	-	-0.9
Small Flood fall rate	-	-	-	-
5. Large Flood				
Large flood peak	-	-	-	47.5
Large flood duration	-	-	-	-
Large flood timing	-	-	-	-
Large flood freq.	-	-	-	-
Large flood rise rate	-	-	-	-
Large flood fall rate	-	-	-	-0.7

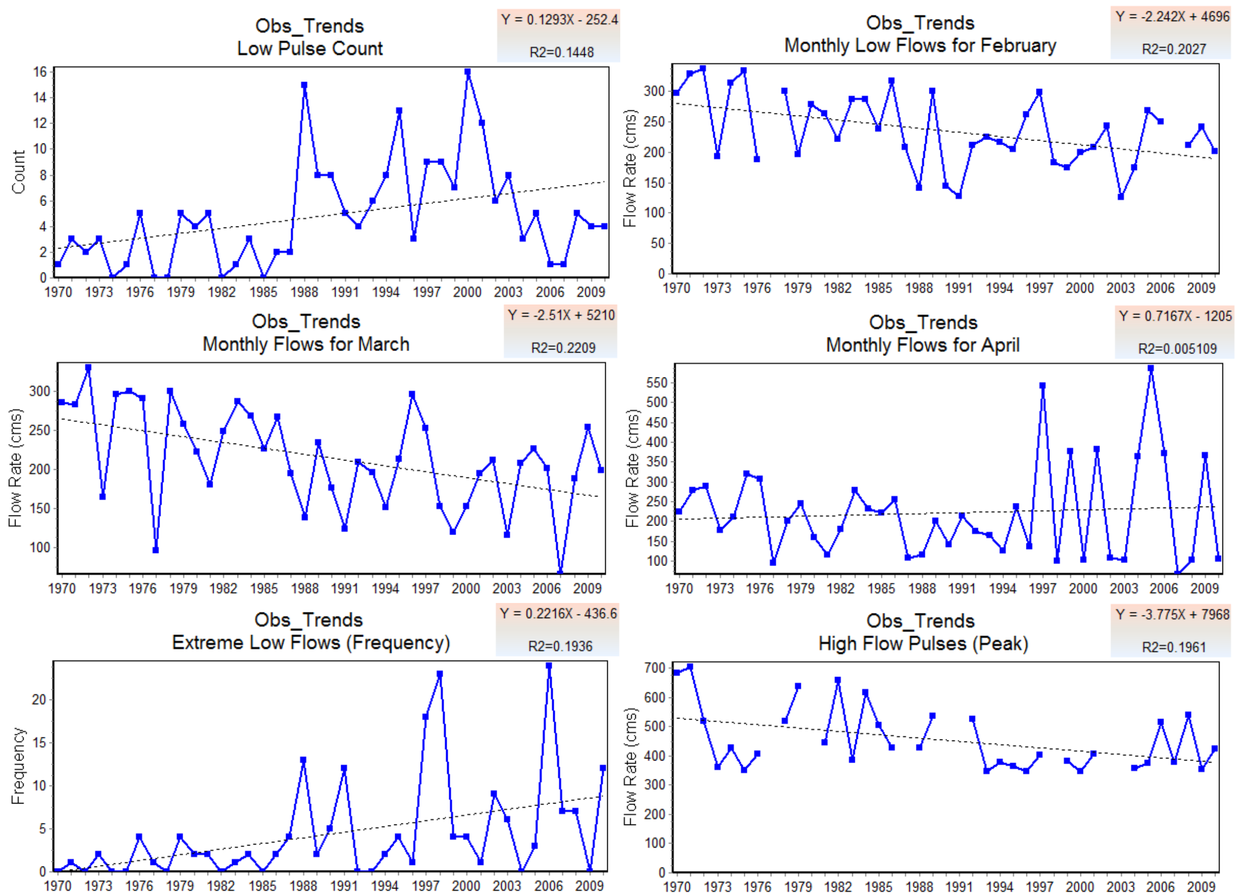


Figure 3.4 Significant trends in observed flows at Fort Frances/International Falls for the 1970-2010 period for the six flow metrics from Table 3.3 with significant trends. Note that changes in the pattern of these flow metrics occur at different dates (cf. Low Pulse Count - upper left vs. Monthly Flows for April- middle right).

3.2.2 Flow duration curve comparisons between periods and reference basins

Flow duration curves show the proportion of time a flow value is equalled or exceeded and, by incorporating the complete range of river flows, provides the most informative summary of a flow regime (Searcy, 1959; Vogel and Fennessey, 1995). Flow duration curves were calculated from flow data for the entire pre- and post- periods. The curves were compared for the following scenarios:

1) Pre- vs post- alteration
2) Pre-Observed vs Pre-State of Nature
3) Post-Observed vs Post-State of Nature

For this initial analysis the State of Nature curves are prorated using the area ratio method.

3.2.2.1 Flow durations during pre- and post- alteration at IFD.

Differences were observed in the flow duration curves for the two periods. The FDCs for the three pre-period decades were plotted to show the range of variability for that period. An envelope of expected variability of discharge for the pre-period can be defined between the upper maximum FDC and lower minimum FDC of the three decades in the pre-period. The post-period FDC plots outside this pre-period envelope for the following percent exceedance flows (Figure 3.5):

1) 0% to 8 % – After 2000, higher flows were of greater magnitude
2) 45% to 90% - After 2000, low flows were of lesser magnitude

Thus, a greater percentage of time in the post-2000 rule curve period was spent at very low and very high flows. Given these more extreme conditions, the post- FDC curve strongly reflects the rule curve release targets. For example,

- Higher flows (0% to 8 % exceedance) were of greater magnitude in the post-period for flows in excess of the maximum turbine capacity of the IFD facilities.
- The inflection point in the post-period FDC curve at 17% exceedance corresponds with the maximum turbine capacity of the Canadian generation station.
- Flows were near the 100 m^3s^{-1} spill rate longer in the post- period (17% of the time), versus the pre- period (5% of the time), indicating the persistence of low Rainy Lake water levels.
- Flows persisted at the drought release discharge rate (65 m^3s^{-1}) for longer in the post- period, maintaining flow rates higher than during the drought in the 1980's, but generally lower than other pre- period decades.

Flows between the maximum capacity of the U.S. station (240 m^3s^{-1}) and the Canadian station (354 m^3s^{-1}) occurred with the same frequently between periods.

3.2.2.2 Flow durations between the observed flows at IFD and local, unregulated reference rivers for the pre-rule curve period.

Differences were observed in the flow duration curves for the observed flows at IFD and the reference rivers for the following percent exceedance flows (Figure 3.6):

1) 0% to 3.5 % – Observed curve plots **lower** than the reference river curve envelope;
2) 41% to 74% - Observed curve plots **higher** than the reference river curve envelope; and
3) 99%-100% - Observed curve plots **higher** than the reference river curve envelope

Thus, during the 1970-2000 rule curve period, the Rainy River at IFD had lower extreme high flows, and higher extreme low flows, relative to the reference rivers. Discharges also occurred at a higher frequency for mid-bank to bankfull flows at IFD, relative to the reference rivers. These differences in flow pattern from the natural rivers are typical for a regulated river.

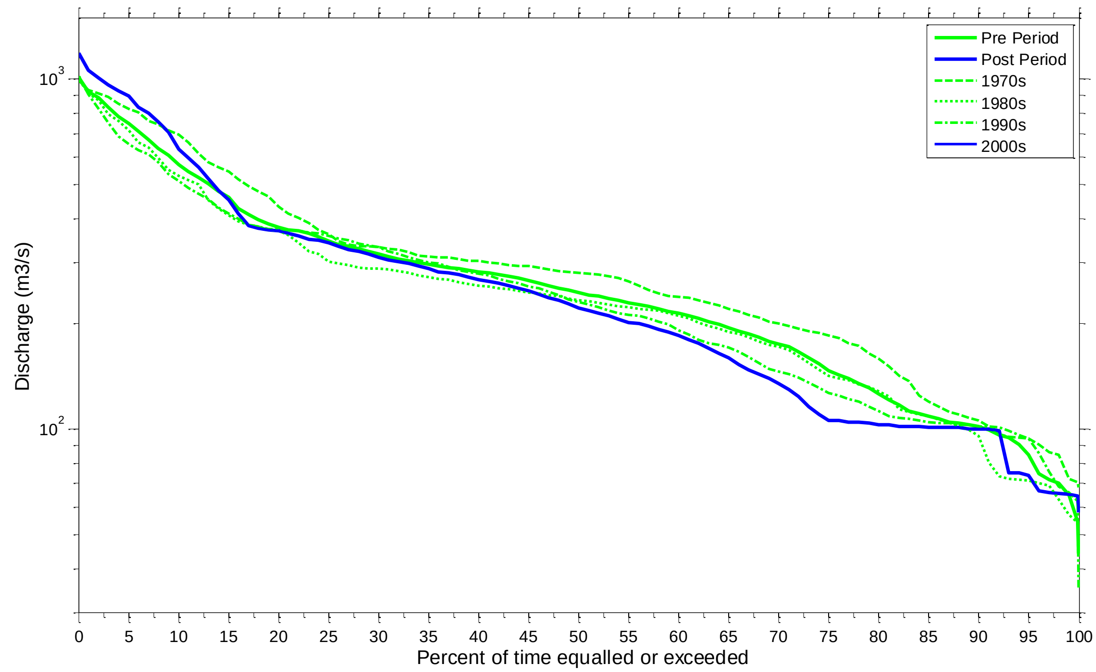


Figure 3.5 Flow duration curves for the Rainy River at Fort Frances for the pre- and post-periods and each decade.

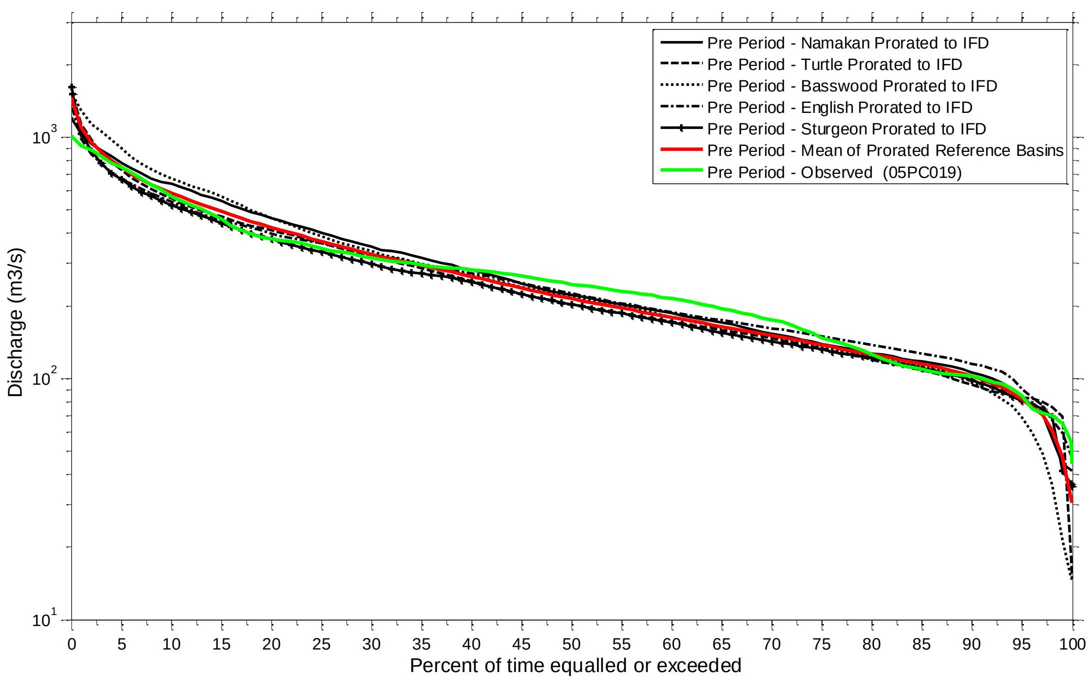


Figure 3.6 Flow duration curves for the pre-period for Fort Frances and for five reference basins prorated to IFD.

3.2.2.3 Flow durations between the observed flows at IFD and local, unregulated reference rivers for the post-rule curve period.

The observed FDC is contained within the envelope defined by the highest and lowest reference river FDC's (Figure 3.7). The extreme low flows at IFD were maintained for a longer duration, relative to the reference river mean FDC. The shape of the FDC curve for IFD is more angular, reflecting the flow management targets as explained in Section 3.2.2.1, relative to the FDC shape of unregulated rivers. These rivers have smoother FDCs, reflecting the dominance of random hydrologic processes, and absence of flow regulation.

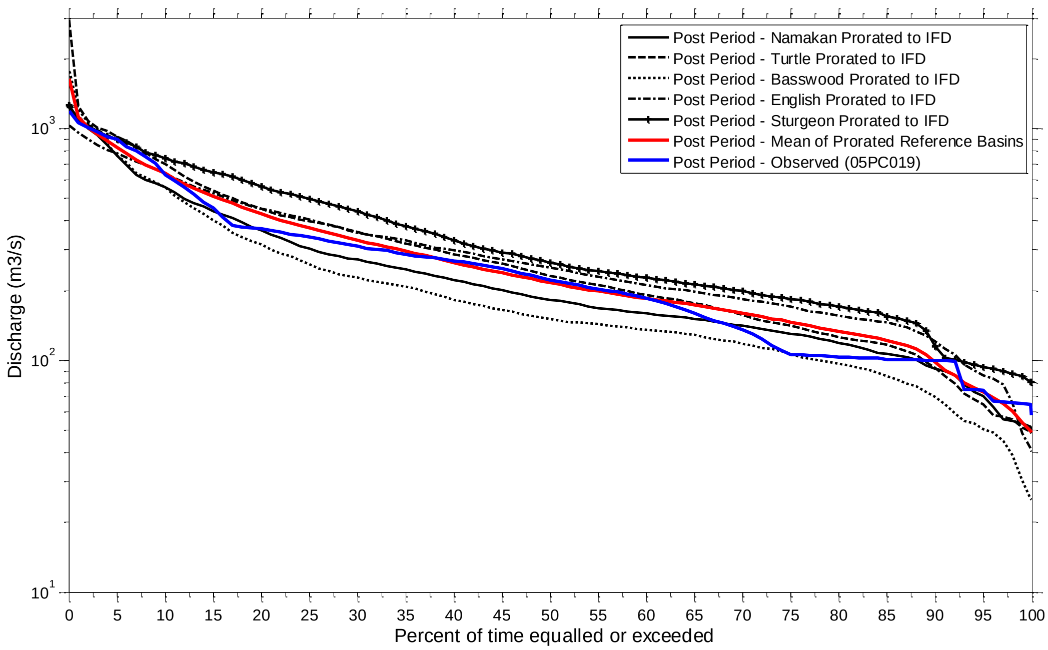


Figure 3.7 Flow duration curves for the post-period for Fort Frances and for five reference basins prorated to IFD.

3.2.2.4 Post-to-pre comparisons and period of record length.

The pre- and post- reference periods vary in length of discharge records (pre=30 years, post=10 years). Extreme events are more likely to appear in longer records (Booker and Snelder, 2012). If extreme events are excluded from the FDC calculation, then the FDC will have a lower slope. Further, regional differences in the occurrence of large events are more likely with shorter records. This would result in there being a larger range of variability in FDCs between reference basins.

There is a larger variability in reference river FDCs in the post- period (Figure 3.7), relative to the pre-period (Figure 3.6), as seen in the wider envelope defined by the maximum and minimum reference river FDCs. This effect may be partially due to the difference in record length between the two periods. As discussed in Section 3.1, there was also an increase in extreme events late in the pre- period (1995), and throughout the post- period. The post- FDC curve more strongly reflects the rule curve release targets, where plateaus in the FDC are evident, indicating water levels were held at target rates for longer periods of time (Section 3.2.2.1). Again, the more stepped appearance of the FDC can result from both a reduced period length and management response to the presence of more extreme conditions during this post-period. Regardless of the cause, there was a higher range of variability in the reference river FDCs in the post- period, which also enveloped the range in flow behavior reflected in the FDC at IDF.

3.2.3 Monthly flow duration curve comparisons between periods

To elucidate the differences observed in the period of record FDCs discussed above, the IHA software was used to calculate monthly flow duration curves for:

1) Pre-and post-2000 periods using observed IFD flows; and
2) 1970-2010 period using simulated State of Nature flows (Method 1).

The monthly flow duration curves for the pre- and post-2000 rule curve periods for the observed discharge series at Fort Frances are shown in Figure 3.8. Key outflow rates for the 2000 rule curve (i.e. drought line discharge, low flow discharge and maximum turbine capacity discharge) have also been plotted. The post-2000 flow duration curves are more stepped in appearance, relative to the pre-2000 FDCs and State of Nature FDCs. This is caused by a greater proportion of time spent at specific discharges, some of which are coincident with regulatory requirements or technological constraints related to dam operation (e.g. drought release rate, low flow release rate, and maximum turbine capacity outflow rate). For example, 50% of the time in the post-period in April was spent at or below the low flow release rate compared to only 8% of the time in the pre-period. In many months, more time was spent at the low flow release rate in the post-period. There was also more time spent at or above maximum capacity implying higher volumes of water spilled in the post-period.

It is not clear from the FDC comparison plots for the observed and SON case (Figure 3.8) if the changes in the monthly flow pattern represented in the FDC's are regulation or climate related. For example, conformance with the SON rule curve can result from a combination of the climate and management regime during each period. In general, the post -2000 rule curve period was closer to the SON case for November through May and July. Under the post-2000 rule curve regulation regime, agreement between altered FDC and State of Nature FDC also improved in May and June for high magnitude flows. These changes may have positive effects on fall spawning fish egg survival and ecological processes associated with the spring freshet.

3.2.4 Range of variability analysis

The IHA software includes the Range of Variability Approach (RVA) described in Richter et al. (1997) for the IHA parameter set. The RVA analysis uses the "pre-development" natural variation of IHA parameter values as a reference for defining the extent to which natural flow regimes have been altered. The "pre-impact" period is typically the pre-dam case. For the Rainy River, the pre-dam State of Nature flow series has a great deal of uncertainty associated with the simulation due to the short calibration/validation period, and intermittent data collection during the 1905-1908 pre-dam period. Furthermore, the large changes in land and water use since the early 1900's make it more realistic to use a

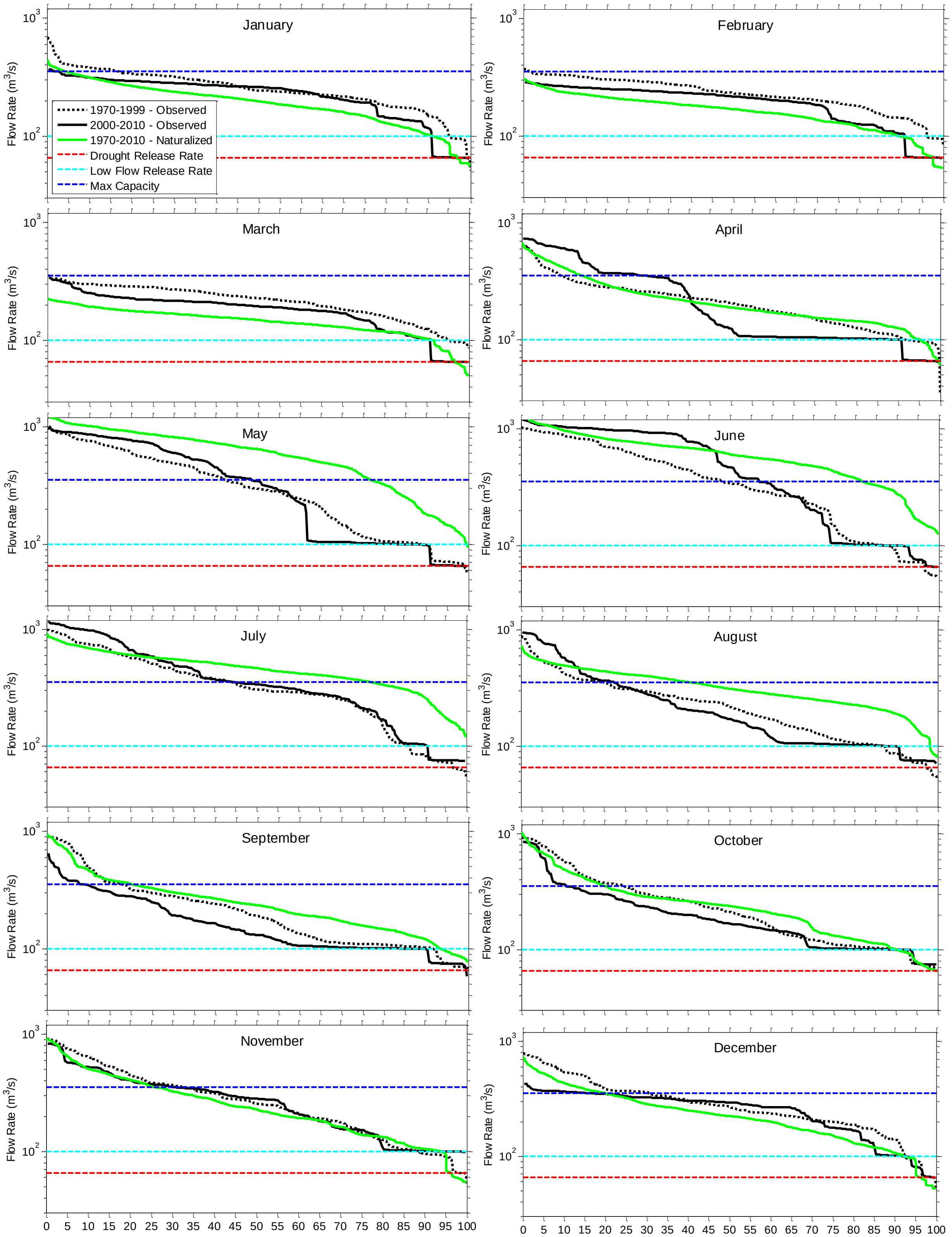


Figure 3.8 Monthly flow duration curves for Rainy River pre- and post-2000 rule curve periods.

contemporary watershed condition as a reference. Specifically, the State of Nature series should represent current day runoff conditions at IFD if the system was not altered.

The primary interest in this study is the effect of the rule curve change on the flow regime and thus the pre- to post-2000 comparison of the observed flow series. However, to gauge whether the changes also occur in unaltered systems, a contemporary State of Nature reference case was also considered. This case provides the reference from which to measure magnitude and direction of individual and cumulative effects. The pre-dam State of Nature case is also included to provide context but should be interpreted with caution.

RVA values were calculated for the pre-to post-2000 period for the following cases (Table 3.4):

1) Pre:Post 2000 rule curve using observed flows
2) Pre:Post 2000 rule curve using simulated State of Nature flows (Method 1)
3) Pre-2000 simulated State of Nature flows (Method 1): Pre-2000 rule curve using observed flows
4) Pre-2000 simulated State of Nature flows (Method 1): Post-2000 rule curve using observed flows

The range of variability in an IHA flow metric in the pre-period was divided into three categories, divided by the 34th and 67th percentile: Low, Medium and High. Each category contains 33% of the observations, corresponding to the low, mid and high range of values. A hydrologic alteration factor was calculated for each of the three categories as:

$$\text{(observed frequency – expected frequency) / expected frequency} \qquad (3.1)$$

The observed frequency is the number of observations in a category (e.g. Low) standardized by the number of years of observation in the pre-period. The expected frequency is calculated by multiplying the number of observations per year for the pre-period, times the number of years in the post-period. When Equation (3.1) yields a positive RVA value, the frequency of values in the category has increased from the pre- to the post- period (with a maximum RVA of infinity), while a negative value means that the frequency of values has decreased (with a minimum RVA of -1).

The median monthly observed flows for the pre- and post-2000 periods are shown in Figure 3.9. The monthly median flows are outside the expected range of variability (RVA) represented by the vertical bars, relative to the 1970-1999 reference period, in April and June.

3.2.4.1 Case 1 and 2 Comparison: State of Nature to Observed flows by Post to Pre

The degree of hydrologic alteration in metric values for extreme flows (min, max) for the observed series and State of Nature series (Method 1) at IFD is shown in Figure 3.10. The pre- and post- periods are divided by the year 2000. Thus, Figure 3.10 shows the RVA indices that were calculated for the

Table 3.4. Results of the RVA analysis.

	Rainy River @ Fort Frances Pre:Post 2000 Rule Curve (Obs)			Rainy River @ Fort Frances Pre:Post 2000 Control (Spatial Int.)			Rainy River @ Fort Frances Pre:Post 2000 Pre-Dam (HBV)			Rainy River @ Fort Frances SptlInterp Pre: Obs Pre			Rainy River @ Fort Frances SptlInterp Pre: Obs Post		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Parameter Group #1.															
January	0.09	-1.00	0.91	-0.45	0.36	0.09	-0.73	-0.73	1.46	0.91	0.91	-0.45	-0.70	1.00	-0.30
February	0.36	-1.00	0.64	-0.45	0.36	0.09	-0.73	-0.73	1.46	1.18	1.18	-0.73	-0.80	1.20	-0.40
March	0.36	-1.00	0.64	-0.45	-0.18	0.64	-0.73	-0.18	0.91	1.18	1.18	-0.73	-0.80	1.40	-0.60
April	0.64	0.36	-1.00	-0.18	0.64	-0.45	-1.00	0.09	0.91	0.36	0.36	-1.00	-0.10	0.50	-0.40
May	0.09	0.36	-0.45	-0.18	0.36	-0.18	-1.00	-0.45	1.46	-0.45	-0.45	-0.18	1.20	-0.70	-0.50
June	0.09	0.64	-0.73	-0.45	0.64	-0.18	-1.00	-0.73	1.73	0.36	0.36	-0.73	0.90	-0.40	-0.50
July	-0.45	0.09	0.36	-0.45	0.09	0.36	-1.00	-0.18	1.18	-0.45	-0.45	-0.18	0.70	-0.40	-0.30
August	0.09	-0.18	0.09	-0.73	0.36	0.36	-1.00	-0.18	1.18	-0.73	-0.73	-0.45	0.70	-0.60	-0.10
September	0.36	-0.45	0.09	0.09	0.09	-0.18	-1.00	-0.18	1.18	-0.73	-0.73	-0.18	0.40	-0.10	-0.30
October	-0.18	-0.45	0.64	-0.18	-0.73	0.91	-0.73	-0.73	1.46	-0.73	-0.73	0.64	0.10	-0.20	0.10
November	0.09	0.09	-0.18	-0.18	-0.18	0.36	-0.73	-0.73	1.46	0.09	0.09	-0.18	-0.20	0.10	0.10
December	-0.18	-0.73	0.91	-0.45	0.36	0.09	-0.73	-0.45	1.18	1.18	1.18	-0.73	-0.70	0.40	0.30
Parameter Group #2															
1-day minimum	0.09	0.09	-0.18	0.09	0.09	-0.18	-1.00	0.09	0.91	-1.00	-1.00	0.91	0.60	-0.60	0.00
3-day minimum	0.09	**-0.73**	**0.64**	0.09	0.09	-0.18	-1.00	0.09	0.91	-1.00	-1.00	0.91	0.10	-0.50	0.40
7-day minimum	-0.18	-0.73	0.91	0.09	0.09	-0.18	-1.00	0.09	0.91	-1.00	-1.00	1.18	0.00	-0.40	0.40
30-day minimum	0.36	-0.45	0.09	0.09	0.36	-0.45	-1.00	0.09	0.91	-0.45	-0.45	0.09	0.10	-0.20	0.10
90-day minimum	0.36	0.09	-0.45	0.09	0.09	-0.18	-0.73	-0.45	1.18	0.09	0.09	-0.45	-0.10	0.20	-0.10
1-day maximum	-0.09	0.36	-0.26	-0.18	0.64	-0.45	-1.00	-0.18	1.18	0.09	0.09	-0.18	0.30	-0.70	0.40
3-day maximum	-0.18	0.36	-0.18	-0.45	0.64	-0.18	-1.00	-0.18	1.18	0.09	0.09	-0.18	0.30	-0.70	0.40
7-day maximum	-0.18	0.36	-0.18	-0.45	0.64	-0.18	-1.00	-0.18	1.18	0.09	0.09	-0.18	0.30	-0.60	0.30
30-day maximum	-0.18	0.64	-0.45	-0.45	0.64	-0.18	-1.00	-0.18	1.18	0.36	0.36	-0.45	0.50	-0.40	-0.10
90-day maximum	0.09	0.64	-0.73	-0.45	0.36	0.09	-1.00	-0.18	1.18	0.09	0.09	-0.45	0.90	-0.50	-0.40
Number of zero days	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Base flow index	1.18	-0.45	-0.73	0.09	0.36	-0.45	0.36	-0.18	-0.18	-0.45	-0.45	0.36	-0.50	0.10	0.40

following two comparisons: 1) Pre:Post 2000 rule curve using observed flows, and 2) Pre:Post 2000 rule curve using simulated State of Nature flows. Figure 3.10 shows:

- The highest RVA values are associated with the 3-day min and 7-day min in the observed series but not in the State of Nature series.
- The RVA values associated with maximum flows are similar between the observed and State of Nature flows series.

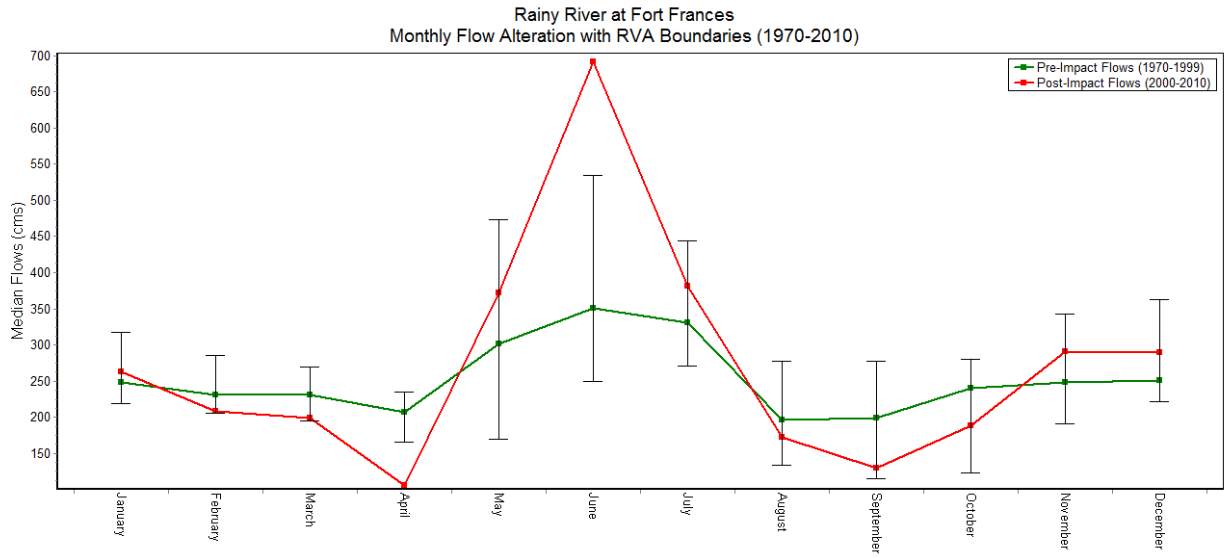


Figure 3.9 Median monthly flows for the pre- and post-2000 periods for the observed flows at IFD.

Figure 3.11 shows the degree of hydrologic alteration in monthly mean flows for the observed series, and State of Nature series (Method 1) at IFD. Again the pre- to post- 2000 rule curve periods are compared. The data in Figure 3.11 show:

- The degree of hydrologic alteration in June is similar between the observed and simulated series for the medium RVA category.
- The degree of hydrologic alteration in August is greater in the State of Nature series than the observed series.
- The degree of hydrologic alteration in September is greater in the observed series than in the State of Nature series.
- The degree of hydrologic alteration is highest in the December through April period, and marginally higher in the observed series.

3.2.4.2 Case 3 and 4 Comparison: State of Nature to Observed by rule curve period

The case 1 and 2 comparisons considered above each have a different pre-period hydrology (e.g. Observed & Simulated). To standardize observations, we compared alterations in the pre- and post-observed period against the variability in the pre-period for the State of Nature series (Method 1). The results of this comparison are shown in Figure 3.12 and suggest:

- The degree of hydrologic alteration in the pre-2000 period was larger for the 1-, 3-, and 7- day minimum flows.
- The degree of hydrologic alteration in the post-2000 period was larger for the 1-, 3-, 7-, and 90- day maximum flows.
- The degree of hydrologic alteration for maximum IHA metrics was less than for minimum IHA metrics.

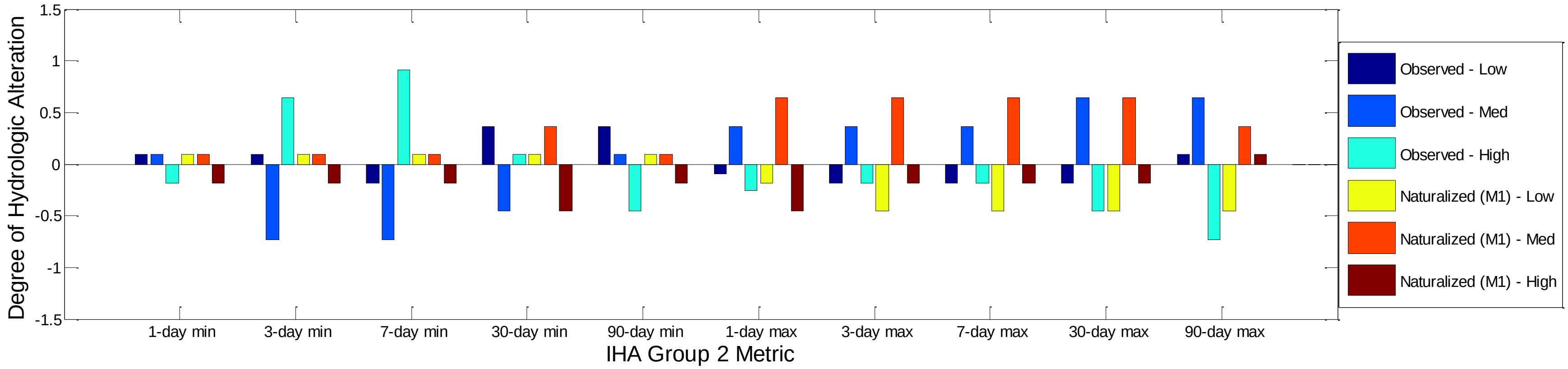


Figure 3.10 Degree of hydrologic alteration for Group 2 IHA metrics (Magnitude and duration of annual extreme water conditions) for the comparative cases shown in the legend. For each flow metric (e.g. 1-day min or 3-day min), the distribution of values are divided into three categories (i.e. Low, Med, High), each of which contain 33 percent of the observations in the pre-period.

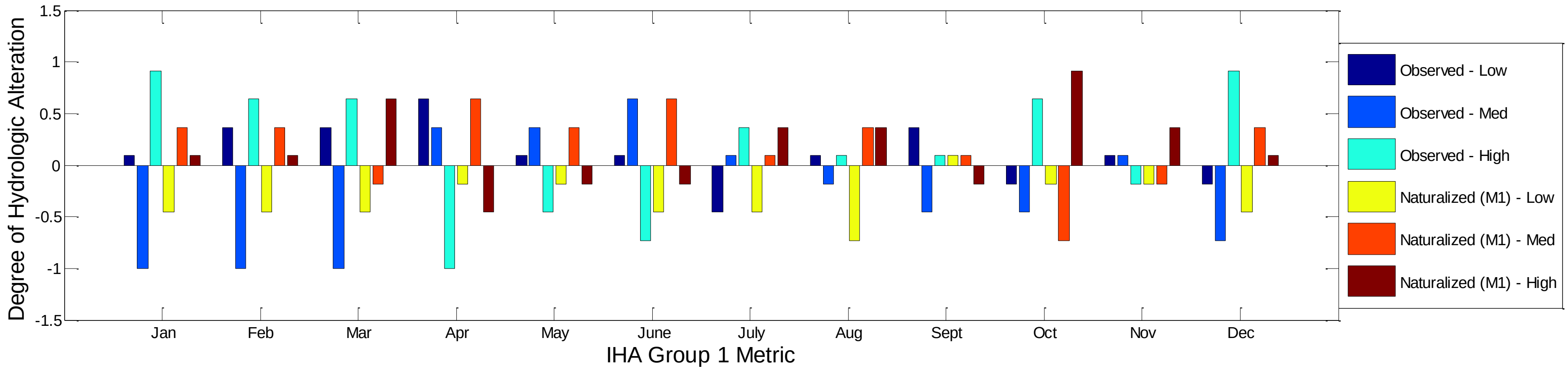


Figure 3.11 Degree of hydrologic alteration for Group 1 IHA metrics (mean monthly flows) for the two cases shown in the legend.

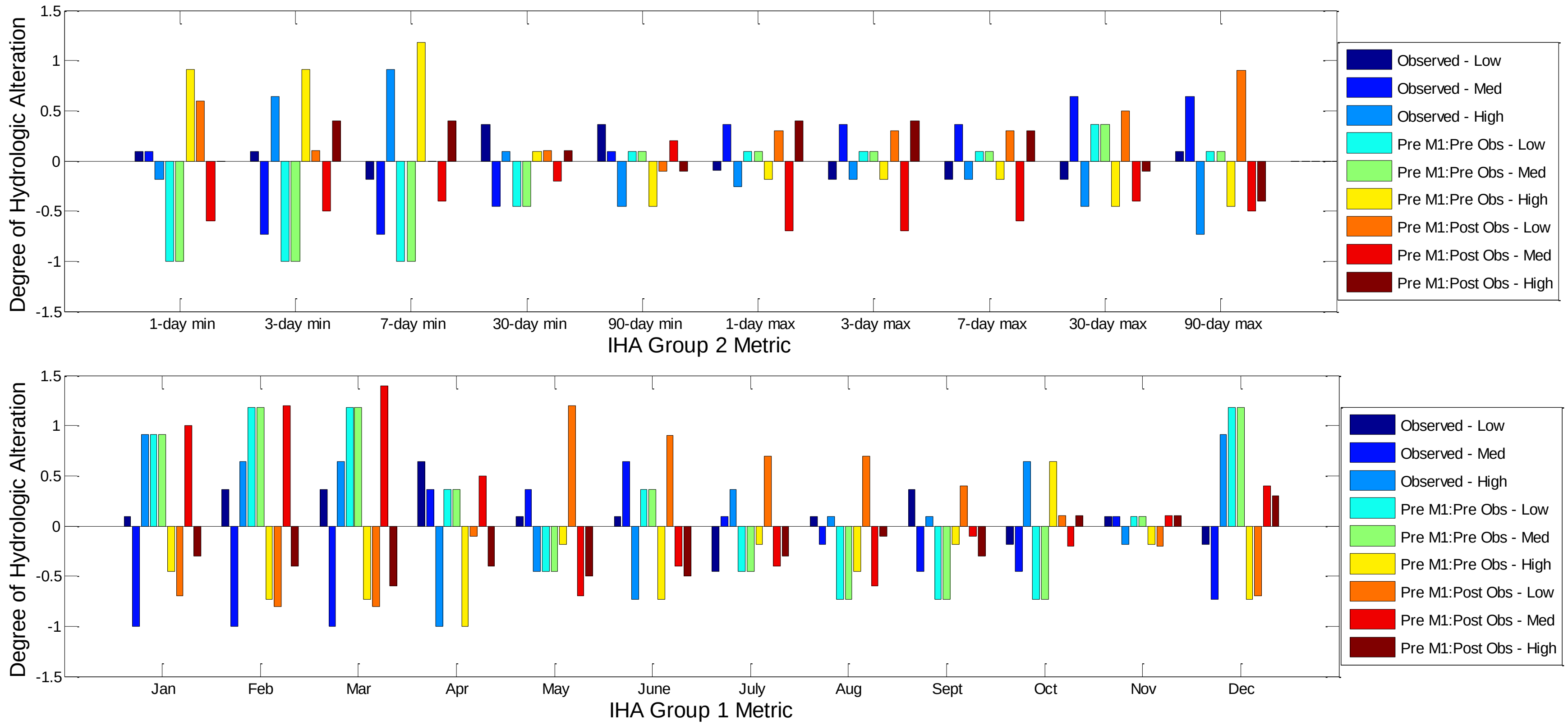


Figure 3.12 Degree of hydrologic alteration for extreme flows (above) and mean monthly flows (below) considering the 1970-1999 State of Nature (method 1) as the benchmark for change.

- The hydrologic alteration was largest in the December to March period in both the pre- and post-2000 periods.
- The hydrologic alteration was larger prior to the 2000 rule curve change for the months of April, September, October and December.
- The hydrologic alteration was larger after the 2000 rule curve change for the months of March, May and August.
- The hydrologic alteration was high in the post-2000 period for May-June, and to a lesser extent for July-August.

3.3 Does the year 2000 divide distinct hydrologic regimes?

The post- to pre- type of comparison approach presupposes that changes in the hydrologic regime occur abruptly at a date which divides the two periods. If a hydrologic shift occurs after the dividing date due to a lag response, then the post- to pre- type of comparison will too strongly weight the pre-alteration case. Alternatively, a shift in hydrologic regime may occur before the alteration, such as the start of the positive AMO cycle in 1995 (i.e. vs 2000), which can not only obscure the cause of the regime shift but can lead to overstating the effect of the management action synonymous with the presupposed split date. In this section we identify dates separating hydrologically distinct periods using Classification and Regression Trees. Thus we both investigate the assumption of using the year 2000 as a split date in our previous analysis and we attempt to uncover more evidence suggesting the cause of any detected regime shifts.

To more rigorously investigate if the year 2000 is a pivotal date in terms of flow regime state, we conducted a classification and regression tree (CART) analysis (*Systat* Software, 2005, V11.0, Richmond, Virginia) on the observed and simulated series IHA metrics. The primary objective of the CART analysis was to determine if statistically robust pivotal dates exist for any flow metrics, dividing the pre- and post-2000 rule curve management regimes for the observed flow series at Fort Frances/International Falls. The dependent variable (e.g. IHA flow metric), and independent variable (e.g. day), did not require transformation. The CART procedure recursively searches through every combination of the flow metric vs. day data for threshold dates ('split points') that divide statistically different means of the dependent variable. Only split points with a proportional reduction of error of greater than 0.05 were retained.

The results of the CART analysis are summarized in Table 3.5 & 3.6 and Figure 3.13. Table 3.5 shows the split points for 33 IHA metrics for the observed IFD series, 1970-2010. On either side of the split point are statistically different mean values for the intervening periods. A comparison of pre-split point and post-split point means indicates the direction of change in the metric. Figure 3.13 shows a histogram of the split points documented in Tables 3.5 & 3.6. For the observed IFD flow series (Figure 3.13, right panel), there is a cluster of split points in 1975, 1986, 1992 and 2002. There were no split points coincident with the 2000 rule curve change. However, the temporally lagged cluster of split points in 2001 and 2002 may reflect the influence of the 2000 rule curve change. If so, we would not expect to see this split point cluster in the State of Nature series. Further, we would expect to see changes in metrics specific to the spring and fall period associated with the 2000 rule curve change.

Table 3.5 Classification and regression tree analysis results showing split points dividing statistically different means for 33 IHA flow metrics generated from the observed flow series for Fort Frances/International Falls for the period 1970-2010. The null hypothesis (H_o) states: There are no significant differences in flow metric means before or after the implementation of the 2000 rule curve change unless they are also observed in the unaltered case (see next table), or intended outcomes. The 'Result' and 'Post/Pre' columns refer to the change in mean value relative to the bolded split point in terms of direction and magnitude, respectively.

Metric	Mean	Split	Mean	Split	Mean	Split	Mean	Result	Post/Pre
Parameter Group #1 - Magnitude of monthly water conditions (mean monthly flows)									
January	333.3	1976	244						
February	300.4	1976	242.9	1987	202.9				
March	253.4	1987	186.6						
April	258.1	1977	179.6	1997	182.9				
May	-	-	-	-	-				
June	411.29	**2001**	773	2006	465.2			Increase	X 1.9
July	-	-	-	-	-				
August	199.2	1992	351.7	**2002**	162			Decrease	X 0.5
September	252.9	**2002**	145					Decrease	X 0.6
October	-	-	-	-	-				
November	512.8	1975	265.8						
December	470.6	1975	270.8						
Parameter Group #2 - Magnitude and duration of annual extreme water conditions									
1-day min	108.9	1986	60.6	1991	86.5				
3-day min	113.3	1987	89.9						
7-day min	132.8	1975	98.7	1982	128	1987	94.6		
30-day min	155	1975	114.6						
90-day min	196	1975	137.5						
1-day max	-	-	-	-	-				
3-day max	-	-	-	-	-				
7-day max	-	-	-	-	-				
30-day max	-	-	-	-	-				
90-day max	-	-	-	-	-				
Zero days	-	-	-	-	-				
Base flow	-	-	-	-	-				
Parameter Group #3 - Timing of annual extreme water conditions									
Date min	July 27	1992	May 2	**2002**	Sept 2			Increase	X 2.0
Date max	Aug 22	1975	May 29	1983	July 14				
Parameter Group #4 - Frequency and duration of high and low pulses									
Lo pulse #	2.01	1988	8.6	2004	3.3				
Lo pulse L	9.4	2006	83.1						
Hi pulse #	7	1994	3.2	**2002**	2.5			Decrease	X 0.8
Hi pulse L	37.5	1994	16.4						
Parameter Group #5 - Rate and frequency of water condition changes									
Rise rate	6.5	1976	3.2	1993	7.6	**2002**	4.1	Decrease	X 0.5
Fall rate	-8	1975	-3.6	1992	-7.5	**2002**	-3.8	Decrease	X 0.5
Reversals	163.6	1987	176.8	**2001**	149.5			Decrease	X 0.8

Table 3.6 Classification and regression tree analysis results showing split points dividing statistically different means for 33 flow metrics generated from the simulated State of Nature, unaltered flow series (Spatial Interpolation) for Fort Frances/International Falls for the period 1970-2010.

Metric	Mean	Split	Mean	Split	Mean	Split	Mean
Parameter Group #1 - Magnitude of monthly water conditions (mean monthly flows)							
January	258.9	1975	158.4	1983	203		
February	201.5	1976	130.4	1983	168.2		
March	171.8	1976	121.3	1983	146.1		
April	185	1997	239.5				
May	-	-	-	-	-		
June	812.9	1975	558	2004	725.5		
July	-	-	-	-	-		
August	274.02	1982	345.8				
September	-	-	-	-	-		
October	-	-	-	-	-		
November	450.2	1975	249.8				
December	352.8	1975	233.2				
Parameter Group #2 - Magnitude and duration of annual extreme water conditions							
1-day min	142.3	1975	92.9	1983	115.4		
3-day min	142.8	1975	94	1983	116.2		
7-day min	145.3	1975	94.9	1983	118.1		
30-day min	152.4	1975	100.3	1983	125.2		
90-day min	177	1975	113.7	1983			
1-day max	929.4	1980	759.9	2004	928.8		
3-day max	926.7	1980	756.1	2004	920.4		
7-day max	918	1980	748.5	2004	909.1		
30-day max	-	-	-	-	-		
90-day max	-	-	-	-	-		
Zero days	-	-	-	-	-		
Base flow	-	-	-	-	-		
Parameter Group #3 - Timing of annual extreme water conditions							
Date min	July 24	1982	May 30				
Date max	June 17	1998	July 18				
Parameter Group #4 - Frequency and duration of high and low pulses							
Lo pulse #	-	-	-	-	-		
Lo pulse L	61.6	1981	147.4	1991	54.5		
Hi pulse #	2.1	1978	1.4				
Hi pulse L	-	-	-	-	-		
Parameter Group #5 - Rate and frequency of water condition changes							
Rise rate	3.7	1992	4.6				
Fall rate	-2.9	2004	-3.64				
Reversals	77.4	1992	57.7	1996	77.8	2004	66.7

The histogram of split points for the State of Nature series (Method 1) is shown in Figure 3.13a. There are no split points in 2001 or 2002. This supports the assertion that any change in flow regime at IFD in 2001-2002 is not related to climatic variability. The flow metrics that changed in 2001-2002 at IFD are:

1) Average monthly flow June 2001 (Increased X1.9)
2) Average monthly flow August 2002 (Decreased X 0.5)
3) Average monthly flow September 2002 (Decreased X 0.6)
4) Date of minimum discharge 2002 (Shifted from 2 May to 2 September)
5) The number of high pulses 2002 (Decreased X 0.8)
6) Rise rate 2002 (Decreased X 0.5)

7) Fall rate 2002 (Decreased X 0.5)
8) Reversals 2001 (Decreased X 0.8)

The post-2000 period Rainy Lake rule curve permits higher water levels in the reservoir in the April-May period and lower water levels are permitted in reservoir in the August-November period (Figure 1.3). The post-2000 period Namakan Lake rule curve permits higher water levels in the reservoir in the December-June period and lower water levels are permitted in reservoir in the July-August period (Figure 1.3). Thus, flow metrics specific to these periods may be significantly different between the pre- and post-2000 rule curve change, if the appropriate weather conditions permitted operation within the rule curve envelopes. Thus, the decrease in average monthly flows in August and September are coincident with the permissible lower water levels in Rainy Lake. The increase in June average monthly discharge may be due to local climatic variations and/or a change in reservoir storage related to the April-May period (e.g. earlier filling of Namakan Reservoir in May). Flow metrics related to extremes (e.g. List items 4 above) must be viewed with more caution. The remaining metrics, related to the number of flow pulses (e.g. List item 5) and rate of change in water condition (List items 6 to 8 above), can vary with reservoir regulation regime. In general, these rates of discharge change are higher than the State of Nature case by a factor of 2.

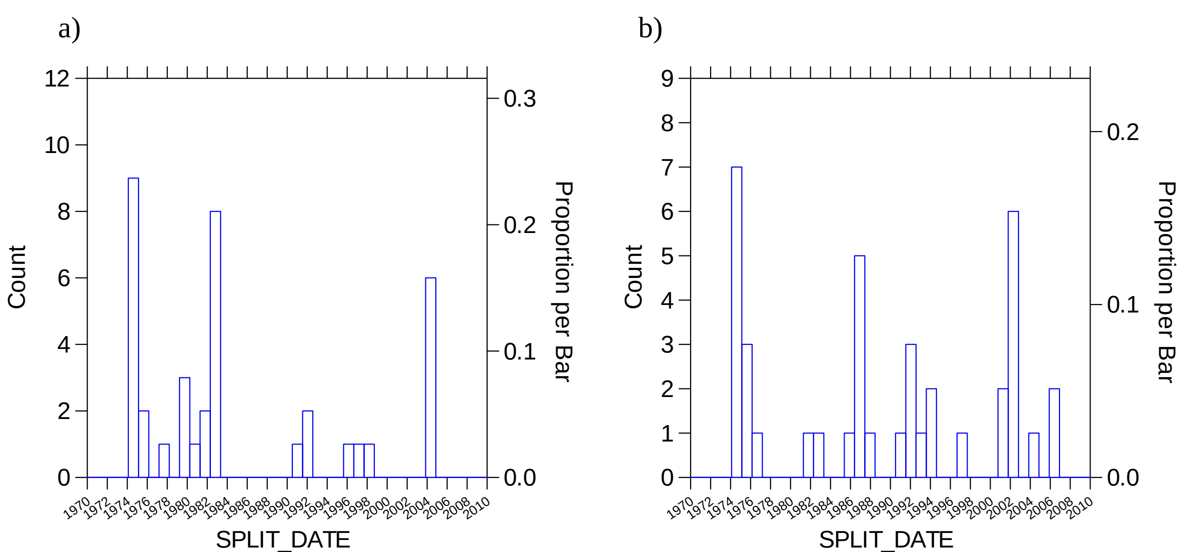


Figure 3.13 Histogram of the split points frequency for 33 flow metrics generated from a simulated State of Nature, a) unaltered flow series and b) observed, altered flow series for the Rainy River at Fort Frances/ International Falls. The height of the bar indicated the number of flow metrics with a split point in the year indicated on the x axis.

While interpretation of the flow metrics requires a caution, the direction of the trends in these metrics after 2000 mimics the directional changes in the Namakan Reservoir rule curve water levels. For example, the 1.9 times increase in average monthly flow in June is coincident with a higher permissible water level in Namakan Reservoir resulting from the earlier permissible date for filling the reservoir to capacity (i.e. end of May). The average monthly flows in August to September decreased by 40-50% and the Namakan Reservoir permissible water levels also decreased in the post-2000 period. This may also be responsible for the shift of the date of minimum discharge from May to September. The narrower range of permissible water levels in winter months (i.e. 1.05 m vs 2.04 m drawdown) at the Namakan Reservoir in the post-period could also lead to a decrease in the number of high pulses and a decrease in the rate of rise and fall and flow reversals.

Figure 3.13 shows a histogram of the split points for the State of Nature flow series (Method 1, Figure 3.13 left panel). There is a cluster of split points in 1975, 1982, and 2004. The large clustering of split points in 1975 in both the State of Nature and observed flow series IHA metric sets suggests a shift in climate is responsible for this regime change. This may also be true for the split points in the mid 1980's and early 2000's but the answer is less clear because the split points do not directly overlap between observed and State of Nature cases. However, the 1970 and 2000 decades are more hydrologically similar (more extreme and unpredictable) than the more stable 1980 and 1990 decades. The slight lag in split point locations between observed and State of Nature cases may reflect that climatic effects propagate through regulated systems at a different rate than for unaltered systems.

The range of variability approach required specification of a split point of comparison, here the year 2000. The classification and regression tree analysis suggested that the use of the year 2000 as a split point is inappropriate for many flow metrics considered. However, with these cautions in mind the preceding analysis in Section 3.2.4 suggests a few possible conclusions.

1) The high alteration indicated in the 3 day and 7 day minimum mean values for the post- rule curve period were not also indicated for the State of Nature case. One explanation for this finding is that the low flow alteration is not climate related and may be driven by flow regulation practice.
2) The high alteration indicated in maximum flow metrics for both observed and natural series suggest that high flow alteration in the post-2000 period may be climate related.
3) The monthly mean flow alteration was high in August through April in both the observed and State of Nature cases but the alteration was slightly higher for the observed series. This finding suggests that the change in mean monthly flow rate for these months is the result of a change in both climate and management.
4) The hydrological alteration was highest in the December through March period during the post-rule curve period when the State of Nature pre-case was considered as the reference. This winter period is coincident with both the period of greatest alteration of the Namakan Reservoir rule curve, and warmer mean monthly temperatures. The hydraulic alteration in the winter period may result from both climate and management related changes in the post-rule curve period.

These four hypotheses are explored further in Section 4.3.2

SECTION 4. FACTORS INFLUENCING CHANGES IN HYDRAULIC REGIME AT IFD

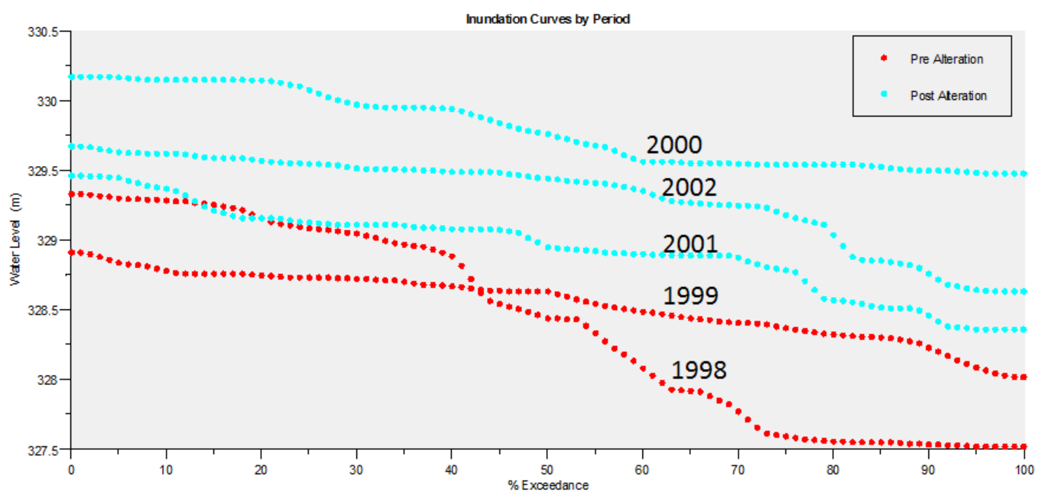
4.1 Differences in the duration of a) water levels and b) inter-daily water level range between the pre-to post-2000 period.

Two methods were used to explore the differences in flow regime between regulation periods: 1) Plotting pre- and post-duration curves for water levels, wetted perimeter and daily stage difference; and 2) Statistical tests to correlate changes in water level regime to factors affecting the differences in duration curves between pre- and post- period.

4.1.1 Assessing differences in the duration of a) water levels and b) daily water level range between rule curve periods.

Frequency duration curves were developed using the following steps:

1) For the period of record (i.e. POR = 1970-2010), a duration curve was calculated for each month of each year (i.e. 40 years X 12 duration curves). Each duration curve consists of 103 exceedance plotting positions and respective water levels. An example for the month of January is shown below for two years in the pre-2000 rule curve period, and three years in the post-2000 rule curve period. Only five years are shown for illustrative purposes; plotting the full 40 years makes the figure unreadable.



2) For each period (i.e. pre- & post-2000), the distribution of values for each plotting point position across all flow duration curves for each month is summarized using the 12^{th}, 37^{th}, 50^{th}, 62^{nd}, 87^{th} percentiles (e.g. For the pre-period, the 30 values associated with the 50^{th} percentile of each January dutration curve).

3) For each month of the year, pre- and post- percentile values are plotted on the same graph for comparison.

4) Steps 1 through 3 were repeated for daily difference data. The daily difference was calculated from the water level data for the POR by subtracting the daily mean water level from the daily mean water level of the previous day.

An example of the duration curves for the Rainy River below IFD (HEC-RAS Station 436630.5) are show in Figure 4.1 for water level, wetted perimeter and daily difference in water level for the month of June. The plots for all the months for this station are in the Appendix.

4.1.2 Statistical analysis of factors affecting differences the duration of a) water levels and b) daily water level range.

A multivariate statistical analysis was conducted to investigate the following questions.

a) Are there significant differences in duration curve sets between the pre- and post- rule curve periods?

b) Are these between period differences still significant if we account for variations in climate and management related effects, specifically: a) monthly climate (precipitation, snowfall, snow depth, and temperature), b) water level durations in Rainy Lake and/or Namakan Reservoir, and c) differences in the upper and lower bounds of the rule curves between the periods?

4.1.2.1 Methods- Multivariate adaptive regression splines (MARS)

Multivariate adaptive regression spline analyses using selected variables were used to answer these questions. The three step approach is described below.

Step 1: Variable selection and dataset preparation

An objective of this study is to determine if a change in hydrologic and hydraulic regime occurred as a result of the rule curve regulation change or if other factors such as shifts in climate regime are responsible. Thus, our statistical model must contain variables that best represent the various factors responsible for the Rainy River hydro-system's behaviour. The variables used and steps taken to assemble the database are described below. Of the suite of variables, the management effect was the hardest to capture due to a lack of data. We included management variables calculated as the difference in lower and upper rule curve elevation limits between the pre-and post- periods. However, these rule curve bounds are only guidelines and do not fully capture daily operations decisions or system specific limitations to being able to meet those targets. Consequently, we included the water level duration curves for Rainy Lake and Namakan Reservoir which implicitly reflect management actions. However, these data also reflect hydrologic system behavior. Consequently, we built models to look at individual independent factor groups (e.g. rule curve differences, lake/reservoir water levels, climate) and a combined model with all factors to determine which variables had the strongest association with Rainy River's water level regime. The variables included in the analysis are summarized in Table 4.1. Data preparation steps included:

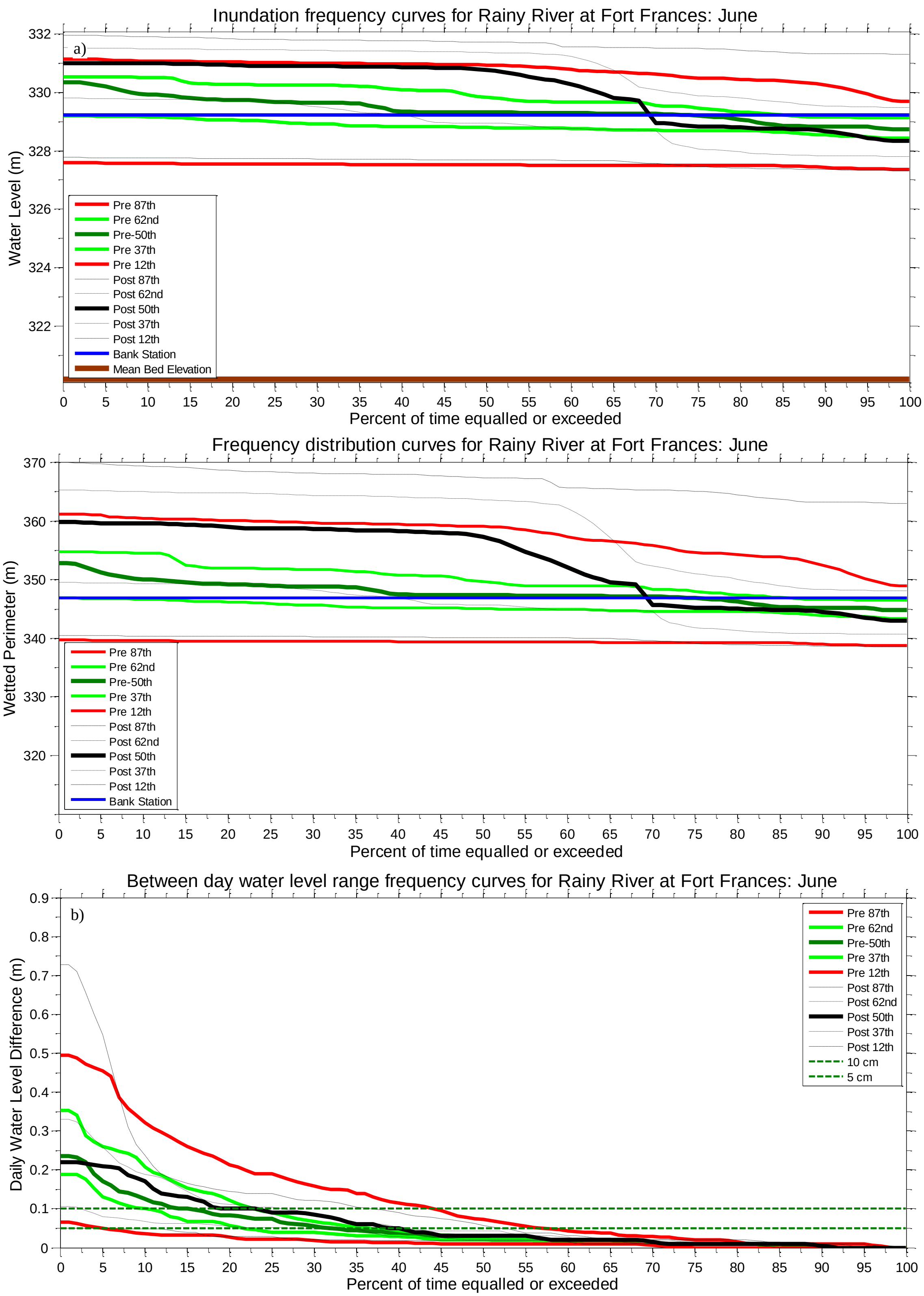


Figure 4.1 Frequency distribution curves for the pre- and post- rule curve periods at IFD for a) water level, b) wetted perimeter and c) daily water level difference. Duration curves for daily water level difference between pre- and post- rule curve periods at IFD. Plots for every month are in the Appendix.

Table 4.1 Summary of MARS model variables by group.

Seq. Id.	Variable Group	Variable Code	Description	Units
1	1. Timing	PostPre	Before (pre) of after (post) 2000	1 or 0
2		YEAR	Year	year
3	2. Climate	PRCPM	Mean Monthly Precipitation	mm
4		PRCPML1	one month prior	mm
5		PRCPMl2	two months prior	mm
6		PRCPMl3	three months prior	mm
7		SNOWM	Mean Monthly Snowfall	mm
8		SNOWML1	one month prior	mm
9		SNOWML2	two months prior	mm
10		SNOWML3	three months prior	mm
11		SNWDE	Mean monthly snow depth	cm
12		SNWDE1	one month prior	cm
13		SNWDE2	two months prior	cm
14		SNWDE3	three months prior	cm
15		TMAXM	Maximum monthly temperature	^{o}C
16		TMAXM1	one month prior	^{o}C
17		TMAXM2	two months prior	^{o}C
18		TMAXM3	three months prior	^{o}C
19		TMINM	Minimum monthly temperature	^{o}C
20		TMINM1	one month prior	^{o}C
21		TMINM2	two months prior	^{o}C
22		TMINM3	three months prior	^{o}C
23		TOBSM	Mean Monthly Temperature	^{o}C
24		TOBSM1	one month prior	^{o}C
25		TOBSM2	two months prior	^{o}C
26		TOBSM3	three months prior	^{o}C
27	3. Rainy Lake Water Levels	WLRLake	Monthly water level duration curve for Rainy Lake	m
28		WLRLake1	one month prior	m
29		WLRLake2	two months prior	m
30		WLRLake3	three months prior	m
31	4. Namakan Reservoir Water Levels	WLNLake	Monthly water level duration curve for Namakan Reservoir	m
32		WLNLake1	one month prior	m
33		WLNLake2	two months prior	m
34		WLNLake3	three months prior	m
35	5. Rainy Lake Rule Curve Difference	RLUpperDiff	Difference in upper rule curve limit between pre-and post - periods by month for Rainy Lake	m
36		RLLowerDiff	Difference in lower rule curve limit between pre-and post-periods by month for Rainy Lake	m
37		RLUpDiffLag	one month prior	m
38		RLLoDiffLag	one month prior	m
39	6. Namakan Reservoir Rule Curve Difference	NLUpperDiff	Difference in upper rule curve limit between pre-and post-periods by month for Namakan Reservoir	m
40		NLLowerDiff	Difference in lower rule curve limit between pre-and post - periods by month for Namakan Reservoir	m
41		NLUpDiffLag	one month prior	m
42		NLLoDiffLag	one month prior	m

1) Calculate duration curves for each-month-of-each-year as described in Section 4.2.1.
2) Calculate duration curves for each-month-of-each-year from water level time series for the POR for both Rainy Lake and the Namakan Reservoir.
3) Calculate monthly climate statistics for each-month-of-each-year using inverse distance weighting of data from 34 climate stations. All stations within a 400 km radius of the basin centroid for the watershed upstream of IFD were considered. The weighting parameter was 0.6.
4) For each month, calculate the difference in rule curve elevation for upper rule curve limit between the pre- and post-periods. Repeat the calculation for the lower rule curve limit. Perform these calculations on both the Rainy Lake and Namakan Reservoir.
5) Code the pre-period as 1 and the post-period as 0.
6) Merge the data in steps 1-5.

Step 2: Multivariate adaptive regression spline analyses

A linear mixed effects model was initially selected for the analysis because we are interested in the random effects of climate and management. The typical parametric application of the mixed effects model requires that the explanatory variables are normally distributed. Many of the explanatory variables in the dataset failed this test under a broad range of transformations (i.e. *ln, log, sqrt, atan, inverse*). Exploration of relationships in the data also revealed nonlinear trends and the presence of threshold type relationships. Consequently, a nonparametric spline regression method was used for the analysis. Specifically, Multivariate Adaptive Regression Splines (MARS) were used to investigate the two questions posed above. MARS is a procedure that combines discriminate analysis and regression analysis (Friedman, 1991). MARS is used for fitting adaptive non-linear regression to define the relationship between a response variable (e.g. *water level variation from an average condition*) and some set of predictors (*time period, year, climate, management*).

Nonlinear trends are represented by a series of piecewise linear basis functions that are separated by 'knot points'. A knot point is a value of the predictor variable where a deflection point exists in the response-predictor relationship. Specifically, the slope of the trend for predictor differs on either side of the knot point. More than one knot point can be specified for a predictor variable which enables complex nonlinear trends to be fitted. For each predictor variable, the algorithm recursively searches through all possible knot point locations to select knot points that maximize the fit on either side of the knot. This automatic knot selection process advanced in a forward step manner until a maximum model size is reached. This over-parameterized model is then pruned back by successively removing basis functions that contribute the least to the model fit. Through this process a predictor variable can be completely removed from the model if the basis function(s) of the variable do not make a meaningful contribution to the model fit. MARS retains a set of models from the pruning procedure for testing. The model with the best predictive fit is selected from this set of models using cross validation to isolate the model with the lowest generalized cross validation error. We used MARS as implemented in *ARESLab* v.1.5.1 *MATLAB* code developed by Jekabson (2011). The default settings were used with the exception of evoking the use of piecewise-linear models, limiting the maximum number of basis functions to 10, and limiting the maximum interaction level at one. These measures were additional precautions taken to avoid deriving over-fitted models.

The correlations that result between response and predictor variables help illustrate the nature of the strongest relationships in the data. The cause and effect cannot be determined using this approach but the MARS models can quickly identify important relationships and help to make inferences about how the system functions. The insight gained from the models can lead to more refined hypotheses that can be tested by more deterministic means (e.g. routing flows through lake chains using hydrologic or hydraulic methods).

The basic models tested in MARS are shown in Equations (4.1) to (4.3):

Water level = *f(% time equaled or exceeded)* (4.1)

Daily Difference in Water Level = *f(% time equaled or exceeded)* (4.2)

Residuals from eq. 4.1 (or eq. 4.2) model = *f(PostPre, Year, Climate variables, reservoir water level regime, and rule curve differences)* (4.3)

Models were developed for each month. The full list of models tested is shown in Table 4.2. The first stage of the analysis involves testing Equation (4.1) using duration curves for the 40 year period of record (i.e. Table 4.2, Model 1). The resulting MARS model is used to predict the water level at each exceedance plotting point position. The predicted water level is then subtracted from the observed water level. This residual is a measure of how far off the observed water level was from the average duration curve for the POR. In the second stage of the analysis, the residual is then used as the dependent variable in Equation (4.3) (i.e. Table 4.2, Model 2e) to isolate the factors that are correlated with deviation from the average duration curve. Through this model we can investigate questions such as, are positive residuals strongly associated with high monthly precipitation and/or high water levels in Rainy Lake? The third stage of the analysis is to calculate MARS models for each of the individual factor groups (e.g. Table 4.2, Model 2a-d) to explore the amount of overlapping variance in explanatory variables. Finally, these three analysis stages are repeated for daily difference data. The resulting models are: Model 3 – Equation (4.2), Model 4e – Equation (4.3) with residuals from Model 3, and Models 4a-d.

Step 3: Interpretation

Models 1 and 3 provide a generalized duration curve that represents the entire 40 year period of record for the month of interest. If a duration curve for one of the months in the period of interest plots above the average duration curve then it has positive residuals. The converse is true for the negative residual case. The regressions of the residuals with the individual factors (Models a-d) and combined factors (e models) provide insight into which factors are most correlated with deviation of plotting position from the average case. Comparison of individual models a-d provides insight into the degree of overlapping variance (i.e. how much both variables can explain the same trend).

4.1.2.2 MARS Results

Monthly Duration Curves: Water Levels

The monthly water level duration curves at IFD (i.e. Model 1) for the POR are shown in Figure 4.2 by season. The monthly curves plot progressively higher in the spring and fall when the hydro-system is being recharged. The summer and winter seasons are typified by progressively lower monthly stages as the season progresses.

Table 4.2 Summary of multivariate adaptive regression spline models.

Model	Dependent	Independent Variables	Question of interest
1	Water Level at IFD	Duration Curve Plotting Point Position	What does the monthly duration curve for daily difference data for the entire POR look like and how variable is it?
2a	Residuals from model 1	Post:Pre	Can the differences in water level from the curve in model 1 be explained by the pre-to post-rule curve periods?
2b	Residuals from model 1	Climate (Group 2)	Can the differences in water level from the curve in model 1 be explained by climate variables?
2c	Residuals from model 1	Rainy and Namakan Reservoir duration curves (Groups 3 & 4)	Can the differences in water level from the curve in model 1 be explained by reservoir water levels?
2d	Residuals from model 1	Rainy and Namakan rule curve differences (Groups 5 & 6)	Can the differences in water level from the curve in model 1 be explained by the difference in rule curve limits?
2e	Residuals from model 1	All variable groups (Groups 1-6)	Which of the variables are highly correlated with differences in water levels from those predicted by model 1?
3	Daily Difference in Water Level at IFD	Duration Curve Plotting Point Position	What does the monthly duration curve for daily difference data for the entire POR look like and how variable is it?
4a	Residuals from model 1	Climate (Group 2)	Can the differences in water level from the curve in model 1 be explained by climate variables?
4b	Residuals from model 3	Climate (Group 2)	Can the differences in water level from the curve in model 1 be explained by climate variables?
4c	Residuals from model 3	Rainy and Namakan Reservoir duration curves (Groups 3 & 4)	Can the differences in water level from the curve in model 1 be explained by reservoir water levels?
4d	Residuals from model 3	Rainy and Namakan rule curve differences (Groups 5 & 6)	Can the differences in water level from the curve in model 1 be explained by the difference in rule curve limits?
4e	Residuals from model 3	All variable groups (Groups 1-6)	Which of the variables are highly correlated with differences in water levels from those predicted by model 1?
5	Water Level at IFD	Duration Curve Plotting Point Position & PostPre	Are there differences between the pre- and post-period?
6	Daily Difference in Water Level at IFD	Duration Curve Plotting Point Position & PostPre	Are there differences between the pre- and post-period?

The correlation coefficient (R_{adj}^2) and root mean square error (RMSE) for Model 1 are shown in Table 4.3. The amount of explained variance is relatively low (4-23%) and the unexplained error is quite high (0.5-1.46 m). However, Model 2e explains 79-89 % of the variance in Model 1 residuals and has a standard error ranging from 0.27-0.51 m. When the variable groups are considered individually, the explained variance in residual water levels was high for both climate predictors (64-86 %) and reservoir water level duration curves (52-87 %) variable groups. This suggests that there is a high degree of overlapping variance in climate and reservoir variables in model 2e, which collectively explained 79-89 % of the variance in Model 1 residuals. Thus, it is difficult to separate the relative effects of these two variable groups. The amount of explained variance in the management related variable, the difference in rule curve maximum and minimum water level elevations, was very low (0-6 %) with a maximum in February and March.

Significant differences were detected in water level duration curves between the post- to pre-period for water levels in the months of Dec-March, June-July, and Sept-Oct (Table 4.4) at IFD. However, the post-to-pre variable was no longer significant when the full model was considered (Model 2e). Table 4.5 shows variable groups that were retained by the MARS model 2e to explain the stage duration curve residuals. Significant variable groups are indicated by a 'yes'. While multiple variables within each group were typically selected, the first basis function variable is shown in brackets. The first basis function contributes more to the model than successive basis functions. Note that the post-to-pre variable

Table 4.3 Summary of MARS model results for water level duration curves (Model 1) and duration curve residuals for factor groups (Models 2a-2c) and the combined model (Model 2d).

	Model 1		Model 2a		Model 2b		Model 2c		Model 2d		Model 2e	
Month	Water Level duration curve		Post:Pre		Climate		Reservoir Water Levels		Difference in Rule Curves		All Variables	
	R2	RMSE	R2	RMSE	R2	RMSE	R2	RMSE	R2	RMSE	R2	RMSE
Jan	0.06	0.7	0.02	0.69	0.78	0.32	0.72	0.37	0.02	0.69	0.85	0.27
Feb	0.05	0.57	0.06	0.55	0.72	0.3	0.74	0.29	0.06	0.55	0.79	0.26
Mar	0.23	0.5	0.06	0.48	0.75	0.25	0.65	0.29	0.06	0.48	0.77	0.24
April	0.19	0.88	0	0.88	0.68	0.5	0.52	0.61	0	0.88	0.71	0.47
May	0.06	1.32	0	1.32	0.86	0.5	0.75	0.66	0	1.32	0.87	0.47
June	0.05	1.46	0.02	1.44	0.78	0.69	0.87	0.53	0.02	1.44	0.89	0.49
July	0.13	1.14	0	1.14	0.7	0.63	0.82	0.48	0	1.14	0.87	0.41
Aug	0.12	0.9	0	0.9	0.64	0.54	0.71	0.48	0	0.9	0.84	0.36
Sept	0.07	0.93	0.03	0.92	0.72	0.5	0.74	0.47	0.03	0.92	0.85	0.36
Oct	0.07	1	0.01	0.99	0.65	0.59	0.72	0.53	0.01	0.99	0.87	0.36
Nov	0.08	1.11	0	1.11	0.73	0.58	0.76	0.55	0	1.11	0.79	0.51
Dec	0.04	0.96	0.01	0.96	0.8	0.43	0.76	0.47	0.01	0.96	0.89	0.32

Table 4.4 Summary of MARS model results testing for significant differences between the pre- to post-rule curve periods for water level duration curves (Model 2a) and daily differences in water level duration curves (Model 4a).

	Model 2a	Model 4a
Month	Post:Pre	Post:Pre
	RMSE	RMSE
Jan	Yes	Yes
Feb	Yes	Yes
Mar	Yes	Yes
April	--	Yes
May	--	Yes
June	Yes	--
July	Yes	Yes
Aug	--	--
Sept	Yes	Yes
Oct	Yes	Yes
Nov	--	Yes
Dec	Yes	Yes

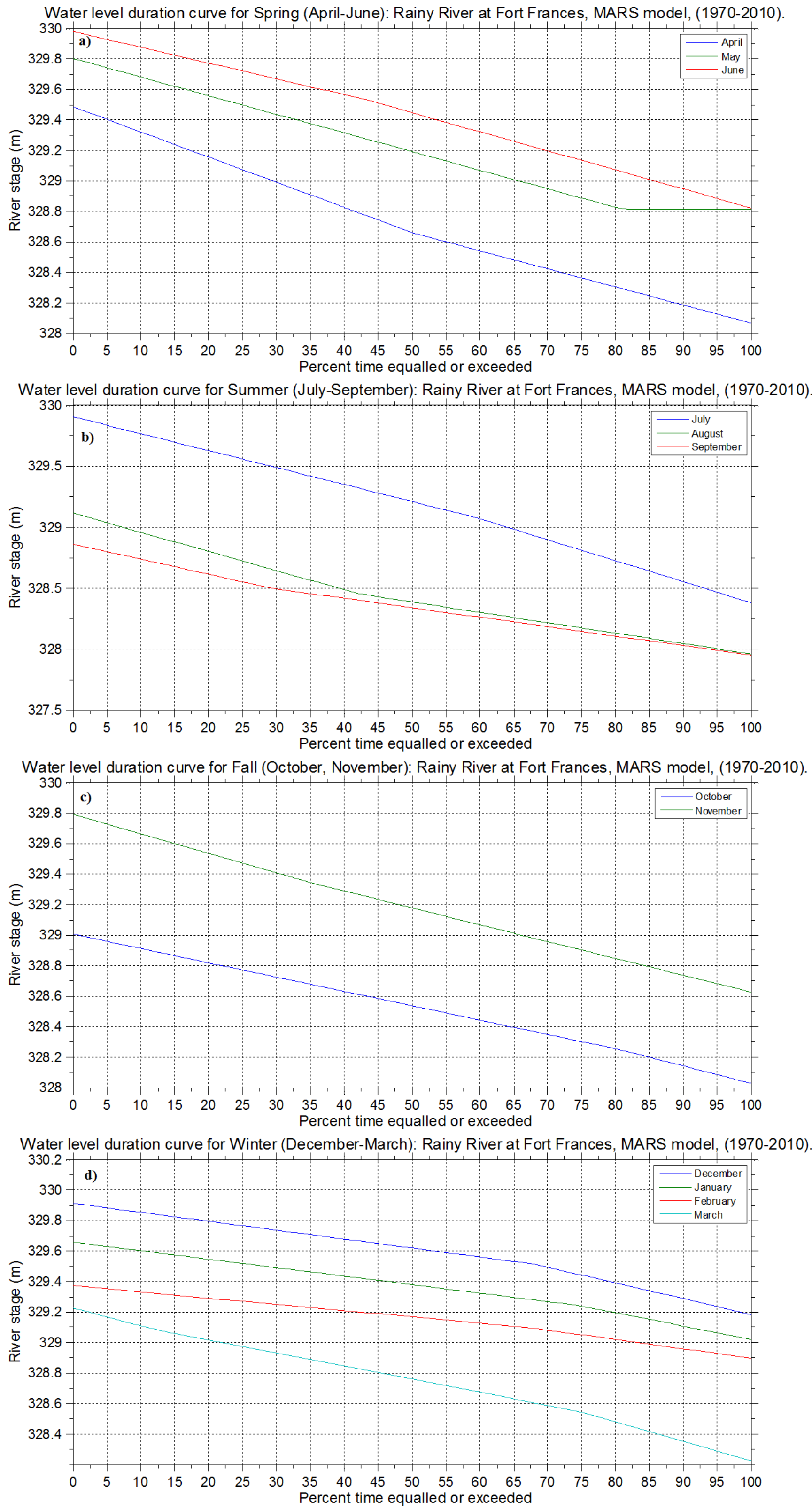


Figure 4.2 Water level duration curves at IFD from MARS models trained to data for the POR for a) spring, b) summer, c) fall, and d) winter months.

Table 4.5 Summary of results for MARS models 1 and 2d. The table indicates if variables were significant enough to be included in the final model (Yes) or not (--). The variables that had a strongest contributions to the model contained in basis functions 1 and 2 are shown in brackets.

	Model 1 Water Level Duration Curve		Model 2d Water Level Duration Curve Residuals vs. Factors						
Month	R2	MPE	R2	Post Pre	Year	Climate	Rainy L. Water Level	Namakan L. Water Levels	Difference in Rule Curve Limits
Jan	0.06	Yes	0.85	--	--	Yes (Precipitation in Nov)	Yes (Water level in Nov)	Yes	--
Feb	0.05	Yes	0.79	--	--	Yes	Yes (Water level in Nov)	Yes	--
Mar	0.23	Yes	0.77	--	Yes (1980)	Yes (Snow depth Feb)	Yes (Water level in Dec)	Yes	--
April	0.19	Yes	0.71	--	--	Yes (Snow depth Mar)	Yes (Lower RC limit)	--	--
May	0.06	Yes	0.87	--	--	Yes (Snow depth Feb)	Yes (Lower RC limit)	--	--
June	0.05	Yes	0.89	--	--	Yes	Yes (Lower RC limit)	--	--
July	0.13	Yes	0.87	--	--	Yes	Yes (Lower & Upper RC limit)*	--	--
Aug	0.12	Yes	0.84	--	--	Yes (Precipitation in July)	Yes (Upper RC limit)	--	--
Sept	0.07	Yes	0.85	--	--	Yes (Precipitation in Aug)	Yes (Lower RC limit)	Yes	--
Oct	0.07	Yes	0.87	--	--	Yes (Precipitation in July)	Yes (Lower RC limit)	Yes	--
Nov	0.08	Yes	0.79	--	Yes[1]	Yes	Yes (Lower RC limit)	--	--
Dec	0.04	Yes	0.89	--	--	Yes (Precipitation in Nov)	Yes (Lower RC limit)*	Yes	--

1 – 1990

and difference in rule curve limits are no longer significant. The flow duration curves in Rainy River at IFD are influenced by climate in every month. The precipitation and snow depth in previous months are correlated with water level duration curve residuals (e.g. Figure 4.2b). While significant, climate variables were not the first or second basis functions for February, June-July, or November.

As can be anticipated, the duration curves for the Rainy Lake reservoir also influenced duration curves in Rainy River below the dam. The basis functions were typically nonlinear and had an inflection point coincident with the lower rule curve limit water level elevation (Figure 4.2c). Rainy River water levels through the winter months (January-March) were correlated with Rainy Lake water levels in November and December. Namakan Reservoir water level duration curves were significant contributors to the model in the winter (December-March) and fall (September & October) but were not contained in the first two basis functions.

Climate and reservoir water levels could not explain all of the variance in Model 1 residuals in March and November. Only March was contained in the first two basis functions and the knot point was 1980 as illustrated in Figure 4.2a. This figure illustrates how the basis function contributes to the model and shows the trend before and after the knot point. There was a declining trend in the water level duration curve residuals before 1980. This trend reversed in the subsequent years (i.e. the duration curve plotting position had to be increased depending on the year considered). This suggests that our statistical model 2e does not fully capture all the processes governing water levels at IFD. However, it is highly unlikely that the process driving the trend in Figure 4.2a is related to the rule curve change in 2000.

Monthly Duration Curves: Daily Stage Range

The monthly duration curves for daily stage range at IFD (i.e. Model 1) for the POR are shown in Figure 4.3 by season. The monthly curves are similar for all seasons. Differences between the curves occur primarily in the fall and winter versus the spring and summer for large daily stage range events (e.g. > 0.15 m). For example, stage range differences of 0.2 m occur 2.5-5% of the time in the spring-summer period but 0-2% of the time in the fall and winter periods.

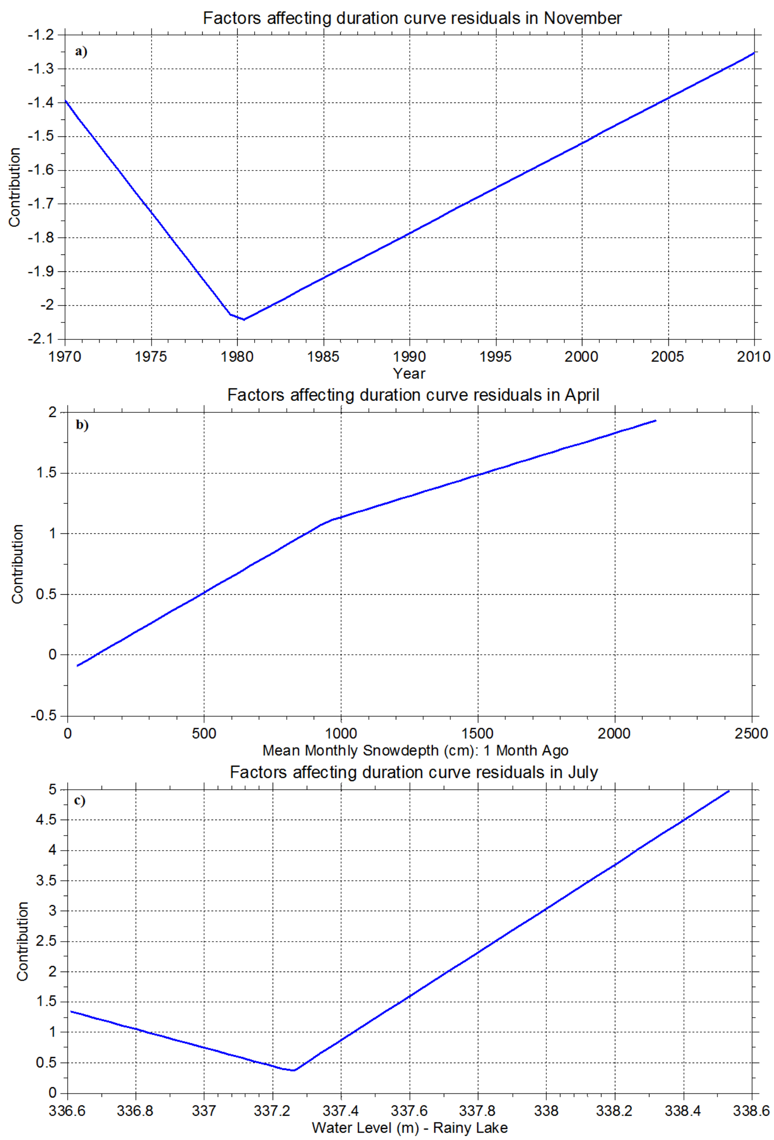


Figure 4.3 Example contribution plots for MARS Model 2e for the variables a) Year, b) Snow depth in the previous month, and c) Rainy Lake water levels.

The correlation coefficient and root mean square error for Model 3 are shown in Table 4.6. The amount of explained variance is 23-65%, higher than for stage range duration curves (e.g. Model 1, 4-23%). The unexplained error is 0.03-0.07 m. Model 4e explains 27-62 % of the variance in Model 3 residuals and has a standard error ranging from 0.03-0.05 m. When considered individually, the explained variance in residual daily stage range was high for both climate predictors (21-63 %) and reservoir water level duration curves (12-39 %) variable groups. This suggests that there is some overlapping variance in climate and reservoir variables in the combined model 4e, which collectively explained 23-65 % of the variance in Model 3 residuals. The amount of explained variance in the difference in rule curve maximum and minimum water level elevations was very low (0-3 %) with a maximum in March and August.

Table 4.6 Summary of MARS model results for daily water level difference duration curves (Model 3) and duration curve residuals for individual factor groups (Models 4a-4c) and the combined model (Model 4d).

	Model 3 Water level difference duration curve		Model 4a Pre:Post		Model 4b Climate		Model 4c Reservoir Water Levels		Model 4d Difference in Rule Curves		Model 4e All	
Month	R2	RMSE	R2	RMSE	R2	RMSE	R2	RMSE	R2	RMSE	R2	RMSE
Jan	0.28	0.07	0.02	0.06	0.56	0.04	0.19	0.06	0.02	0.06	0.5	0.05
Feb	0.23	0.07	0.02	0.07	0.63	0.04	0.39	0.06	0.02	0.07	0.62	0.04
Mar	0.42	0.07	0.03	0.06	0.47	0.05	0.5	0.05	0.03	0.06	0.58	0.04
April	0.65	0.04	0.01	0.04	0.32	0.04	0.32	0.03	0.01	0.04	0.37	0.03
May	0.53	0.05	0	0.05	0.21	0.04	0.3	0.04	0	0.05	0.27	0.04
June	0.45	0.06	0	0.06	0.26	0.05	0.38	0.05	0	0.06	0.45	0.05
July	0.54	0.06	0	0.06	0.25	0.05	0.34	0.05	0	0.04	0.4	0.05
Aug	0.64	0.04	0	0.04	0.27	0.03	0.28	0.03	0.03	0.05	0.35	0.03
Sept	0.48	0.06	0.03	0.05	0.3	0.05	0.3	0.05	0.02	0.05	0.38	0.04
Oct	0.5	0.05	0.02	0.05	0.35	0.04	0.22	0.04	0	0.03	0.37	0.04
Nov	0.61	0.03	0	0.03	0.23	0.03	0.25	0.03	0	0.03	0.33	0.03
Dec	0.43	0.06	0.01	0.06	0.36	0.04	0.12	0.05	0.01	0.06	0.37	0.04

Significant differences were detected in water level duration curves between the post- to pre-period for water levels in the months of July and Sept-May (Table 4.4) at IFD. However, the post-to-pre variable was no longer significant when the combined model was considered (Model 4e Table 4.7). Table 4.7 shows which variable groups were retained by the combined MARS model 4e to explain the daily stage difference duration curve residuals from model 3. While multiple variables within each predictor variable group were typically selected, only the first and second basis functions variables are shown in brackets. The daily stage range duration curves in Rainy River at IFD were correlated with climate variables for every month. The mean monthly snow depth and snowfall affect daily stage ranges in the winter and spring. In September they are correlated with daily stage range duration curve residuals (e.g. Figure 4.4a). While significant, climate variables were not the first or second basis functions for March, May, or July.

The duration curves for the Rainy Lake reservoir were correlated with daily stage range duration curve residuals for the Rainy River below the dam. Rainy Lake water level duration curves were significant explanatory variables and contained within the first two basis functions for the months of April to August. The basis functions were typically nonlinear and had an inflection point coincident with either the lower- or upper- rule curve limit water level elevation (Figure 4.4b). In August, the daily stage range was higher than average when the stage in Rainy Lake exceeded 337.56 m, near the upper rule maximum. This likely reflects attempts to stay within the rule curve limits, and climatic or hydrosystem related limitations to achieving that goal (Jenkinson, 2011).

Table 4.7 Summary of results for MARS models 3 and 4d. The table indicates if variables were significant enough to be included in the final model (Yes) or not (--). The variables that had a strongest contributions to the model contained in basis functions 1 and 2 are shown in brackets.

	Model 3 Daily Water Level Range Duration Curve		Model 4d Daily Water Level Range Duration Curve Residuals vs. Factors						
Month	R^2	MPE	R^2	Post Pre	Year	Climate	Rainy L. Water Level	Namakan L. Water Levels	Rule Curve Limits
Jan	0.28	Yes	0.5	--	Yes (2001)	Yes (Snow depth)	--	--	--
Feb	0.23	Yes	0.62	--	Yes (2000)	Yes (Snowfall)	--	--	--
Mar	0.42	Yes	0.58	--	Yes (1999)	Yes	--	Yes (Upper RC limit > 339.54)	--
April	0.65	Yes	0.37	--	--	Yes (Snow depth Mar & Precipitation in Feb)	Yes (Lower-Mid RC limit)	--	--
May	0.53	Yes	0.27	--	--	Yes	Yes (Upper RC limit)	Yes	--
June	0.45	Yes	0.45	--	--	Yes (Precipitation in May)	Yes (Lower RC limit)	Yes	--
July	0.54	Yes	0.4	--	Yes	Yes	Yes (Upper RC limit)	Yes	--
Aug	0.64	Yes	0.35	--	--	Yes (Mean Temperature)	Yes (Upper RC limit)	--	--
Sept	0.48	Yes	0.38	--	--	Yes (Spring snow depth)	--	--	--
Oct	0.5	Yes	0.37	--	--	Yes (Mean Temperature & Precipitation)	--	--	--
Nov	0.61	Yes	0.33	--	--	Yes (Mean Temp Sept)	Yes	Yes (Upper RC limit – 341 in Aug)	--
Dec	0.43	Yes	0.37	--	Yes (2000)	Yes (Snow Depth)	--	--	--

Namakan Reservoir water level duration curves were significant contributors to the model in March, May-July, and November. However, this variable was only contained in the first two basis functions in March and November. In March, daily stage ranges were greater when Namakan Reservoir water levels exceeded 339.54 m (Figure 4.4c). In November, daily stage ranges were higher than average if Namakan Reservoir water levels exceeded 341 m in August (Figure 4.4d). While this latter correlation may be spurious, it could also suggest antecedent reservoir or aquifer conditions govern system runoff response times (e.g. high antecedent moisture conditions lead to higher than average daily stage ranges).

Climate and upstream reservoir water levels could not explain all of the variance in model 3 residuals in winter months (Dec-March) and July. Temporal trends were also significant suggesting that our predictor variables do not fully capture the systems behavior, or an additional process should be included in the model (e.g. routing times, antecedent moisture conditions, daily dam operations decisions). Only winter months (Dec-March) were contained in the first two basis functions and the knot points occurred between 1999 and 2001 (Figure 4.6). In general, the daily stage range increased from the average state between 1970 to near the time of the rule curve change in 2000. After 2000, the daily stage range progressively

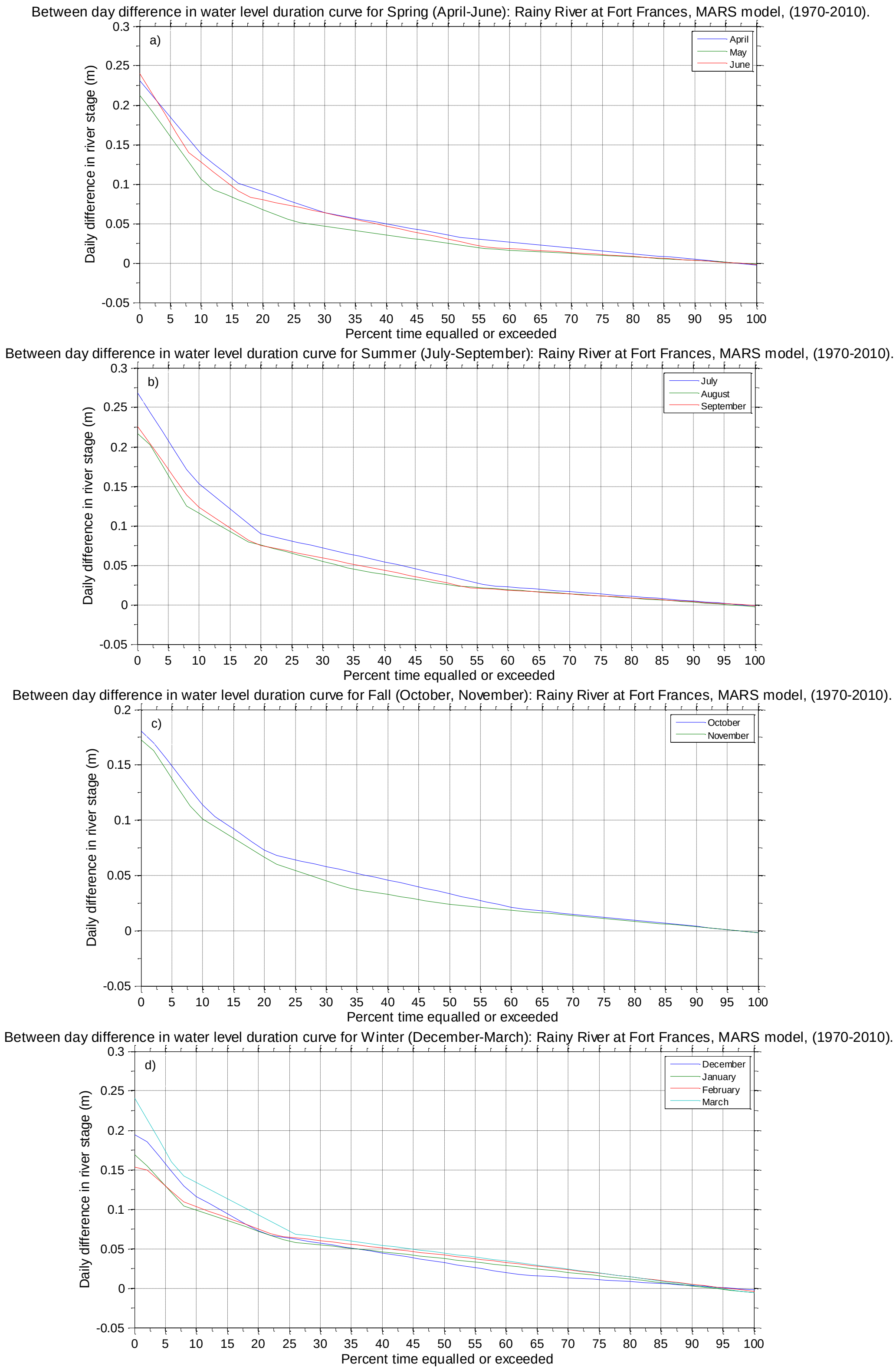


Figure 4.4 Duration curves for daily water level difference at IFD from MARS models trained to data for the POR for a) spring, b) summer, c) fall, and d) winter months.

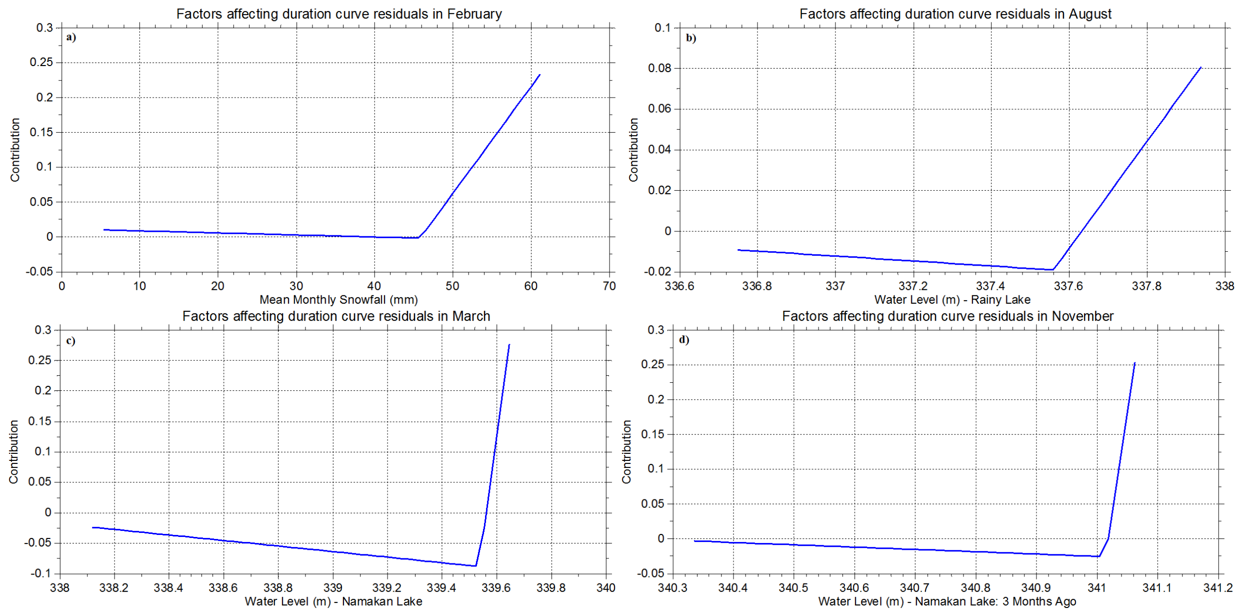


Figure 4.5 Contribution plots for MARS Model 4e for the variables a) mean monthly snowfall in February, b) water level in Rainy Lake in August, c) water level in Namakan Reservoir in March, and d) water level in Namakan Reservoir in August (as it correlates with November water levels in Rainy River).

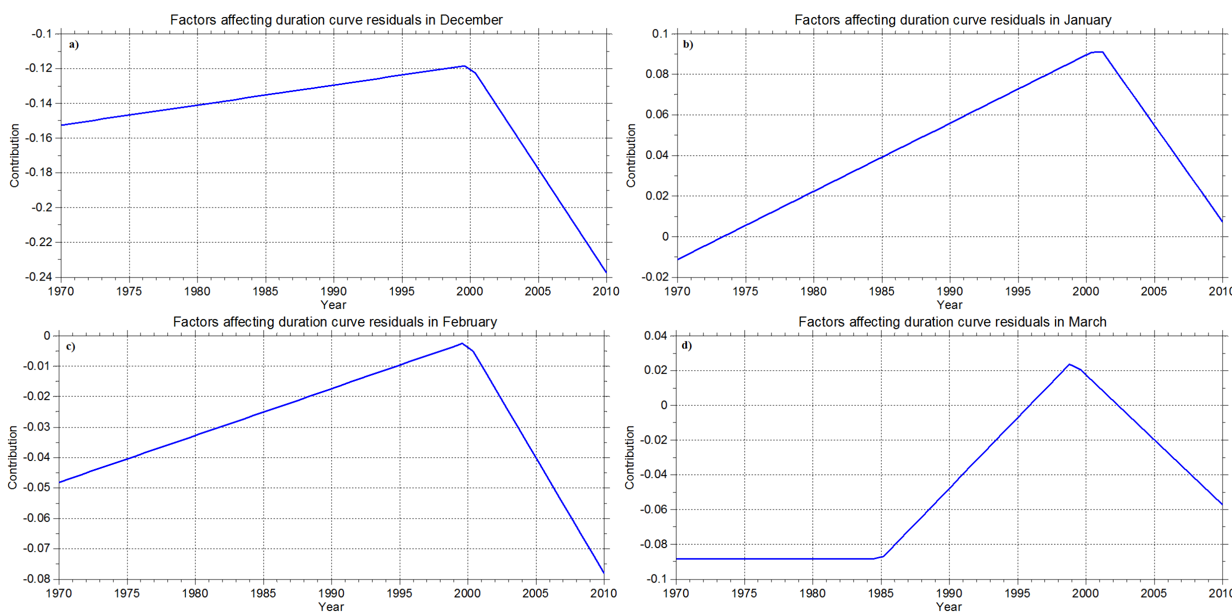


Figure 4.6 Contribution plots for MARS Model 4e for the variable Year for a) December, b) January, c) February, and d) March.

decreased from the average state to 2010. This change may have positive effects on the rivers biota such as reducing frequency and severity of substrate disturbances that perturb benthic macroinvertebrates in the winter (when biomass is highest), or by reducing energy demands on fish that can now respond less frequently/energetically to changing hydraulic conditions.

4.1.3 Historical trends in monthly climate data

Independent of the preceeding MARS analysis, we examined climate trends using a separate climate database resolved at a monthly time scale. Precipitation, snowfall and temperature data was downloaded from the Adjusted Historical Canadian Climate Data (AHCCD) series for selected stations within the study area. These include Sprague 5022759, Fort Frances 6022476, Mine Centre 6025205, Atikokan 6020384, and Tranquillo Ridge 6048864 from the *Southern Station Set* and Kenora 6034075, Dryden 6032119, Sioux Lookout 6037775, and Armstrong 6040330 from the *Northern Station Set*. This AHCCD data consists of rehabilitated and homogenized climate records that have been corrected for inhomogeneities and missing data. The adjusted and homogenized Canadian climate data were used to characterize differences in total precipitation, total snowfall and temperature for the period 1880 to 2010. A Bonferoni analysis of variance was used to test for statistical differences in the means of monthly precipitation, snowfall and temperatures between decades. Figure 4.7 shows box plots of decadal means ($\pm SD$) in total precipitation, total snowfall and temperature. The amount of precipitation during the 2000-2010 decade was significantly higher than during the 1890's (p=0.004), 1900-1920 (p=0.015, 0.002, 0.003, respectively) and 1950's (p=0.003). The temperature during the 2000-2010 decade was significantly (p=0.013) warmer (1.67 ^{o}C) than 1920. The temperature in the 1970's was 1.07 ^{o}C cooler than the post-2000 rule curve period but the difference was not significant (p=0.78). There was a significant difference between the highest snow water equivalent values recorded in the 1880's, and lowest snow water equivalent values in the 1900-1910 decade (p=0.024).

Despite differences in mean values for the decades between 1970 and 2010, there was no significant difference (p=0.05) in mean monthly precipitation, snowfall or temperature between these decades. However, the mean precipitation and temperature were higher in 2000-2010 relative to the three previous decades. These positive trends in precipitation and temperature in the post- rule curve period are consistent with entering the positive phase of the Atlantic Multi-decadal Oscillation, as shown in Section 3.1.

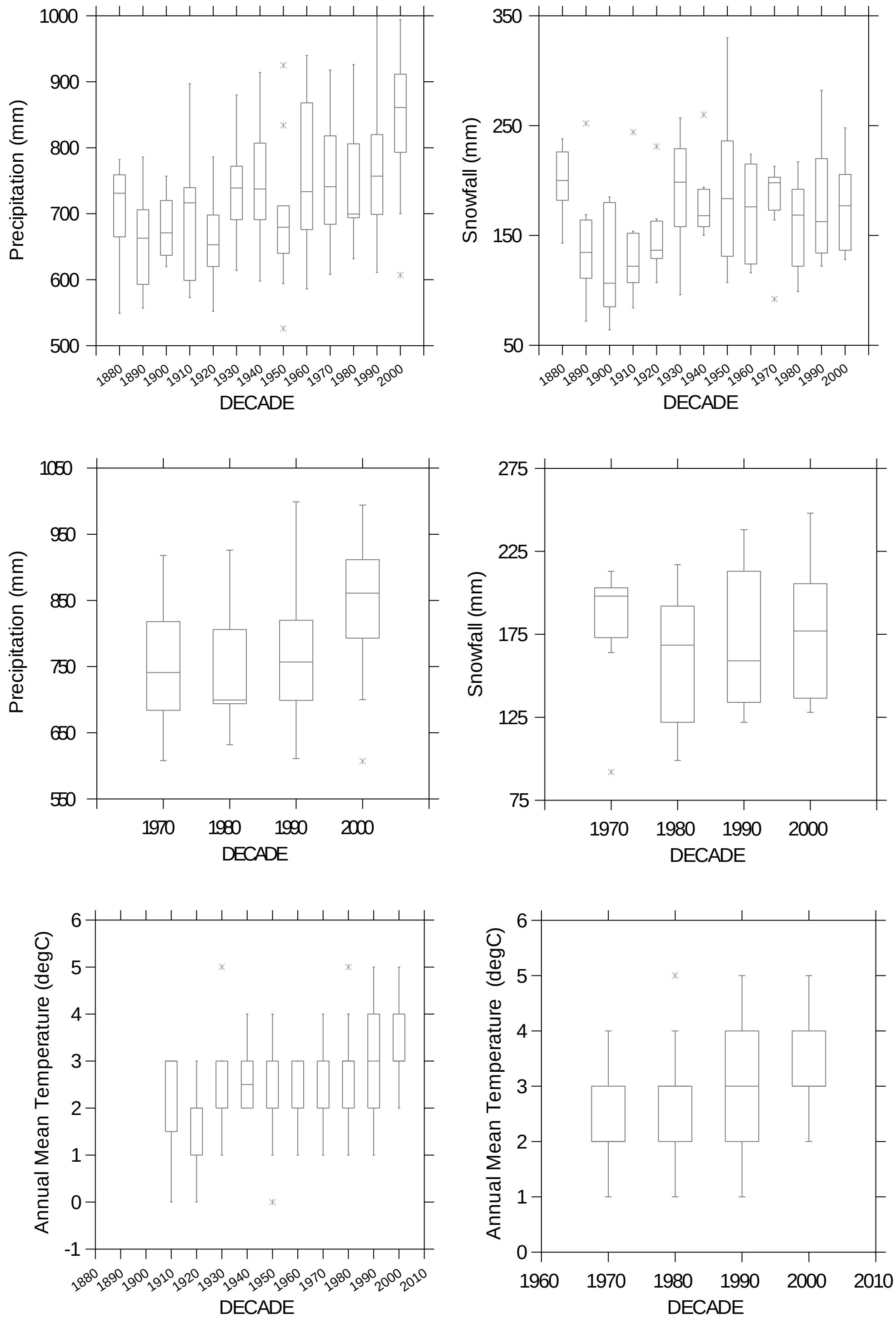


Figure 4.7 Adjusted and homogenized Canadian climate data by decade for total precipitation, total snowfall and temperature for the 1880 to 2010 period. Boxes represent the interquartile range (i.e. 25th to 75th percentile). The whisker lines show data within 1.5 times the interquartile range. The asterisks are outliners. Median values for temperature are shown but fall on interquartile range boundary for all cases except 1940 and 1990.

SECTION 5: DOWNSTREAM DIFFERENCES IN RIVER REGIME

The previous two Sections have focused on examining how the flow regime has changed at IFD, a location where the signal from regulation from IDF should be strongest. We now shift focus to examine how flow pulses progress down the river (Section 5.1), and examine downstream differences in flow duration, daily stage range and wetted perimeter at gauged sites between IFD and LOW (Section 5.2). In section 5.3 we also examine downstream differences in wetted perimeter at the eleven response reaches below IFD. Thus this Section presents the results of the HECRAS simulation runs for the Observed case and State of Nature case, comparing and contrasting hydraulic response between the pre- and post- rule curve periods. The results will show that while changes in hydraulic regime are detectable between the pre- and post- period in the upper river, these changes are not large relative to the hydraulic regime change associated with the backwater effect from damming LOW at the turn of the century (i.e. State of Nature state).

5.1 Hourly flow data and downstream trends in hydraulic response

The nature of the pulses observed downstream of IFD on the Rainy River was investigated to help provide insight into hydraulic modeling considerations. Uncorrected (i.e. provisional) water level data were acquired from the real time USGS and WSC sites at the highest resolution possible for gauge sites located between Namakan Reservoir and Lake of the Woods (Table 5.1). Water levels for all sites were plotted for the 2011-2012 period to examine differences in the patterns of flow. Each data series was standardized to the minimum water level to improve the illustration of data from multiple gauges (Figs 3.15-16). The gauge at the town of Rainy River malfunctioned between March and early July 2012 causing some erroneous fluctuations in hourly water levels. While data are plotted for this 5 month period for the Rainy River gauge, they should not be interpreted.

Figure 5.1 shows water level fluctuations in the Namakan River, Rainy Lake and four points along the Rainy River from below Rainy Lake to the Lake of the Woods for the period 16 Feb 2011 to 1 Sept 2012. Note that the data shown have different sampling intervals which are reported in the legend. The location of the Rainy River stream gauges are shown in Figure 2.6. Note the peak in the Namakan River stage in May 2011, and later peak in the receiving water body (i.e. Rainy Lake) in August 2011. The long term water level patterns in the 2 lower Rainy River gauging locations are notably less variable than the upper 2 stations. The upper river also appears to stay ice free much longer than the lower river. The daily water level fluctuations in the upper river stations (i.e., Boat Landing & Manitou Rapids) are influenced by the pattern of reservoir releases. The lower river stations (i.e. Town of Rainy River & Wheelers Point) are in the Lake of the Woods backwater influence and may also be influenced by seiche, fluctuating Lake of the Woods water levels, and tributary inflows along the Rainy River.

Figure 5.2 illustrates water level fluctuations for the same gauges shown in Figure 5.1, focusing in on a period free of any spates (17-23 August, 2012). The water level range that occurred during this period is summarized in Table 5.2. A strict comparison of differences in water level range between gauge sites is not possible due to the different sampling frequencies. However, Figure 5.2 and the values in Table 5.2 generally illustrate how flow pulses propagate down the Rainy River.

Table 5.1 Gauge information for model boundary condition and validation data.

Gauge	Number	Location
Rainy River @ Manitou Rapids	WSC 05PC018	48°38'4" N ,93 ° 54'48" W ,48.634470 ,-93.913360
Rainy River @ Manitou Rapids	USGS 05133500	
Rainy River @ Rainy River	WSC 05PC021	48°43'0" N ,94°34'3" W ,
Lake of the Woods at Hanson Bay	WSC 05PD008	49°7'58" N ,94°17'0" W ,49.1328000 ,-94.283490
Lake of the Woods at Warroad	WSC 05PD001	48°54'15" N ,95°18'57" W ,48.904220 , -95.316059

Table 5.2 Water level fluctuation range for a period of stable flow August 17–23, 2012 at 5 sites between Rainy Lake and Lake of the Woods.

Gauge (sampling resolution)	Observed Water level range (cm)
Rainy Lake (hourly)	5.8
Rainy River – Fort Frances (15 min)	52.4
Rainy River – Manitou Rapids (30 min)	17.7
Rainy River – Rainy River (hourly)	17.6
Rainy River – Lake of the Woods (15 min)	18.6

5.2 Downstream differences in flow duration, daily stage range and wetted perimeter

We investigated if there were differences in water level (Model 5), daily stage range (Model 6) and wetted perimeter (Model 7) between the pre- and post- period for four stations downstream of IFD.
The results are summarized in Table 5.3. The serial discontinuity concept posits that the alteration caused by a discontinuity (e.g. dam) extends downstream until the effect can no longer be detected. In other words, the downstream extent of the alteration extends to the point where the signal being measured (e.g. water level fluctuations) returns to the normal range of behavior. A value of 1 in Table 5.3 indicates if significant differences in the duration curves between the rule curve periods were detected at the station. For example, for January, there was a significant difference between the pre- and post- period detected at IFD, Manitou Rapids, and Rainy River but not at Lake of the Woods. Thus, a detectable difference between the pre- and post- period water level duration curves was detectable for 110-131 km. The downstream differences in exceedance curves between the pre- and post- periods are illustrated in Figures 5.3 to 5.5 for the month of August. The results indicate:

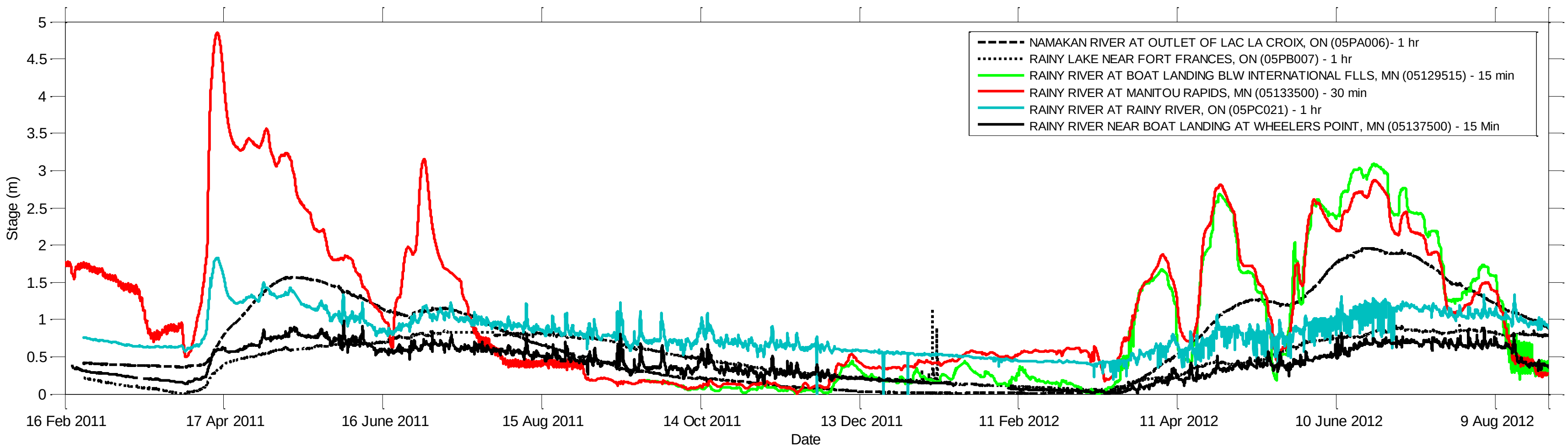


Figure 5.1 Water level fluctuations in the Namakan River, Rainy Lake and four points along the Rainy River from below Rainy Lake (i.e. US Boat Landing) to the Lake of the Woods (i.e. Wheelers Point) for the period 16 Feb 2011 to 1 Sept 2012.

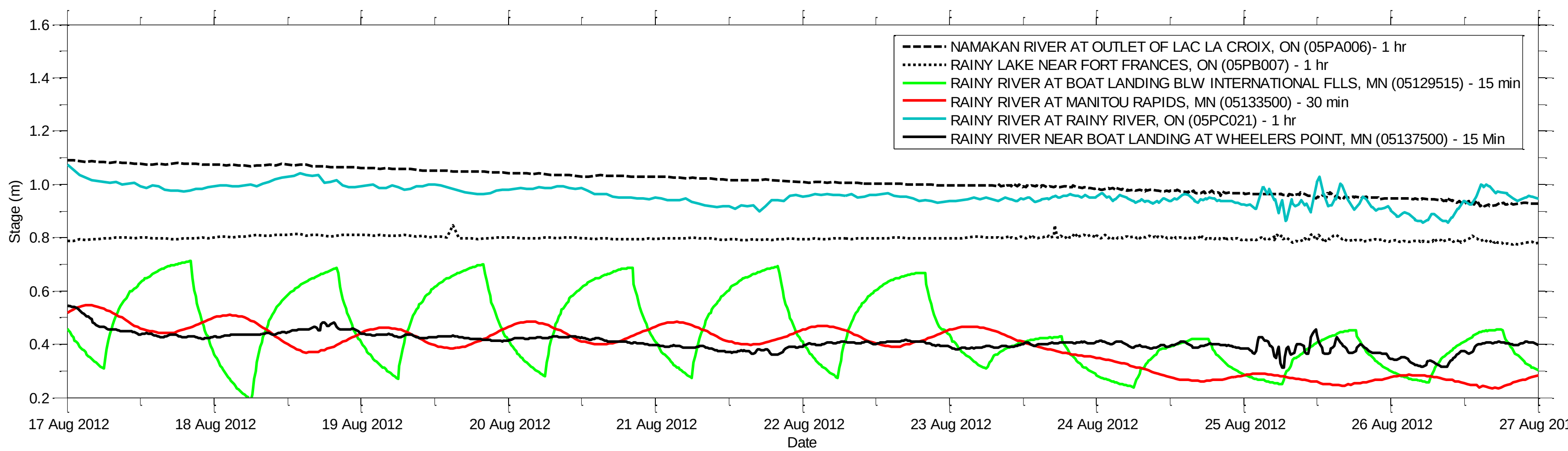


Figure 5.2 Water level fluctuations in the Namakan River, Rainy Lake and four points along the Rainy River from below Rainy Lake to the Lake of the Woods for the month of August 17-23, 2012.

Table 5.3 Application of models 5, 6 and 7 to four locations downstream of IFD to investigate how far downstream effects can be detected. Significant differences between the pre- and post-period are indicated by 1=Yes and 0=No. Bolded values are to illustrate differences between scenarios (e.g. Model 5 vs 7).

	Model 5 at 4 sites Water Level					Model 6 at 4 sites Inter-Daily Differences					Model 7 at 4 sites Wetted Perimeter				
	Fort Frances 0 km	Manitou Rapids 55 km	Rainy River 110 km	Lake of the Woods 131 km	DS Effect km	Fort Frances 0 km	Manitou Rapids 55 km	Rainy River 110 km	Lake of the Woods 131 km	DS Effect km	Fort Frances 0 km	Manitou Rapids 55 km	Rainy River 110 km	Lake of the Woods 131 km	DS Effect km
Jan	*1*	*1*	*1*	0	110-131	*1*	*1*	0	1	55 - 110	*1*	*1*	*1*	0	110-131
Feb	*1*	*1*	*1*	0	110-131	*1*	*1*	*1*	0	110-131	*1*	*1*	*1*	**1**	> 131
Mar	*1*	*1*	*1*	0	110-131	*1*	*1*	*1*	0	110-131	*1*	*1*	*1*	**1**	> 131
Apr	0	0	1	1	0?	*1*	*1*	*1*	0	110-131	**1**	0	1	1	0?
May	0	0	1	0	0?	1	0	1	0	0-55	**1**	0	1	**1**	0?
Jun	*1*	*1*	*1*	*1*	> 131	0	0	1	1	0?	*1*	*1*	*1*	*1*	> 131
Jul	*1*	*1*	*1*	*1*	> 131	1	1	0	1	55 - 110	*1*	*1*	*1*	*1*	> 131
Aug	0	0	1	1	0?	1	1	1	1	> 131	0	0	1	1	0?
Sep	*1*	*1*	*1*	*1*	> 131	*1*	*1*	0	1	55 - 110	*1*	*1*	*1*	*1*	> 131
Oct	*1*	*1*	*1*	*1*	> 131	*1*	*1*	0	1	55 - 110	*1*	*1*	*1*	*1*	> 131
Nov	0	0	0	1	0?	0	1	1	0	0?	*1*	0	0	1	0-55
Dec	*1*	*1*	*1*	0	110-133	*1*	0	1	1	0-55	*1*	*1*	*1*	**1**	> 131

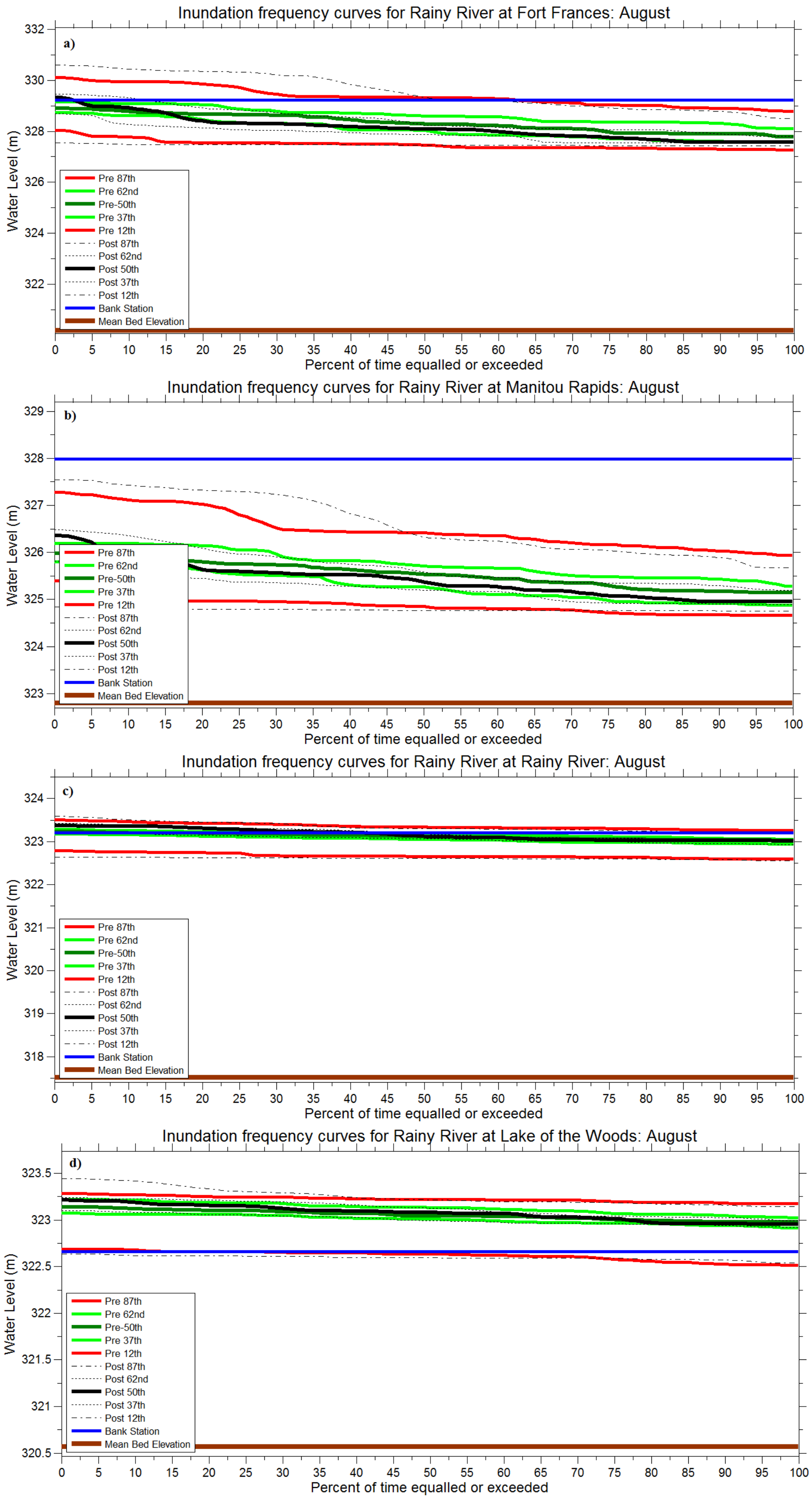


Figure 5.3 Inundation frequency for sites of increasing distance from the reservoir: a) Fort Frances 0 km, b) Manitou Rapids 55 km, c) Rainy River 110 km, and d) Lake of the Woods 133 km.

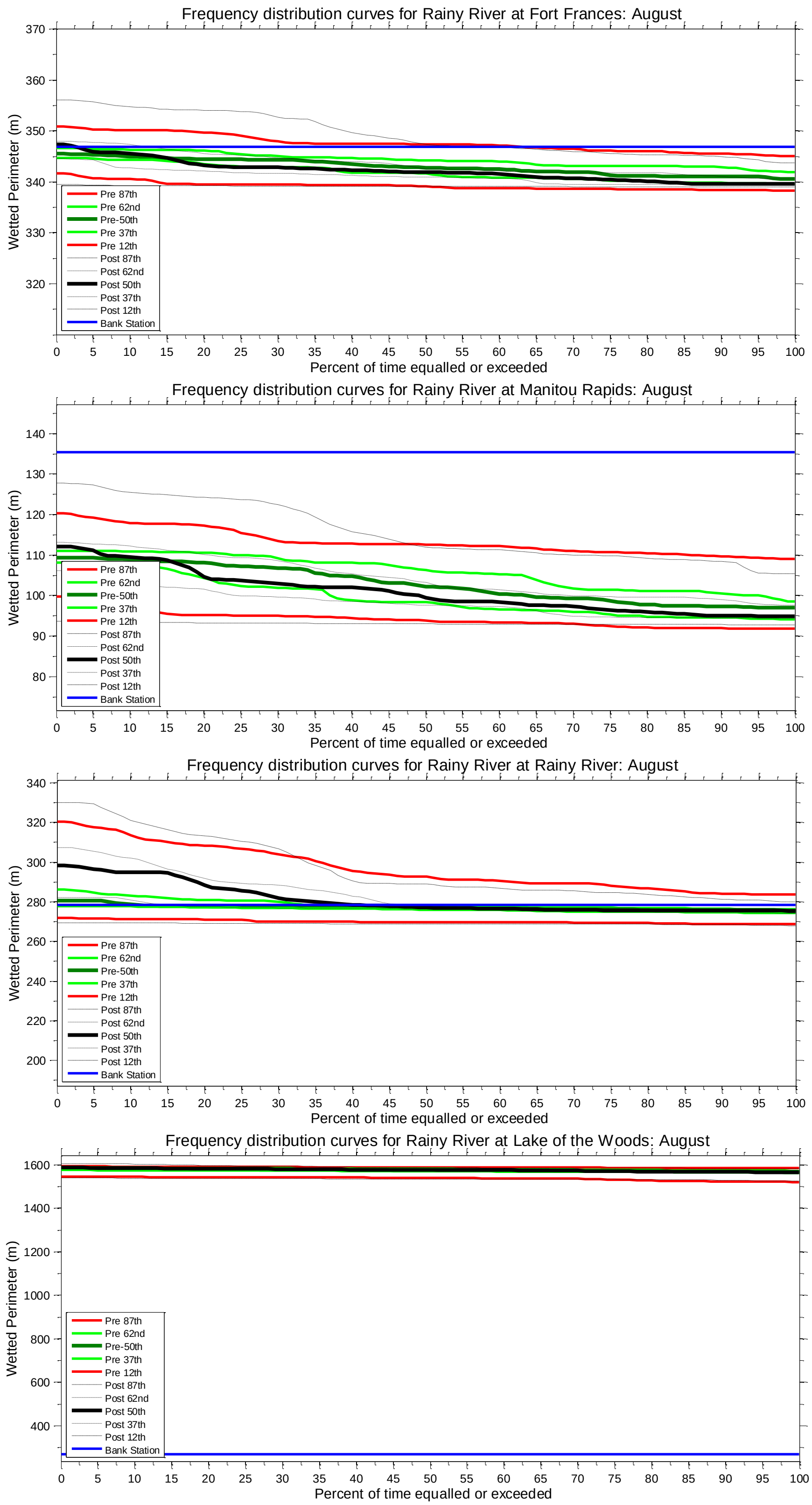


Figure 5.4 Frequency distribution curves of wetted perimeter for sites of increasing distance from the reservoir: a) Fort Frances 0 km, b) Manitou Rapids 55 km, c) Rainy River 110 km, and d) Lake of the Woods 133 km.

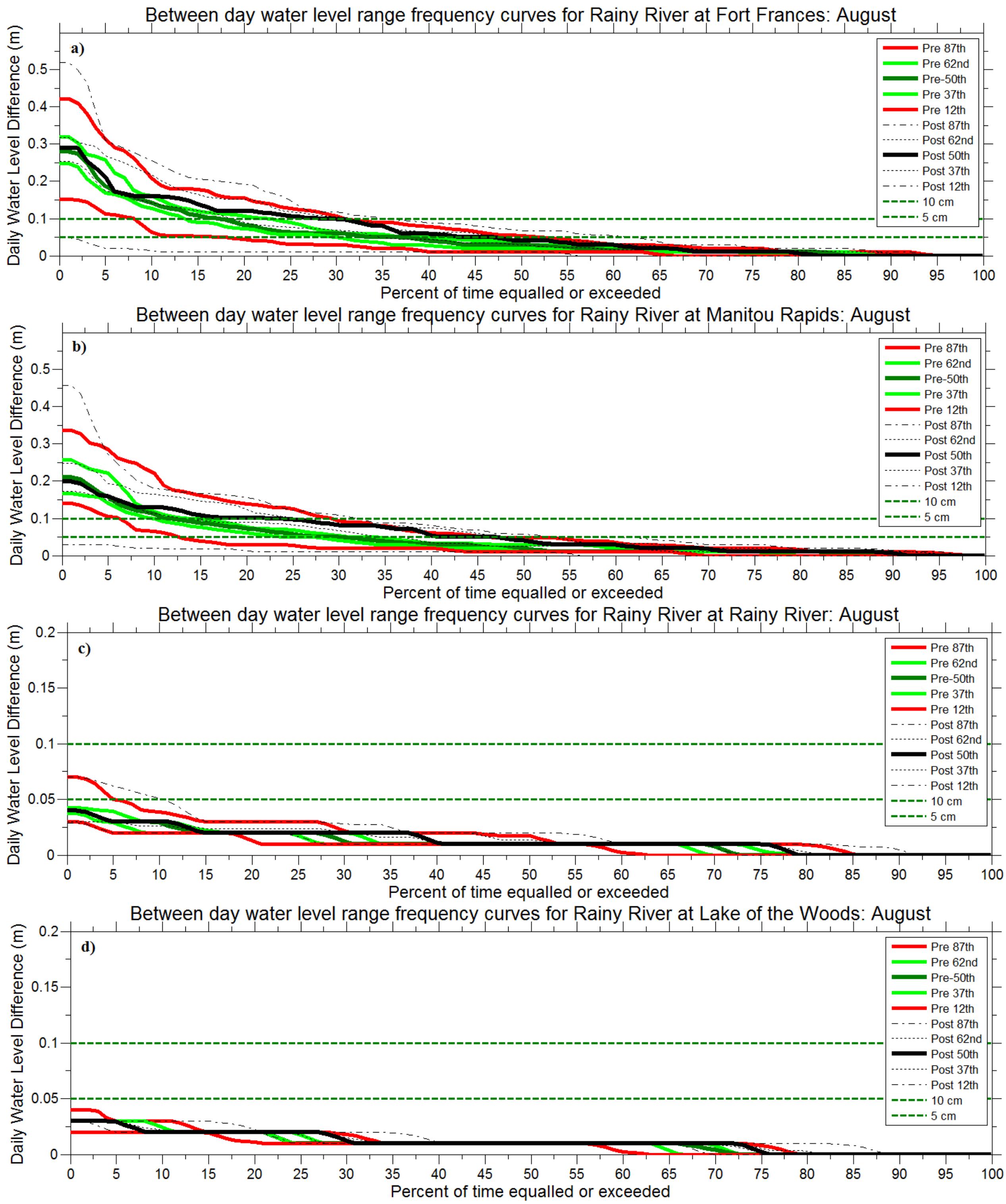


Figure 5.5 Exceedance duration of inter-daily range of water levels for sites of increasing distance from the reservoir: a) Fort Frances 0 km, b) Manitou Rapids 55 km, c) Rainy River 110 km, and d) Lake of the Woods 133 km. Note that the y axis scale varies between plots a), b) and c), d).

1) Significant differences in pre- to post- duration curves were detected for 110-130 km downstream of the dam for a) water levels in winter months (Dec-March), and b) daily stage differences in February to April.
2) Significant differences in pre- to post- duration curves were detected for > 131 km for a) water level in June, July, September and October, and b) daily stage differences in August.
3) Significant differences in post- and pre- duration curves are detectable further downstream for water levels than for daily stage differences. This suggests that absolute differences in water levels are a more sensitive indicator of downstream alteration effect than daily water level amplitude.
4) The downstream pattern of detectable differences between pre- and post- periods for wetted perimeter are very similar to that of water level. However, wetted perimeter was more sensitive to change than water level, particularly in February, March, May and December. For April and May the alteration effect likely extends beyond 131 km but is undetectable in the narrow Manitou Rapids section.

5.3 Downstream differences in wetted perimeter between 11 response reaches.

The eleven response reaches are illustrated in Figure 5.6. The valley and channel morphology varies with each reach which is reflected in the different wetted perimeter curves shown in Figure 5.7. The procedure to develop wetted perimeter duration curves was as follows:

1) For the HEC-RAS project RainyRiv (i.e. FinalMRevised.prj) run the unsteady flow analysis for the observed (i.e. Plans: 1970_1990 Seasonal roughness 1.14 & 1990_2010 Seasonal roughness 1.14) and State of Nature condition (i.e. Plans: 1970_1990 Seasonal roughness 1.14 SNat2 & 1990_2010 Seasonal roughness 1.14 SNat2) .
2) For each of model run extract stage hydrographs for the simulation period, and water surface versus elevation curve data.
3) Format the data into files for the Matlab script entitled ALL_REACHES.m in Excel and save as the following scv files:
    a) Ext_Cond_Ras.csv
    b) Nat_Cond_Ras.csv
    c) ElevWPEst.csv
    d) ElevWPNat.csv
4) Run the Matlab script entitled ALL_REACHES.m which does the following for each of the 11 reaches:
    a) Reads in the data from step 3
    b) Fits a MARS model to the wetted perimeter vs elevation data
    c) Reads in the water surface hydrograph and translates it into a wetted perimeter series using the MARS model.
    d) For the wetted perimeter series, calculate the wetted perimeter duration curves for the following scenarios:
        1) Pre- vs Post-rule curve periods for the observed wetted perimeter series;
        2) Observed vs State of Nature for the pre-rule curve period; and
        3) Observed vs State of Nature for the post-rule curve period.
    e) Plot graphs of the above scenarios for all 11 response reaches and save them as .emf files.

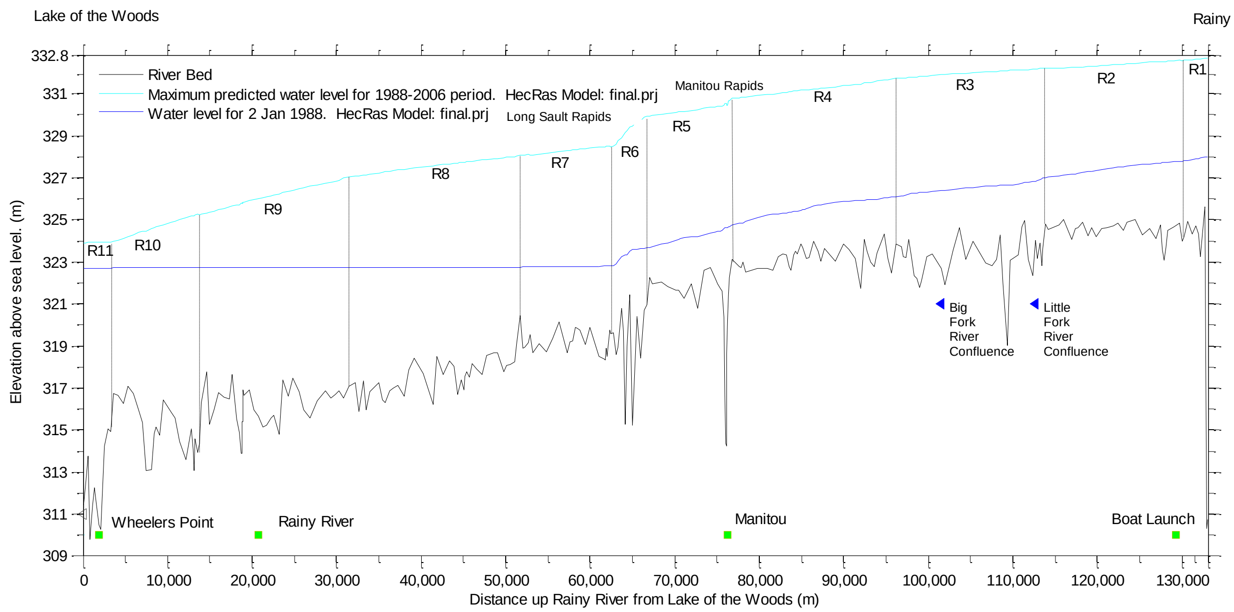


Figure 5.6 Long profile of the Rainy River from the dam at Fort Frances/International Falls to Lake of the Woods. The water surface slope for a high and low flow are shown as modeled by the 2011 Unsteady HEC-RAS model. Note the location of the gauge stations at the base of the plot. We have divided the river into eleven reaches based on breaks in water surface slope and bed morphology.

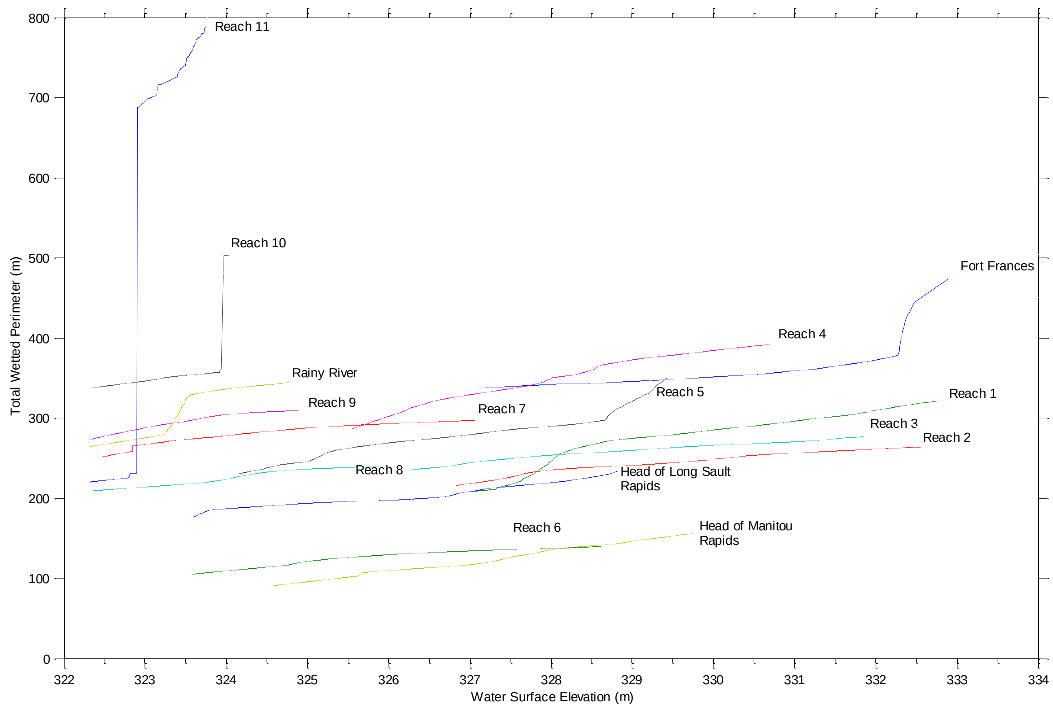


Figure 5.7 Wetted perimeter vs. elevation curves for the existing conditions simulation. The curves consider the range of flows during the 1970-2010 period.

5.3.1 Differences in wetted perimeter frequency duration curves between the pre- and post-rule curve periods along the Rainy River

The wetted perimeter duration curve for the post-2000 period differed from the pre-2000 curves in three exceedance regions (Figure 5.8):

1) 0% to 25% – The post 2000 period wetted perimeter was **wider** than during the pre-development period for these relatively infrequent events.
2) 45% to 90% - The post-2000 period wetted perimeter was **narrower** than during the pre-development period for these mid-range flows.
3) 95%-100% - The post 2000 period wetted perimeter was **wider** than during the pre-development period for infrequent, low flow events.

For a given exceedance, the wetted perimeter increased in the post-period for floodplain and baseflows, relative to the pre-development period. However, the wetted perimeter decreased per given exceedance value in the post-period for all other sub-bankfull flows.

The difference between the post- to pre- period wetted perimeter decreases with distance downstream, being minimal below the Rapid River (Reaches 9-11). This downstream trend can result from both the decreasing influence of releases from IFD, and increasing influence of the backwater from LOW.

5.3.2 Differences in wetted perimeter frequency duration curves between the observed and State of Nature cases for the pre-rule curve periods along the Rainy River.

The largest difference between the observed and State of Nature wetted perimeter duration curves for the pre-rule curve period occur in the lower river from Reach 7 to Lake of the Woods (Figure 5.9). The State of Nature duration curve plots below the observed curve, indicating that the wetted perimeter is now much wider in the lower river. This finding reflects the backwater effect of raising the water level in LOW by an average of 0.9 m, resulting in more frequent inundation of the State of Nature channel and floodplain (i.e. exceedances from 5-100%). Thus the change in river habitat between the State of Nature case and pre-rule curve period was most pronounced below the Long Sault Rapids. This change would shift the lower river to a more lentic state, relative to the pre-development case.

The other notable difference between the observed and State of Nature wetted perimeter duration curves for the pre-rule curve period occurs in the upper river between Reach 1 and Reach 6. There are two notable differences:

1) The main difference is that there has been a reduction in wetted perimeter from the State of Nature case. This is indicated by the observed duration curve plotting below the State of Nature duration curve for frequent flows (i.e. exceeded between 75% and 100% of the time). As expected, this effect diminishes with distance downstream, but is masked by the larger backwater effect after Reach 6. Thus, the regulation effect of IFD is to reduce the amount of useable habitat in the baseflow to mid bankfull flow range.

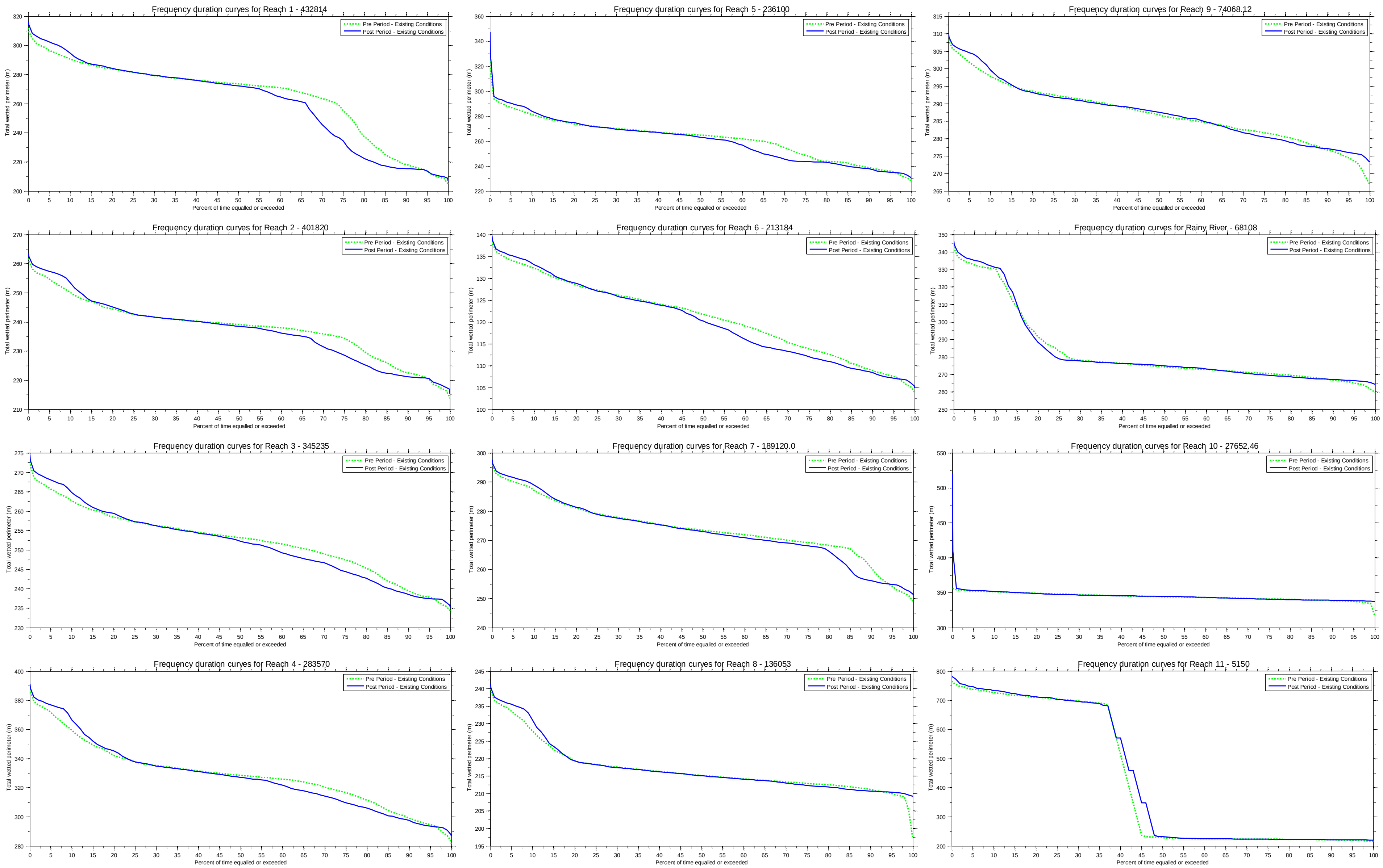


Figure 5.8 Frequency duration curves for wetted perimeter for the eleven response reaches between Fort Frances/International Falls and Lake of the Woods illustrating the difference between the pre-(green dashed) and post-(blue) rule curve periods for observed flows.

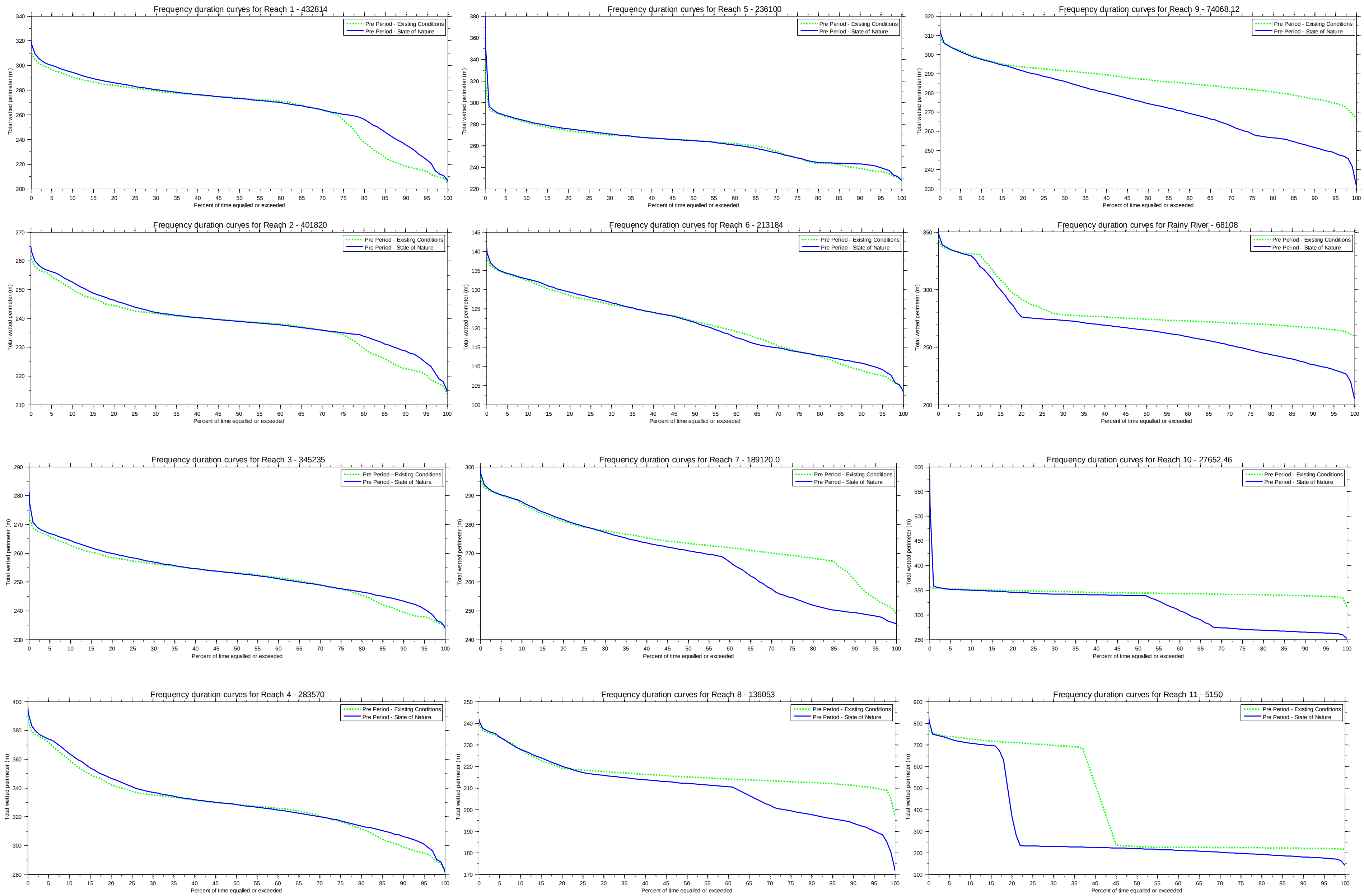


Figure 5.9 Frequency duration curves for wetted perimeter for the eleven response reaches between Fort Frances/International Falls and Lake of the Woods illustrating the difference between the observed (green dashed) and State of Nature (blue) cases for the pre-rule curve period.

2) There has also been a reduction in wetted perimeter for riparian flows. Note that the observed duration curve also plots below the State of Nature duration curve for infrequent, flows (i.e. exceeded between 0.1% and 35% of the time). This suggests that a narrower band of floodplain is inundated for a given frequency of flow.

It is interesting to note that the wetted perimeter for flows in the 35% to 75% exceedance range have changed little. Flows in this exceedance range are typically associated with the bankfull flow, a discharge that has a frequency and magnitude combination to do the most work in transporting sediment on unregulated rivers.

5.3.3 Differences in wetted perimeter frequency duration curves between the observed and State of Nature cases for the post-rule curve periods along the Rainy River.

The differences between these two cases (Figure 5.10) are as described for the pre- case in section 5.3.2 with the minor exceptions as described in Section 5.3.1, for the post- to pre- comparison. More specifically:

1) The differences between the observed and State of Nature wetted perimeter curves in the upper river were slightly larger in the post-rule curve period.
2) The wetted perimeter during the extreme low flow exceedances (e.g. >95%) were slightly higher for the post-period in both the upper and lower river, relative to the pre-period.

The alteration in wetted perimeter was larger between the observed case and State of Nature case, relative to the pre- to post-rule curve periods.

5.3.4 Upstream extent of the backwater effect from LOW.

As a first order approximation, we calculated the backwater length ($L_{Backwater}$) effect using the Equation of (Samuels, 1989):

$$L_{Backwater} = 0.7D/s_0 \qquad (2)$$

where, D is the bankfull depth and s_o is the bed slope. We calculated the backwater length for the average slope and flow depth values for the whole river and for each individual river reach. The average backwater effect was 75 km but it ranged from (10 km in rapids to 165 km in deep low gradient reaches). In all cases the calculated backwater effect was longer than the length of the Reach (i.e. backwatering was predicted to extend up the full length of the Long Sault and Manitou Rapids).

Using the validated HEC-RAS model, we simulated the outflow of Rainy River for the State of Nature case with no backwater effect from the Lake of the Woods, by running Normal_Depth.m without adjusting the channel invert. The results indicate that the backwater effect from removing the influence of LOW completely (i.e. not just the 3 foot increase in LOW water levels considered in the State of Nature Case) extended up to at least Reach 3 (Figure 5.11). This result concurs with the first order

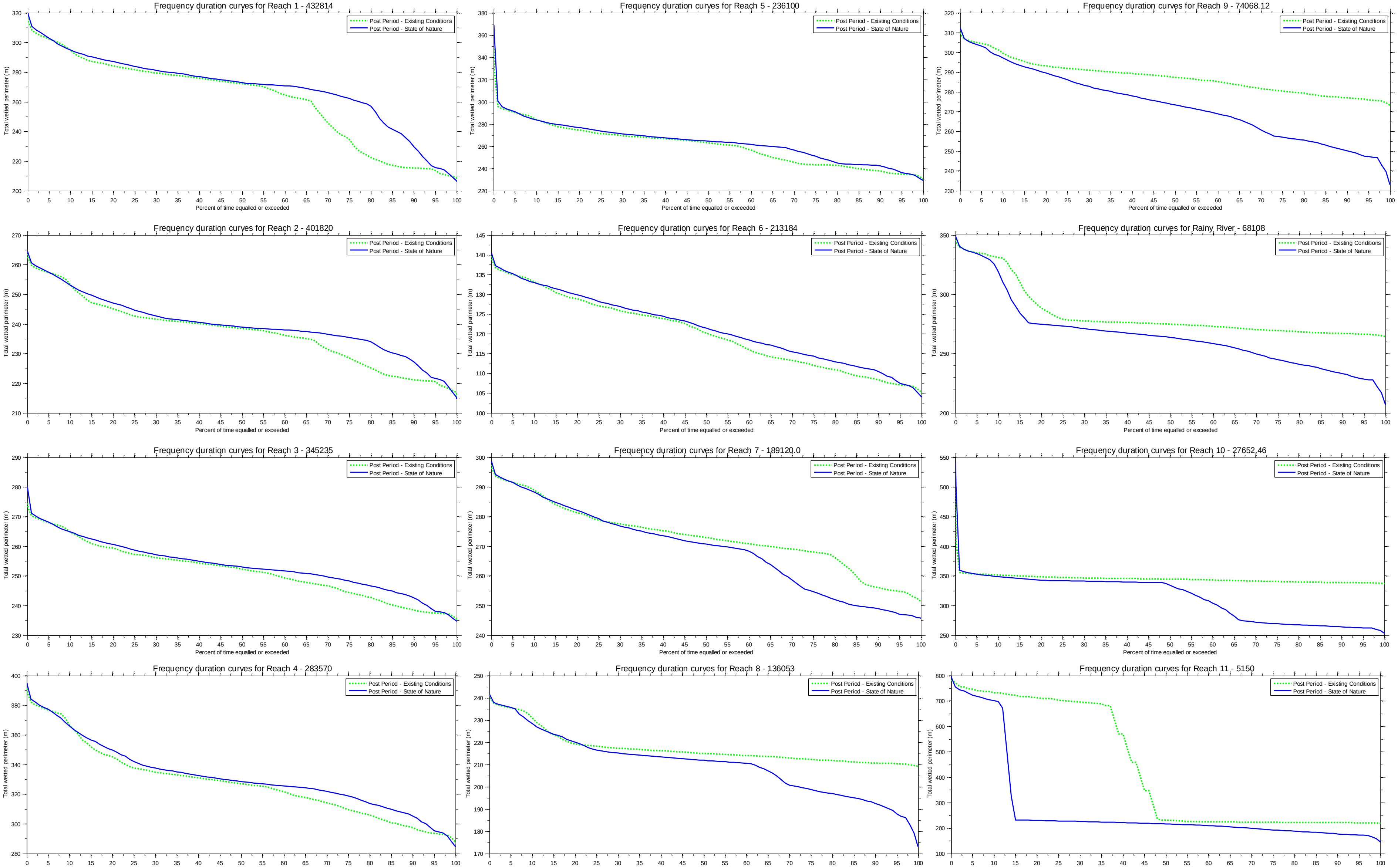


Figure 5.10 Frequency duration curves for wetted perimeter for the eleven response reaches between Fort Frances/International Falls and Lake of the Woods illustrating the difference between the observed (green dashed) and State of Nature (blue) cases for the post-rule curve period.

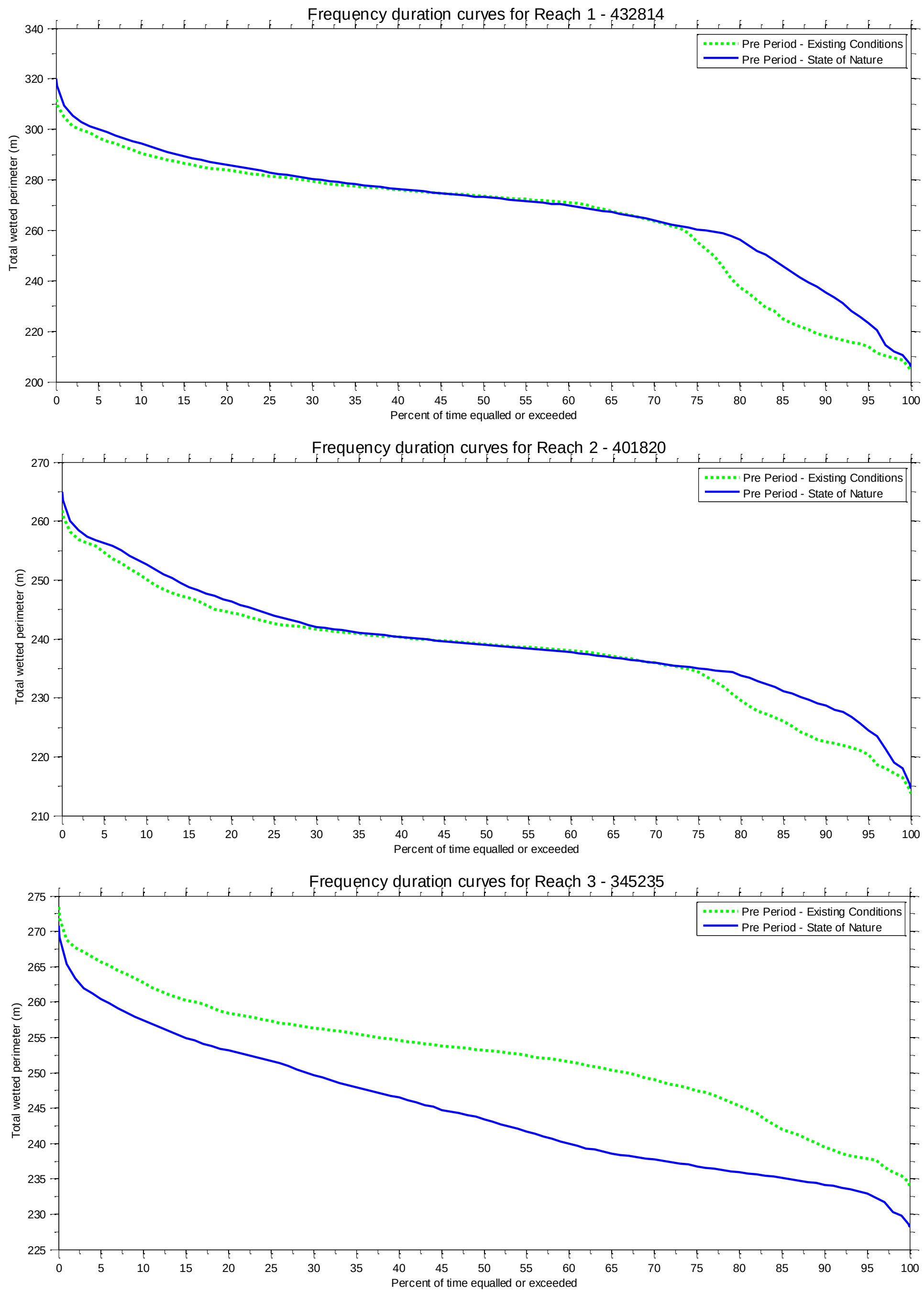


Figure 5.11 Frequency duration curves for wetted perimeter for the first three response reaches below Fort Frances/International Falls showing the difference between the observed flows (green dashed) and simulated removal of Lake of Woods (blue) for the pre-rule curve period.

approximation and with observations of water level fluctuations in the upper river that occur in the absence of flow releases from IFD.

5.4 Potential HEC-RAS model refinements

The HEC-RAS model has been calibrated at two points that are not boundary condition locations. Some further steps could be taken to increase confidence in the predictions being made between calibration locations:

1) Calibrate the model to downstream water surface and hydraulic data collected during the benthic survey data of May 2006 (Figure 5.12). Update downstream Manning's *n* using calculated Manning's *n* values from the ADCP data (Figure 5.13).

2) Calibrate the HEC-RAS model to downstream water surface elevation data extracted from the Lidar survey.

3) Use a riparian zone map to assign floodplain roughness values and vary Manning's n with depth either at each cross section or within the 11 reaches using the vary n with discharge function.

4) Incorporate the new updated HEC-RAS model from the study entitled "A study of the relationship of Rainy River hydrology to distribution and abundance of freshwater mussels".

5) As part of the model validation process, map the results using HEC-GEORAS. This step requires refining the DEM with bathymetric data and Lidar data (Figure 5.14). A discordance was discovered between the US and Canadian elevation data, despite being registered to the same datum.

6) Further investigate the errors associated with freeze up. Improvements can include:
   a) Refinement of predicted flows for small catchments for the winter period. Isolating the conditions promoting runoff initiation during winter months in smaller catchments may require threshold modeling with temperature as input.
   b) Defining seasonal roughness factors for the 11 response reaches identified in this study. The outlet reach at Lake of the Woods typically has ice conditions for 1-2 weeks after the river melts.

Other State of Nature Scenarios should also be investigated to characterize the range of potential error associated with this special case. Potential avenues of refinement include the following actions:

1) Rerun our State of Nature HEC-RAS model using the State of Nature rating curve for the Lake of the Woods as the downstream boundary condition.
2) Rerun our State of Nature model using the Lake of the Woods water levels as the downstream boundary condition, as simulated using the existing mass balance model used by the LWCB.

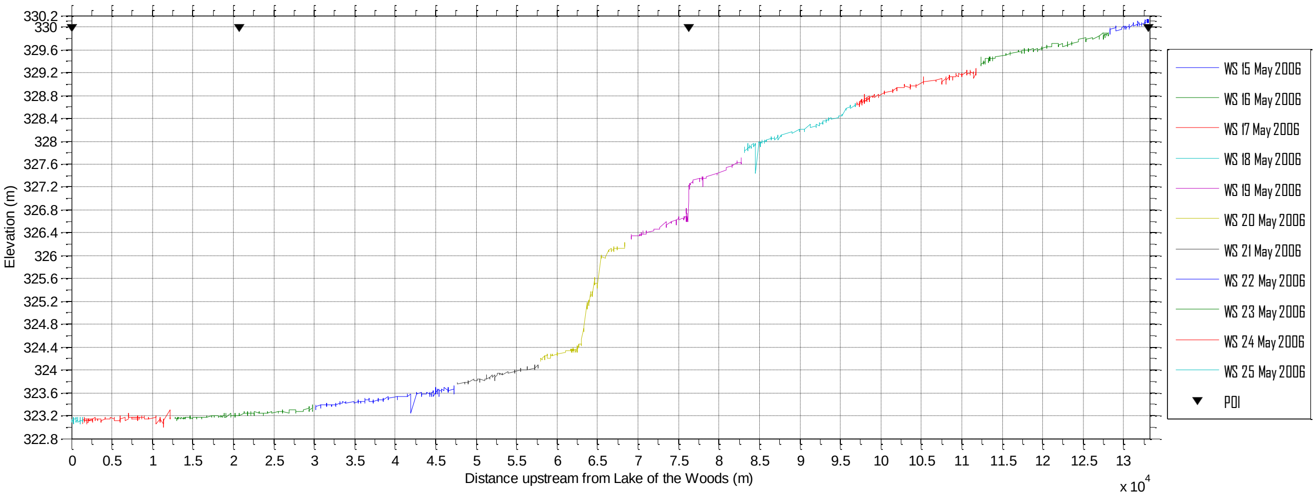


Figure 5.12 Water surface profile from the benthic survey of 2006.

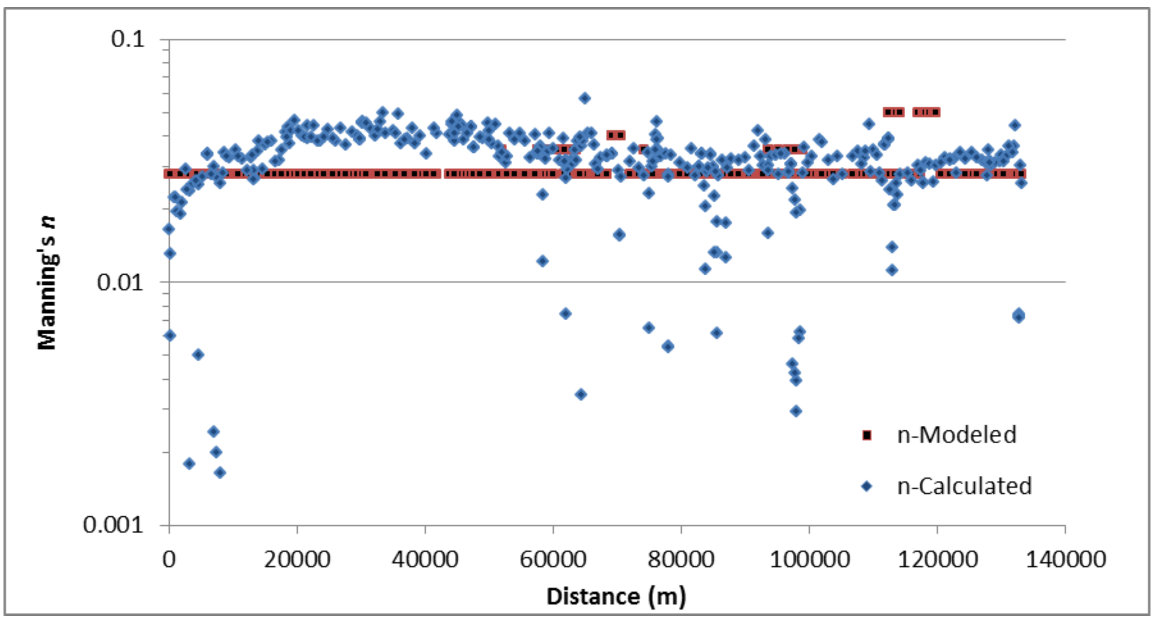


Figure 5.13 Manning's *n* values used in the HEC-RAS model and calculated from the 2006 survey versus distance upstream from Lake of the Woods. Note that the calculated Manning's *n* values are increased by an arbitrary offset and are actually lower than shown.

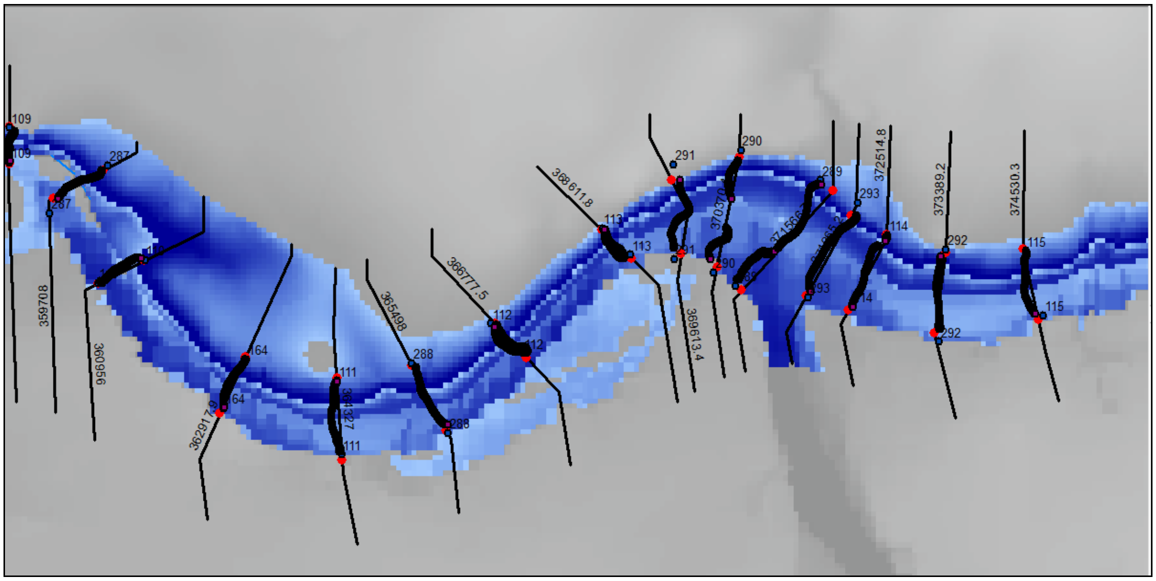


Figure 5.14 HEC-GEORAS mapping of results for the Rainy River showing the data seam down the centre of the river which results from merging Canadian and US digital elevation data.

SECTION 6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

We set out to document any differences in flow regime between the pre- and post- 2000 rule curve periods for observed and State of Nature conditions, to investigate the potential causes of any observed differences, and to determine the effect of any changes in the duration and timing of water levels and by extension, habitat availability. We examined changes in hydrology at IFD and hydraulic conditions at IFD and along the Rainy River using a HEC-RAS model. The key findings are summarized below:

HYDROLOGY

Are there changes in the flow regime of Rainy River between the pre- and post- 2000 periods?

Post- to Pre- Rule curve period differences in observed discharge at IFD

Differences in the hydrologic regime were investigated using the a) period of record flow duration curves, b) monthly flow duration curves, and c) flow metrics.

a) Period of record flow duration

There was a difference between the pre- and post-rule curve periods at IFD in terms of flow duration (Section 3.2.2.1 Figure 3.5). The flow duration curve for the post-2000 period was not within the limit bounds defined by the maximum and minimum extents of the decadal flow duration curves for the pre-2000 period. A greater percentage of time in the post-2000 rule curve period was spent at very low and very high flows. Given the more extreme runoff conditions in the post-period, the post- FDC curve strongly reflected the rule curve release targets. For example:

- The inflection point in the post-period FDC curve at 17% exceedance corresponds with the maximum turbine capacity of the Canadian generation station. Higher flows (up to 8 % exceedance) were of greater magnitude in the post-period for flows in excess of the maximum turbine capacity of the IFD facilities.
- Flows were near the 100 m^3s^{-1} low flow spill rate longer in the post- period (17% of the time), versus the pre-period (5% of the time), indicating the persistence of low Rainy Lake water levels.
- Flows persisted at the drought release discharge rate (65 m^3s^{-1}) longer in the post- period, maintaining flow rates higher than during the drought in the 1980's, but generally lower than other pre- period decades.

Flows between the maximum capacity of the U.S. (240 m^3s^{-1}) and Canadian hydroelectric facilities (354 m^3s^{-1}) occurred with the same frequency between pre- and post- periods.

b) Monthly flow duration

In the post-2000 period, the discharge at IFD was at or below the low flow release rate 50% of the time. The post-2000 monthly flow duration curves are more stepped in appearance, relative to the pre-2000 FDCs (Figure 3.8). In many months, more time was spent at the low flow release rate in the post-period. There was also more time spent at or above maximum turbine capacity implying higher volumes of water spilled in the post-period.

c) Flow metrics

Monthly median flows for April and June were outside the expected range of variability associated with the 1970-1999 period (Figure 3.9). In the post-rule curve period, the monthly median flows were lower in April and higher in June than expected from the pre-period.

Are these hydrologic trends associated with the change in rule curve ruling in 2000 or other factors (e.g. climate)?

Observed to SON (Reference Rivers) differences in discharge at IFD

The variability of observed flow exceedances at IFD was outside the range of flow variability for local, unregulated reference rivers (i.e. SON) for the pre-rule curve period (Section 3.2.2.2, Figure 3.6). Specifically, the observed flow duration curves were not contained within the limit bounds defined by the highest and lowest discharge values from the reference river flow duration curves. During the 1970-2000 rule curve period, the Rainy River at IFD had less extreme high flows, and more extreme low flows, relative to the reference rivers. Discharges also occurred at a higher frequency for mid-bank to bankfull flows at IFD, relative to the reference rivers.

The variability of observed flow exceedances at IFD was not outside the range of flow variability for local, unregulated reference rivers (i.e. SON) for the post-rule curve period (Section 3.2.2.3, Figure 3.7). The observed FDC is contained within the limits defined by the highest and lowest reference river FDC values. However, the Rainy River at IFD experienced flows being held at rule curve targets, as described above, unlike the reference rivers. The Rainy River FDCs were stepped in appearance, relative to the reference river FDCs. The extreme low flows at IFD were maintained for a longer duration, relative to the reference river mean FDC. Extreme high flows at IFD were lower relative to the unregulated rivers. This suggests that some mitigation of drought occurs in Rainy River as a result of flow regulation.

There appeared to be more variability in runoff response between reference rivers in the post- period, relative to the pre-period (c.f. Figure 3.6 & 3.7). This assertion was suggested by differences in the FDC plots for the reference rivers between periods. Specifically, the reference river FDCs were more widely distributed in the post-period relative to the pre- period, when the FDC curves were more tightly grouped. This apparent difference in flow variability between periods may be partially due to the shorter length of record length in the post-periods (i.e. 10 years vs. 30 years). The probability of the occurrence of extreme events generally decreases with length of record. This does not mean that a series of extreme events cannot occur at the beginning of the short, post- period of record. Ideally, it is best to make comparisons between periods of record of similar length. Regardless, other evidence suggests that flow variability increased in the post-period. There was an increase in extreme events late in the pre- period (1995), and throughout the post- period. Further, there was an increase in monthly precipitation and temperature in the post-rule curve period. These post-period trends in climate and the more extreme runoff response exhibited are consistent with being in the positive phase of the Atlantic Multi-decadal Oscillation cycle.

There is some uncertainty associated with using reference rivers that have basins smaller than IFD to represent SON conditions. Our reference basins have a similar physiography (Section 2.3.4) and regional climate to the IFD basin but the routing effects of Rainy Lake in the SON case are not considered by the proration method. Further, the reference basins are smaller than at IFD. Larger basins generally take longer to respond to rain events than smaller basins. Basins with large active lake storage volumes attenuate flows more than basins with less lake storage. In practice large basins with lake storage should have flatter flow duration curves, relative to small basins that lack storage. Given these concerns we tested for scale and storage effects. We could not find any statistically significant effect between the proration constant (see Equation 2.1) and both drainage basin area and percent lake area, considering a range of drainage basin areas

(458 km^2 to 50000 km^2) that encompasses our application of the method (Section 2.3.1.2). The effect of scale on predictive accuracy was substantial for drainage basins smaller than 458 km^2. The percent lake area is a surrogate for surface water storage but large lakes can have small active storage volumes depending on the lake bathymetry and outlet architecture. Thus, differences in routing effects may exist between IFD in SON and the reference basins despite our statistical test that employed percent lake area, unless the active storage in IFD is small relative to its aerial extent.

Given the above caveats, there are a few possible explanations for the observed differences in flow pattern relative to the SON reference river case at IFD. If the effects of scale and lake storage are minimal, as our statistical analysis suggests, the higher extreme high flows and higher extreme low flows observed in the pre-period are not driven by climate, as is the case in the reference basins. Further, for the post- rule curve period, the containment of the flow duration curve at IFD within the range of variability for the reference rivers suggests that any flow regulation during this period helped keep the Rainy River within the expected range of variability for climate driven flow patterns on natural rivers. However, if the scale and lake storage effects are larger than we have detected, these effects can explain the lower extreme high flows, and higher extreme low flows, relative to the reference rivers during the 1970-2000 rule curve period. The uncertainty in this reference river comparison led to further analysis using simulated flows at IFD (see below), and a statistical analysis of climatic and regulation effects (see Hydraulics section below).

Observed to SON (Simulated Using Method 1) differences in monthly flow duration at IFD

The effect of flow management on the Rainy River discharge at IFD was evident in the stepped appearance of the monthly flow duration curves, where the steps occurred at release rate targets, in both the pre- and post- rule curve periods. However, the relative influence of climate or regulation on changes in the monthly flow pattern was not clear from the FDC comparison plots for the observed and SON case (Figure 3.8). Conformance with the SON rule curve can result from a combination of the climate and management regime during each period. In general, the post -2000 rule curve period was closer to the SON case for November through May and July. Under the post-2000 rule curve regulation regime, agreement between the altered and SON FDCs also improved in May and June for high magnitude flows.

Observed to SON (Simulated Using FDC Transference) differences in flow metrics at IFD

We examined the assumption of using the year 2000 for comparison of post- to pre- periods using Classification and Regression Trees (Section 3.3). Natural breaks in flow metrics occurred within the pre- and post- periods (e.g. 1975 1986, 1992, and 2002) but none were directly coincident with the year 2000 (Table 3.6). A few flow metrics were significantly different after the years 2001 to 2002: 1) Average monthly flow June 2001 (Increased by 1.9 times); 2) Average monthly flow August 2002 (Decreased X 0.5); 3) Average monthly flow September 2002 (Decreased X 0.6); 4) Date of minimum discharge 2002 (Shifted from 2 May to 2 September); 5) The number of high pulses 2002 (Decreased X 0.8); 6) Rise rate 2002 (Decreased X 0.5); 7) Fall rate 2002 (Decreased X 0.5); 8) Number of reversals 2001 (Decreased X 0.8). These flow characteristics in the post- rule curve period are more typical of a natural flow regime. The change in flow pattern indicated by the CART analysis is consistent with anticipated effects from both the cessation of hydro-peaking in the U.S. facility, and elimination of weekend ponding in the Canadian facility in 2001.

Linear trends in the flow metrics for the entire period of observation (1970 to 2010) were documented using linear regression (Table 3.2 & 3.3). No trends were detected for the SON flows simulated using either FDC transference or proration. Some changes were anticipated in the SON flow series as the positive phase of the AMO cycle started in 1995 (Figure 3.2), however simple linear regression does not detect oscillatory trends such as those generated by the AMO cycle. In contrast to the SON cases, the following significant trends were detected in the observed flow series: Increases in low pulse count and frequency of extreme low flows; and decreases in mean monthly flow in February and March, the three day minimum flow, low flows in February, March and April, and high peak flows. Most of these trends showed a consistent pattern throughout the pre- and post- period, without any change in year-to-year pattern to suggest that the trends are dependent on the rule curve change (Figures 3.3 & 3.4). A change in behaviour over the study period was observed in some variables but again, not temporally coincident with the rule curve change in 2000. For example, the annual variability in the 3 day minimum was less variable after 1988, the low pulse counts were much higher and variable between 1987 and 2002, the monthly flows in April were higher and more variable after 1996, and the extreme low flow frequency increased and was more variable after 1987. The change in pattern of these flow metrics may reflect the intensification of hydro-peaking activities between the late 1980's and 2001, and the change in the AMO cycle after 1995 (Figure 3.2). The presence of these confounding influences on the flow pattern makes isolation of pre- to post- 2000 rule curve flow regime differences challenging. This is because the climate and hydro-peaking periods are contemporaneous but out of phase with each other, and nearly coincident with the rule curve change. The comparison of pre- to post- distribution of flow regime metrics is not the best method to use for isolating causal linkages when the period specific distributions of a flow metric combines multiple confounding influences on the flow pattern that span both periods. Regardless, one would expect more evidence of a change in flow pattern in 2000 if the effects of the rule curve change were stronger than other confounding influences on runoff pattern.

Despite differences in mean values for the decades between 1970 and 2010, there was no significant difference ($p=0.05$) in mean monthly precipitation, snowfall or temperature between these decades (Section 4.1.3). However, the mean precipitation and temperature were higher in 2000-2010 relative to the three previous decades. These positive trends in precipitation and temperature in the post- rule curve period are consistent with entering the positive phase of the Atlantic Multi-decadal Oscillation, as shown in Section 3.1. The examination of runoff drivers in isolation can lead to erroneous conclusions about runoff trends because insignificant trends in water balance components (e.g. rainfall, snowfall) can collectively lead to significant trends in runoff.

The ten year post- rule curve period was too short to calculate extreme value statistics. The most extreme discharge events occurred in the current positive phase of the Atlantic Multi-decadal Oscillation cycle (i.e. after 1995, Section 3.1, Figure 3.1). There were only four years with discharges exceeding 1000 m^3/s at IFD during the 1970 to 2010 period. These discharges in order of highest to lowest occurred in 2002, 2001, 2008 and 1996, respectively. The post-period also had a lower minimum discharge, relative to the pre- period (Table 3.1).

We sought out other regional studies so we could place the flow regime changes for our study period within a longer term natural runoff regime context. St George (2008) inferred summer climate conditions in the Winnipeg River region from regional tree growth for the period AD 1783 to 2004. He used an extensive, multi-tree species record of tree ring data across the Winnipeg river system. For this 221 year record, there were only two periods when large ring widths were observed for three years in a row (1950-53 and 1999-2001), implying persistent cool wet conditions. St. George cautions that the association between tree ring widths and average annual flow conditions is weak on the Winnipeg River system, however, it is interesting to note that the maximum instantaneous flow observed on the Rainy River at Fort Frances in the year following these persistent cool wet conditions were similar (1140 m^3s^{-1} in 1954 and 1190 m^3s^{-1} in 2002). This observation may be coincidental, but the observation evokes the hypothesis that the flood flow conditions in 2002 were positively influenced by regional climate and the year-to-year antecedent water recharge conditions within the basin.

HYDRAULICS

Are there changes in river bed inundation in the Rainy River between pre- and post- 2000 periods and are these hydraulic trends associated with the change in rule curve ruling in 2000 or other factors (e.g. climate)?

A statistical analysis of output from the revised HEC-RAS model showed significant differences in duration curves between the rule curve periods for both water level and daily water level difference at IFD (Section 4.1, Table 4.5, Model 1). However, these differences were not significant if other factors were also considered such as climate, water levels in Rainy Lake and Namakan Reservoir or year of observation (Table 4.5, Model 2b). We included a variable in the statistical model that was a measure of the difference in water levels permitted between the two rule curve periods. This term was not significant for any month. These results collectively support the assertion that the pre- and post- hydraulic conditions in the Rainy River are influenced by climate and reservoir water levels. Thus, there was no strong evidence to suggest that the post- rule curve flow pattern was governed solely by the change in rule curve operation guidelines in 2000. An event based statistical analysis would be required to further parse out the relative effects of climate and management on post- rule curve hydraulic differences in the Rainy River. A complimentary analysis would involve using a routing model to help determine if a reduction in the active storage in one month (e.g. May) can affect the water levels in the Rainy River in subsequent months.

We investigated if there were differences in water level and daily stage range between the pre- and post- period for four stations downstream of IFD (Section 4.1). The serial discontinuity concept posits that the alteration caused by a discontinuity (e.g. dam) extends downstream until the effect can no longer be detected. Our results indicated two key findings (Table 5.3): 1) Significant differences in pre- to post- duration curves were detected for 110-130 km downstream of the dam for a) water levels in winter months (Dec-March), and for b) daily stage differences in February to April.; and 2) Significant differences in pre- to post- duration curves were detected > 130 km downstream for a) water level in June, July, September and October, and b) daily stage differences in August.

There was a difference in wetted perimeter frequency duration curves between the pre- and post-rule curve periods along the Rainy River (Section 5.3.1). The wetted perimeter increased in the post-period for floodplain and baseflows, relative to the pre- development period. However, the wetted perimeter decreased per given exceedance value in the post-period for all other sub-bankfull flows. The difference in wetted perimeter between the post- and pre- periods decreases with distance downstream, being minimal below the Rapid River (Reaches 9-11). This downstream trend can result from both the decreasing influence of releases from IFD, and increasing influence of both confluent tributaries and the backwater from LOW.

There was a difference in wetted perimeter frequency duration curves between the observed and State of Nature cases for the pre-rule curve periods along the Rainy River (Section 5.3.2). The largest difference between the observed and State of Nature wetted perimeter duration curves for the pre-rule curve period occur in the lower river from Reach 7 to Lake of the Woods. The backwater effect of raising the water level in LOW by an average of 0.9 m was illustrated using wetted perimeter duration curves. This turn of the century increase in LOW water levels resulted in more frequent inundation of the State of Nature channel and floodplain. Thus the change in river habitat between the State of Nature case and pre- rule curve period was most pronounced below the Long Sault Rapids. This change would shift the lower river to a more lentic state, relative to the SON case.

The other notable difference between the observed and State of Nature wetted perimeter duration curves for the pre-rule curve period occurs in the upper river between Reach 1 and Reach 6 (Figure 5.9). There are two key differences:

1) The main difference is that the observed wetted perimeter is narrower more frequently (i.e. exceeded between 75% and 100% of the time), relative to the State of Nature. As expected this effect diminishes with distance downstream, but is masked by the larger backwater effect after Reach 6. Thus, the regulation effect of IFD is to reduce the amount of useable habitat in the baseflow to mid-bankfull flow range.

2) The wetted perimeter is also narrower for infrequent, riparian flows (i.e. exceeded between 0.1% and 35% of the time), relative to the State of Nature. This suggests that a narrower band of floodplain is inundated for a given frequency of flow in the upper river.

There was a difference in wetted perimeter frequency duration curves between the observed and State of Nature cases for the post-rule curve periods along the Rainy River (Figure 5.10). The differences between the observed and State of Nature wetted perimeter curves in the upper river were slightly larger in the post-rule curve period. The wetted perimeter during the extreme low flow exceedances (e.g. >95%) were slightly higher for the post-period SON comparison in both the upper and lower river, relative to the pre-period SON comparison. The alteration in wetted perimeter was larger between the observed case and SON case, relative to the pre- to post-rule curve periods. The length backwater effect of LOW is seasonally variable and dependent on LOW water levels (Section 5.3.4). At high LOW water levels, the backwater effect can extend upstream 110 + km. Lowering the LOW water levels to State of Nature conditions causes much less backwatering in the lower river, particularly downstream of the Long Sault Rapids. Relatively small changes in LOW water levels can change the hydraulic conditions over long distances of the lower Rainy River. This provides a potential management opportunity to meet habitat targets in the Rainy River, beyond flow regulation in the Namakan Reservoir and Rainly Lake.

Inferences related to the effects of the Namakan River reservoir rule curve resulting from our statistical analysis should be evaluated within the context of the study entitled “Develop a hydrologic reservoir routing model for Rainy Lake and the Namakan Reservoir to assess the hydrodynamic changes due to the 2000 Rule Curves.” The HEC-RAS model has been calibrated at two points that are not also boundary condition locations. For studies requiring more refined and spatially distributed river stage estimates, some further steps could be taken to increase confidence in the predictions being made between calibration locations. These model-related recommendations are provided in Section 5.4.

6.2 Rule curve related recommendations

1) Inferences related to the effects of the Namakan River reservoir rule curve resulting from our statistical analysis should be evaluated within the context of the study entitled “Develop a hydrologic reservoir routing model for Rainy Lake and the Namakan Reservoir to assess the hydrodynamic changes due to the 2000 Rule Curves.”

2) Further statistical analyses should consider applying a nonparametric mixed effects model and adding more refined management related measures such as events when the water levels in the reservoirs exceed the rule curve limits.

3) The statistical models can be further mined to illustrate how the system may respond to management actions such as changing the upper or lower rule curve limit.

6.3 HEC-RAS related recommendations

The assessment of ecological impacts using the Hec-Ras model typically requires different levels of refinement of the hydrologic model, depending on the question being addressed (e.g. which species, which life cycle, what time of the year, etc). Our hydrologic and hydraulic assessment and conclusions primarily focused on locations where data exist for model validation and encompassed a range of flows. The HEC-RAS model has been calibrated at two points that are not boundary condition locations. A comprehensive list of recommendation for further refinement of the Hec-Ras model are provided in Section 5.4. Three of primary recommendations are:

1) Incorporate the new updated HEC-RAS model from the study entitled "A study of the relationship of Rainy River hydrology to distribution and abundance of freshwater mussels".
2) Calibrate the model to downstream water surface and hydraulic data collected during the benthic survey data of May 2006 (Figure 5.12). Update downstream Manning's *n* using calculated Manning's *n* values from the ADCP data (Figure 5.13). Calibrate the HEC-RAS model to downstream water surface elevation data extracted from the Lidar survey.
3) Use a riparian zone map to assign floodplain roughness values and vary Manning's n with depth either at each cross section or within the 11 reaches using the vary n with discharge function.

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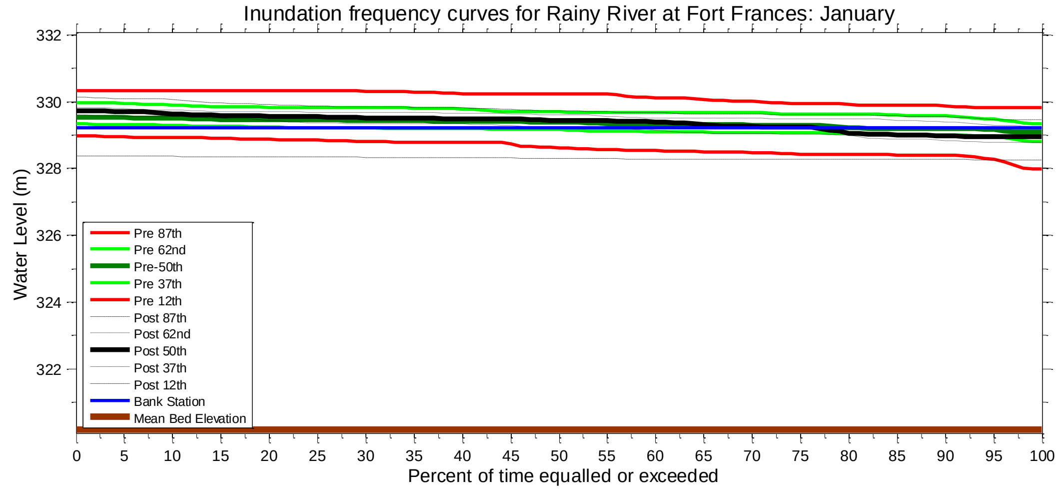
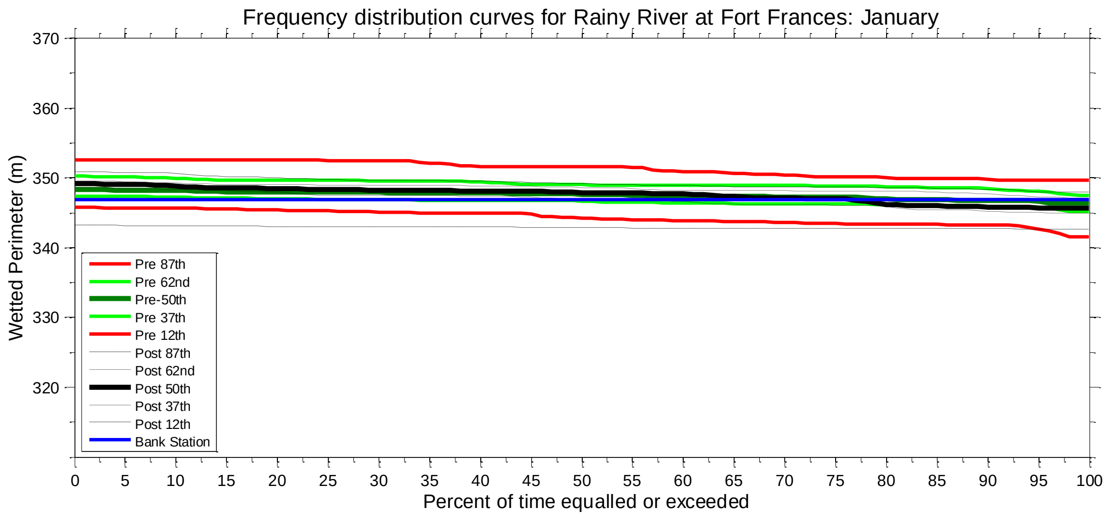
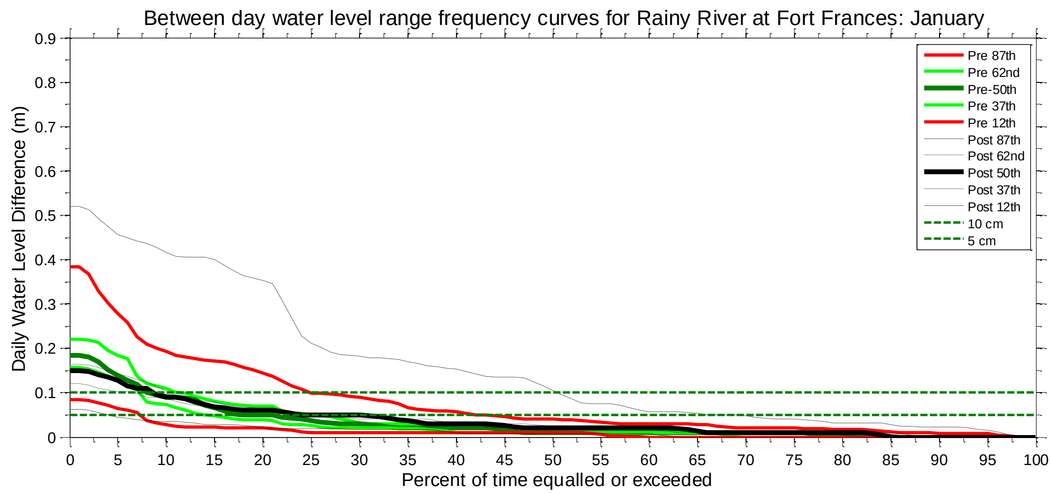
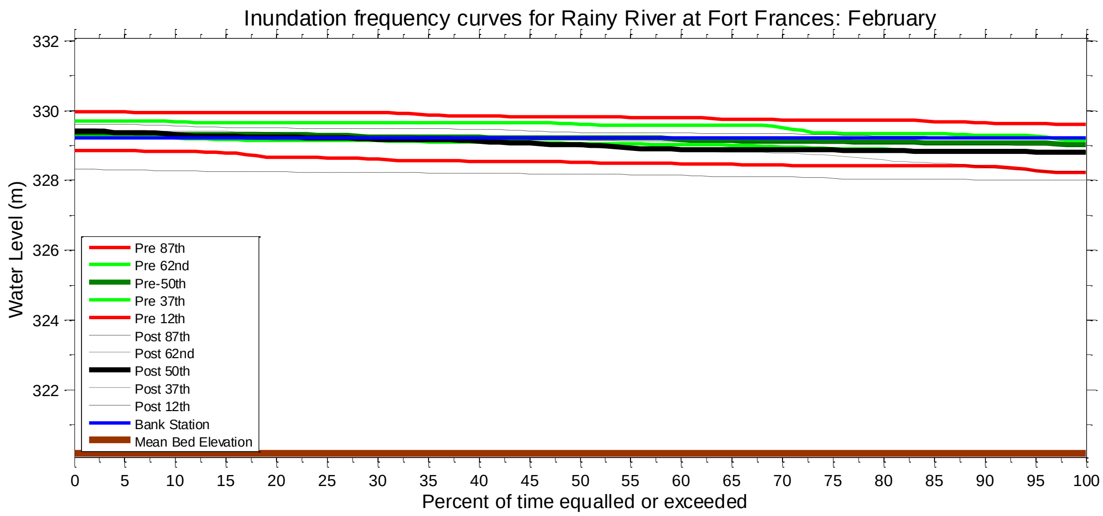
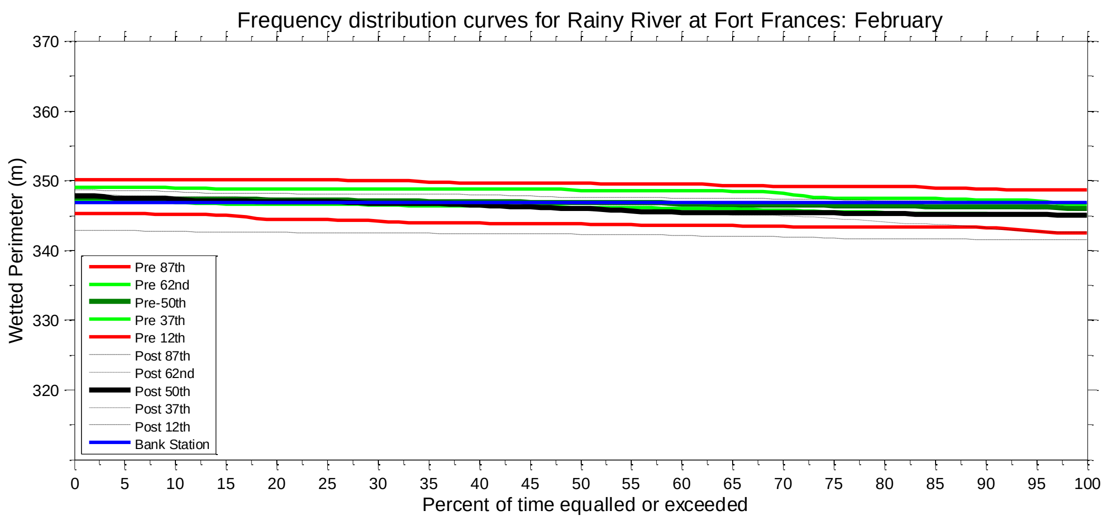
Appendix 1 Pre- and Post- cumulative distribution curves of water level, wetted perimeter and daily water level difference for Fort Frances.

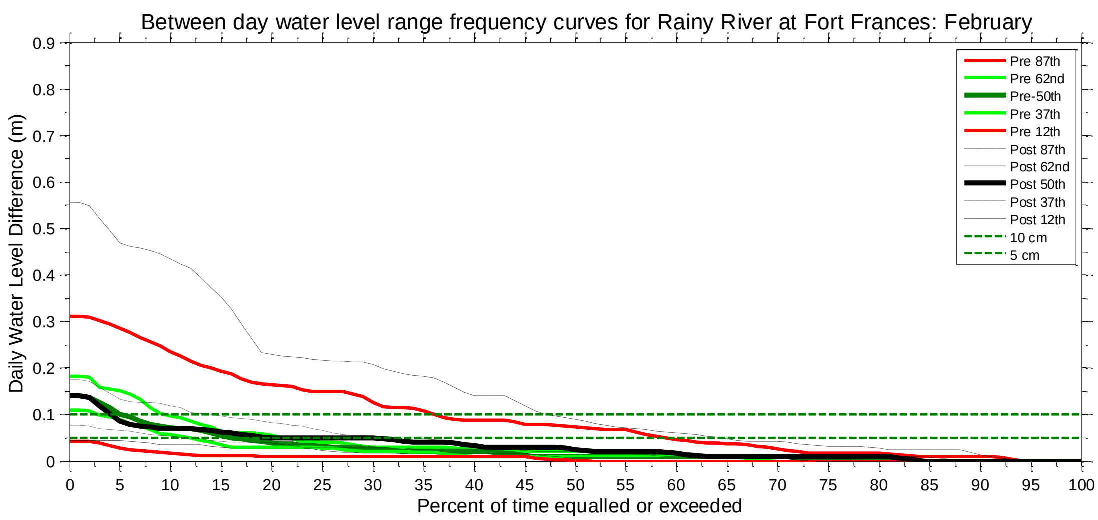


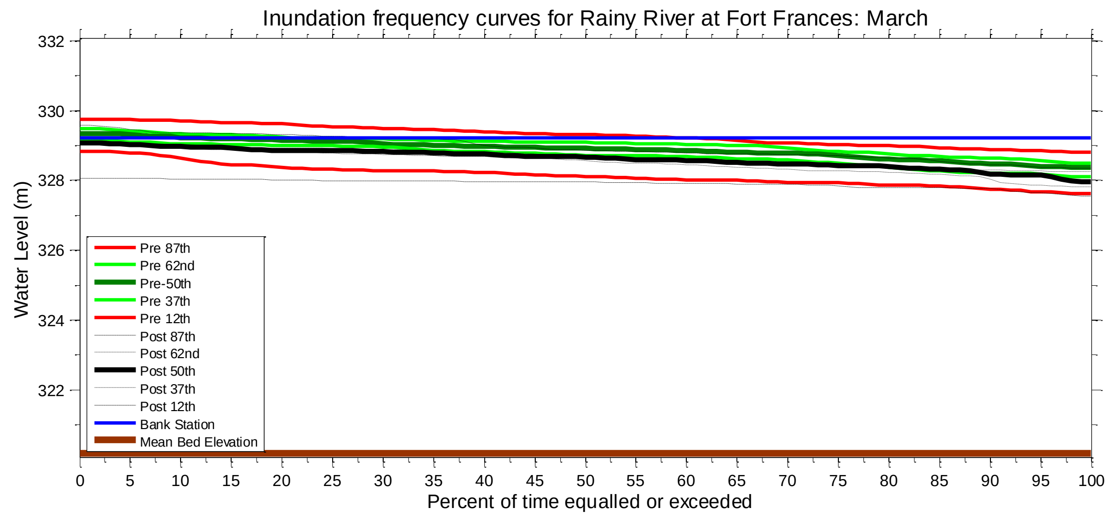




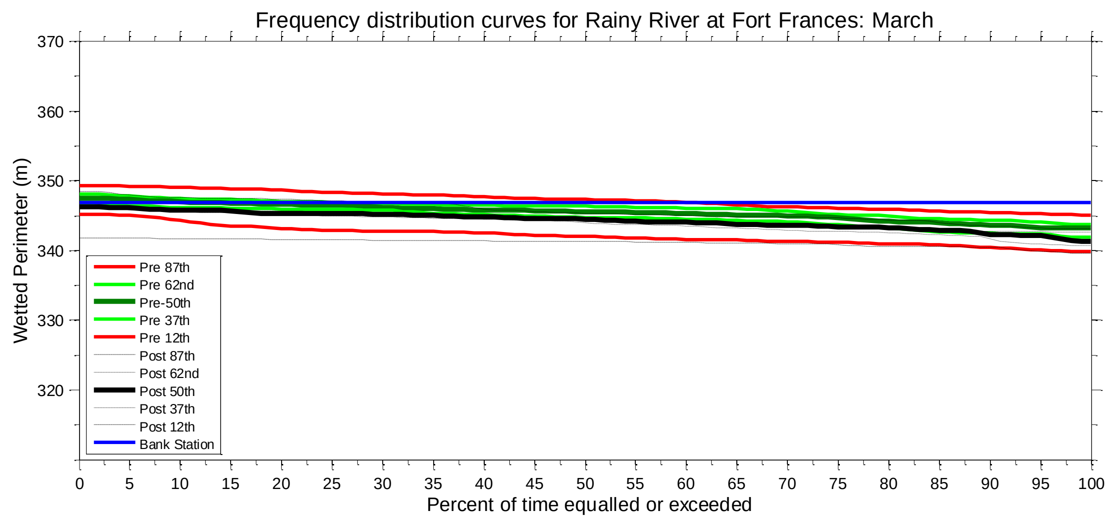

Inundation frequency curves for Rainy River at Fort Frances: February
Water Level (m)
332
330
328
326
324
322
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
Mean Bed Elevation
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded


Frequency distribution curves for Rainy River at Fort Frances: February
Wetted Perimeter (m)
370
360
350
340
330
320
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded

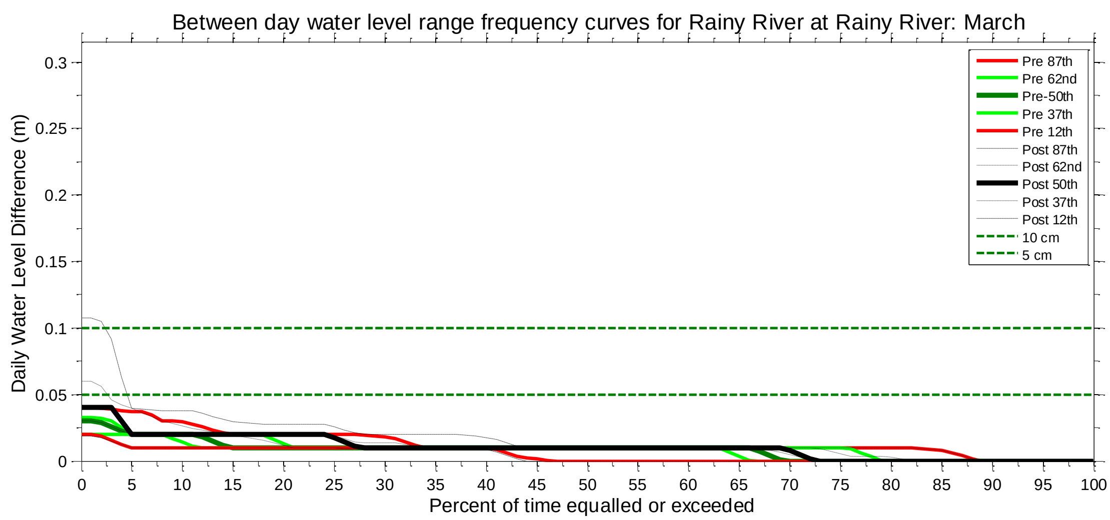

Between day water level range frequency curves for Rainy River at Fort Frances: February
Daily Water Level Difference (m)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
10 cm
5 cm
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded



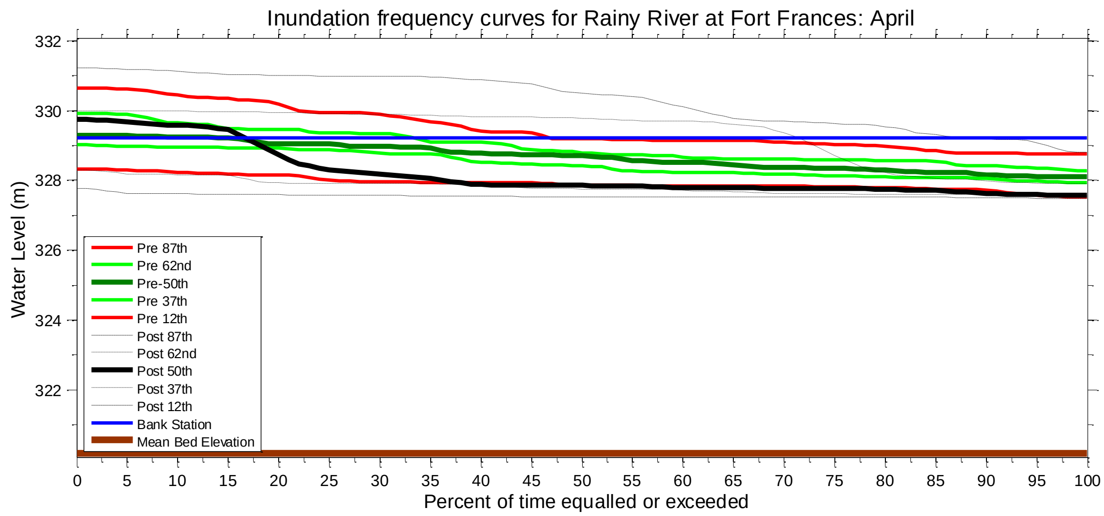
Inundation frequency curves for Rainy River at Fort Frances: March
Water Level (m)
332
330
328
326
324
322
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
Mean Bed Elevation
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded

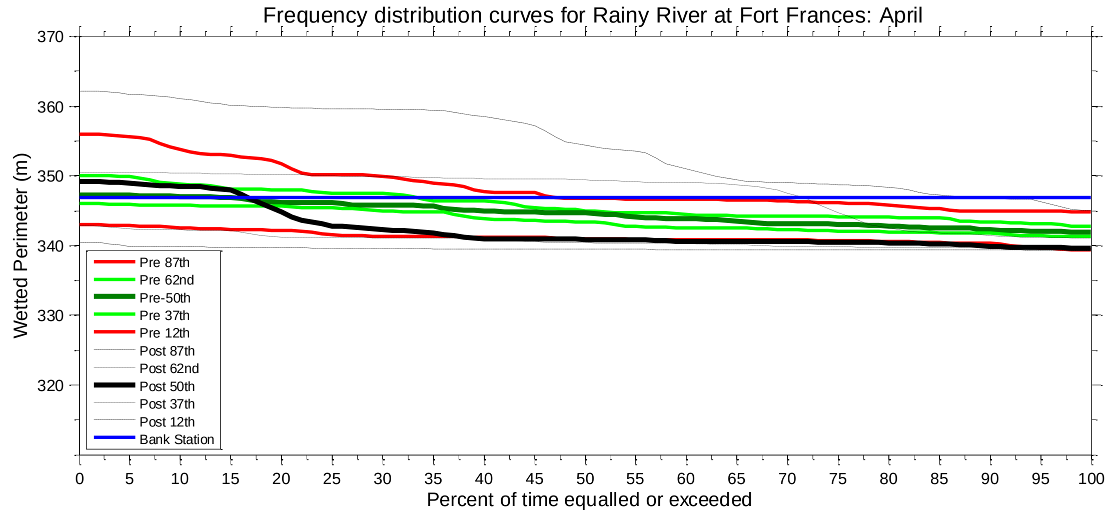


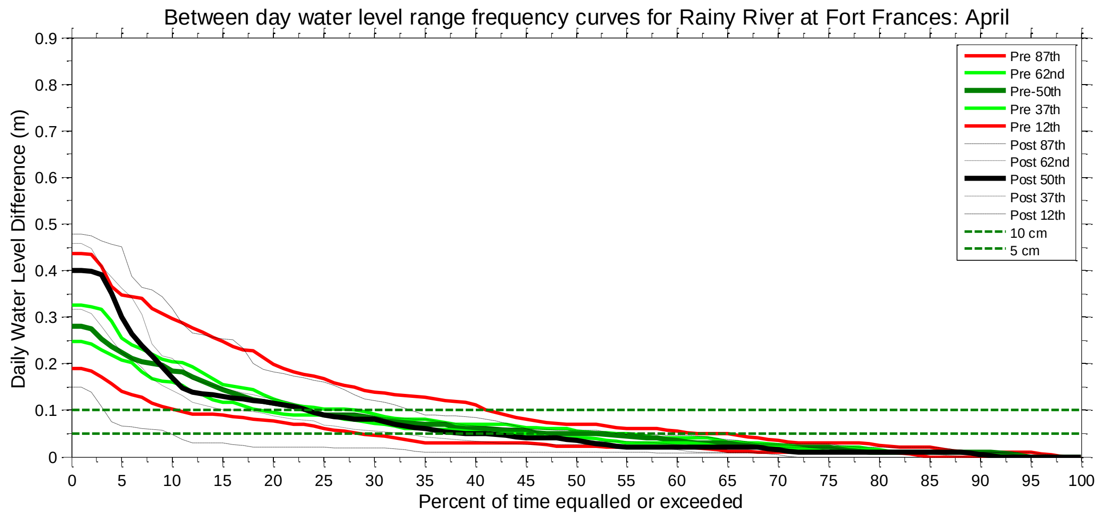
Frequency distribution curves for Rainy River at Fort Frances: March
Wetted Perimeter (m)
370
360
350
340
330
320
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded

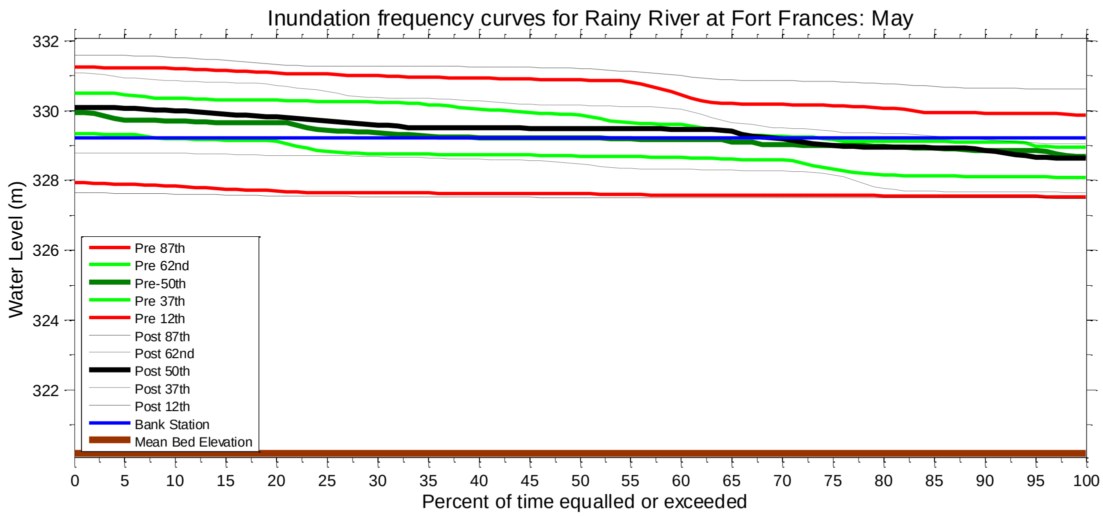


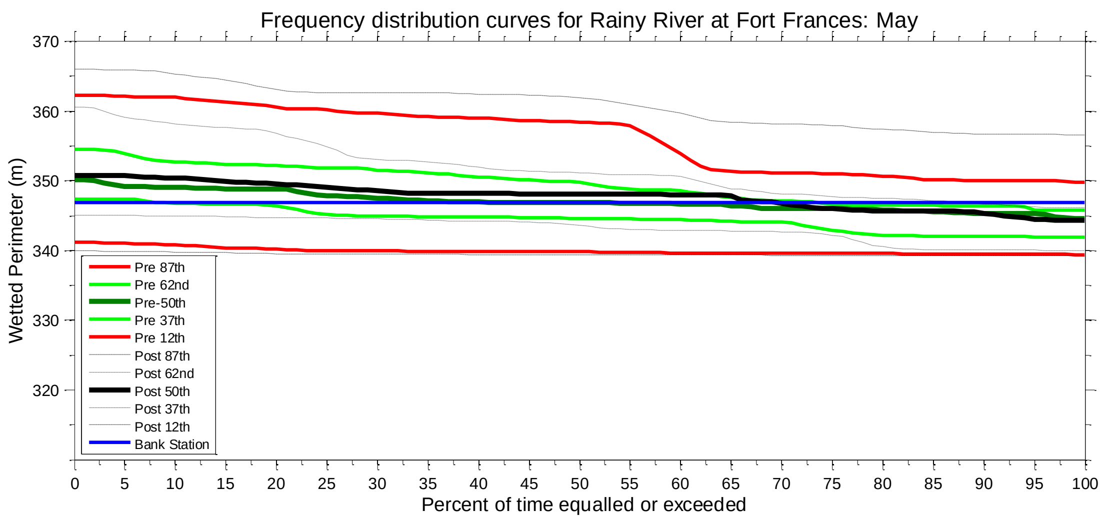
Between day water level range frequency curves for Rainy River at Rainy River: March
Daily Water Level Difference (m)
0.3
0.25
0.2
0.15
0.1
0.05
0
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
10 cm
5 cm
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded

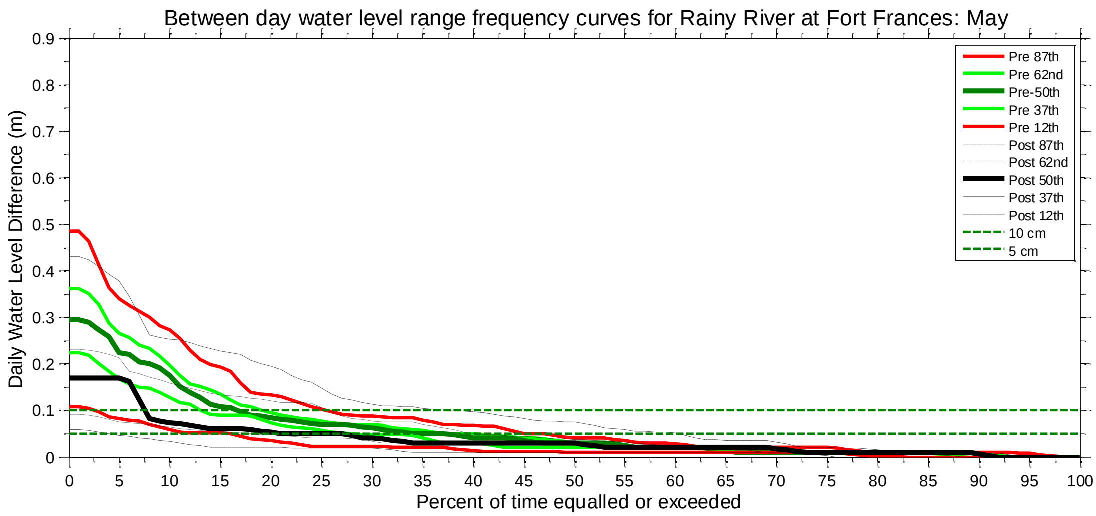

Inundation frequency curves for Rainy River at Fort Frances: April
Water Level (m)
Percent of time equalled or exceeded
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
Mean Bed Elevation

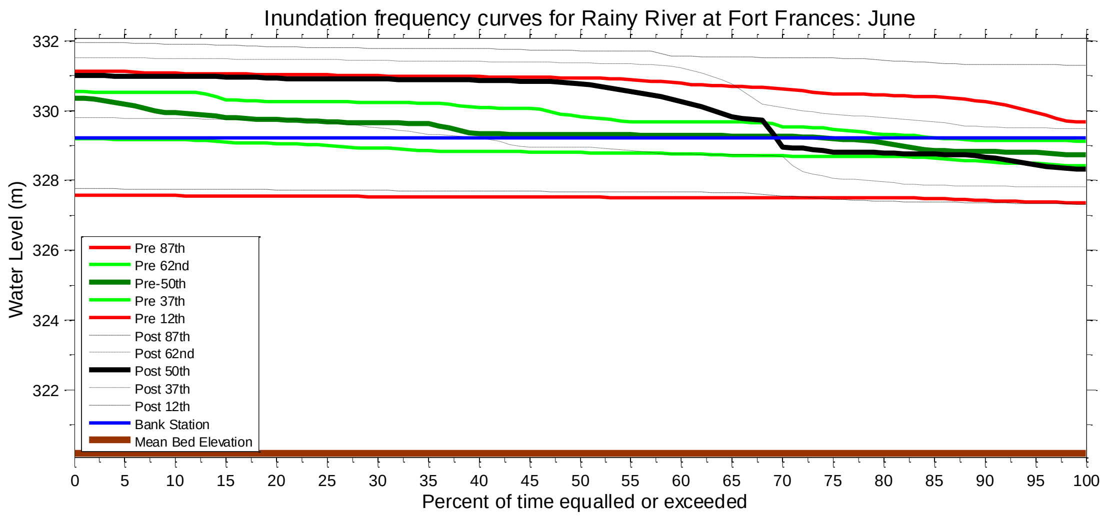

Frequency distribution curves for Rainy River at Fort Frances: April
Wetted Perimeter (m)
Percent of time equalled or exceeded
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station

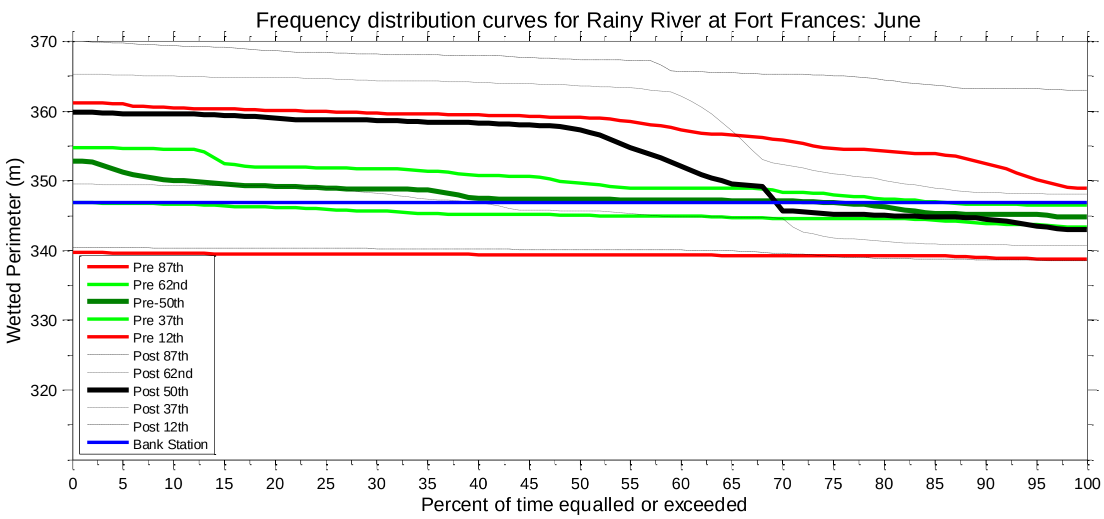

Between day water level range frequency curves for Rainy River at Fort Frances: April
Daily Water Level Difference (m)
Percent of time equalled or exceeded
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
10 cm
5 cm

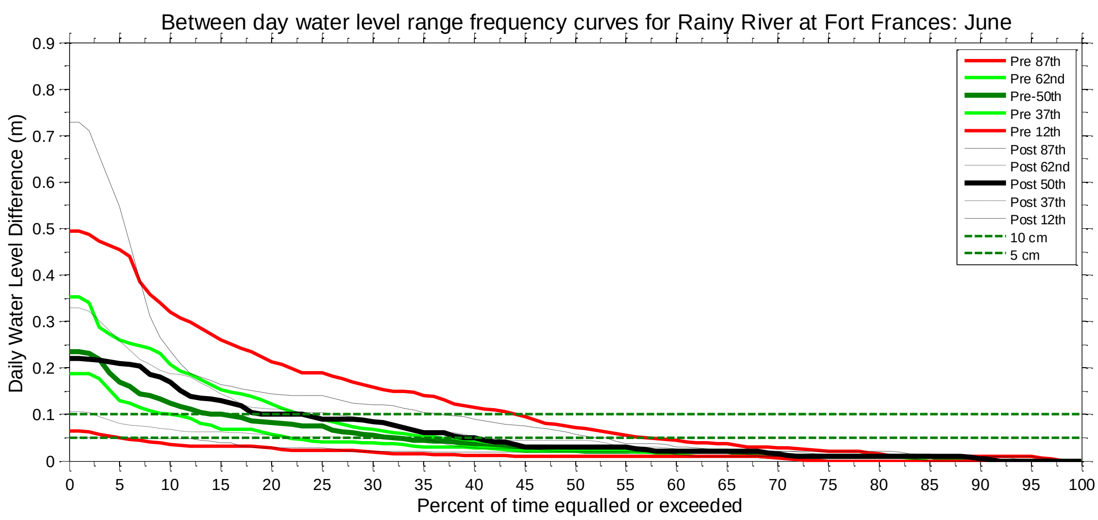

Inundation frequency curves for Rainy River at Fort Frances: May
Water Level (m)
332
330
328
326
324
322
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
Mean Bed Elevation
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded

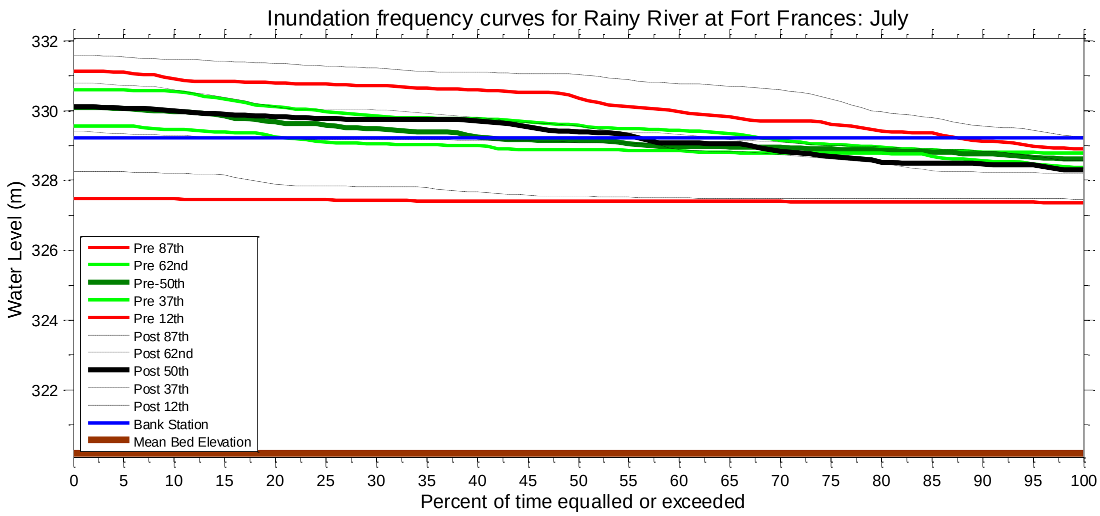

Frequency distribution curves for Rainy River at Fort Frances: May
Wetted Perimeter (m)
370
360
350
340
330
320
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded

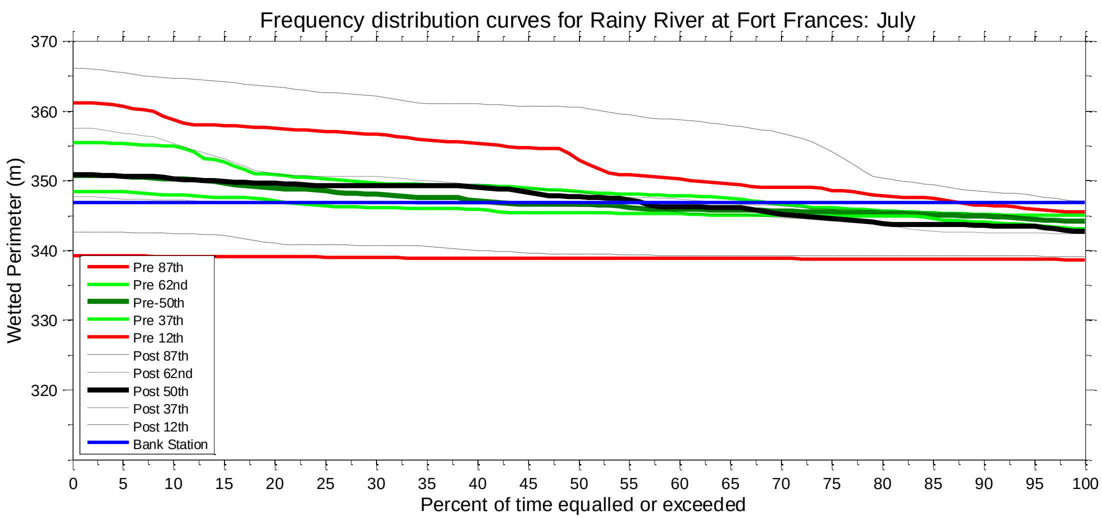

Between day water level range frequency curves for Rainy River at Fort Frances: May
Daily Water Level Difference (m)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
10 cm
5 cm
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded

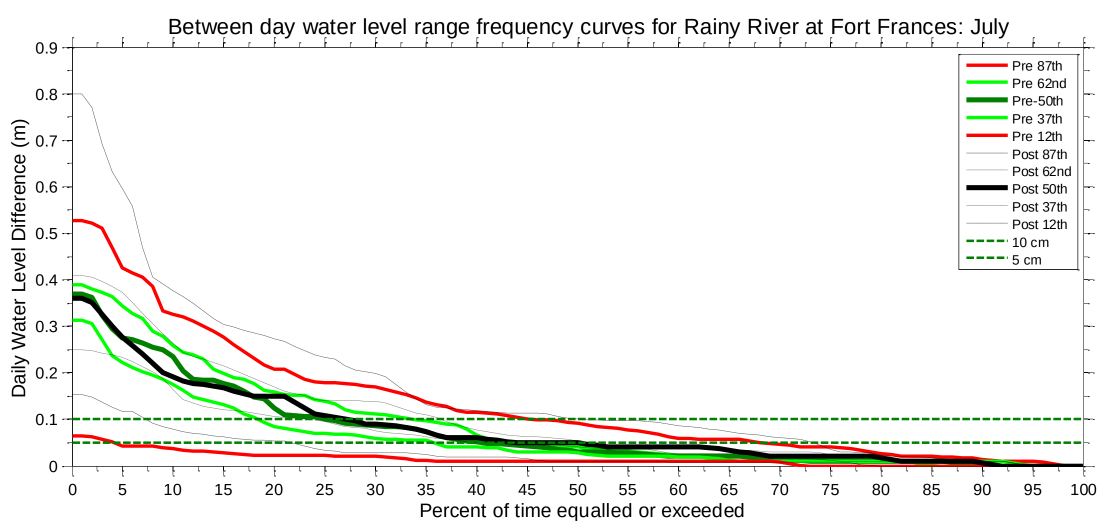

Inundation frequency curves for Rainy River at Fort Frances: June
Water Level (m)
Percent of time equalled or exceeded
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
Mean Bed Elevation

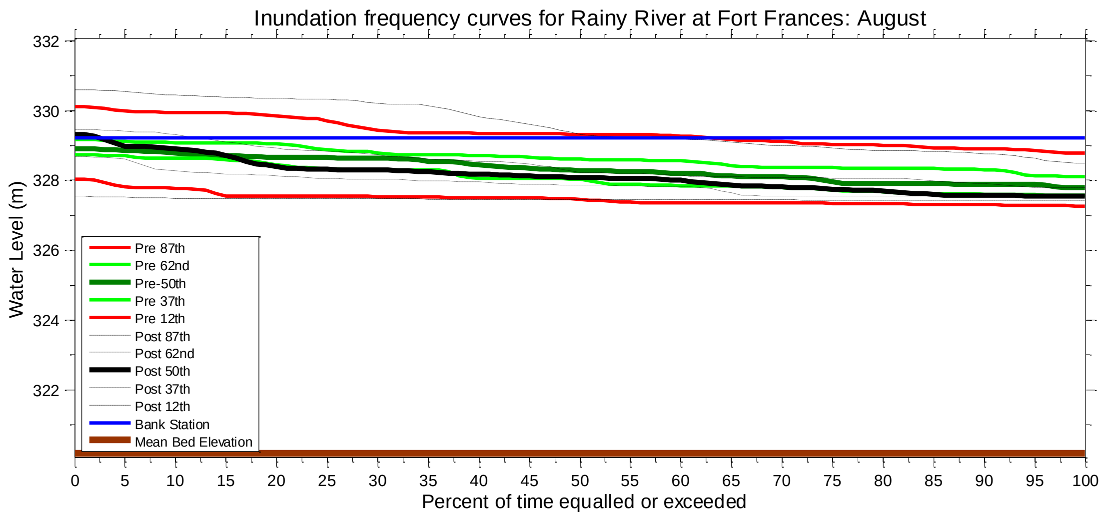

Frequency distribution curves for Rainy River at Fort Frances: June
Wetted Perimeter (m)
Percent of time equalled or exceeded
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station

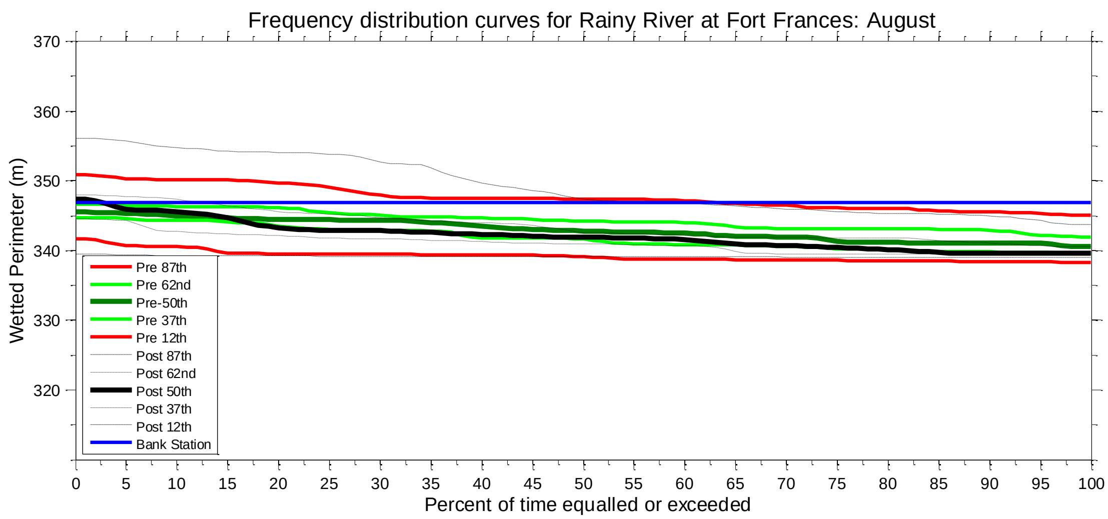

Between day water level range frequency curves for Rainy River at Fort Frances: June
Daily Water Level Difference (m)
Percent of time equalled or exceeded
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
10 cm
5 cm

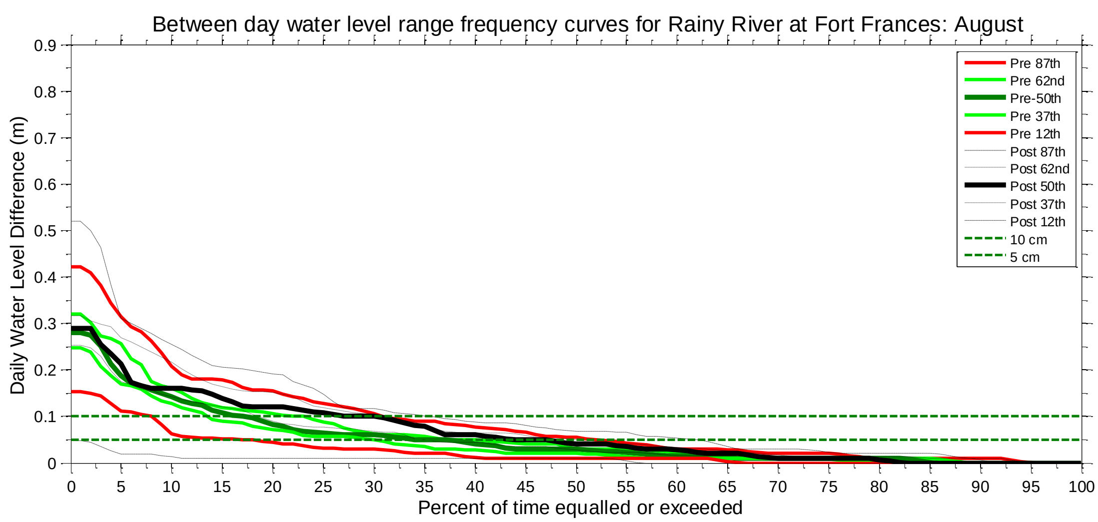

Inundation frequency curves for Rainy River at Fort Frances: July
Water Level (m)
Percent of time equalled or exceeded
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
Mean Bed Elevation

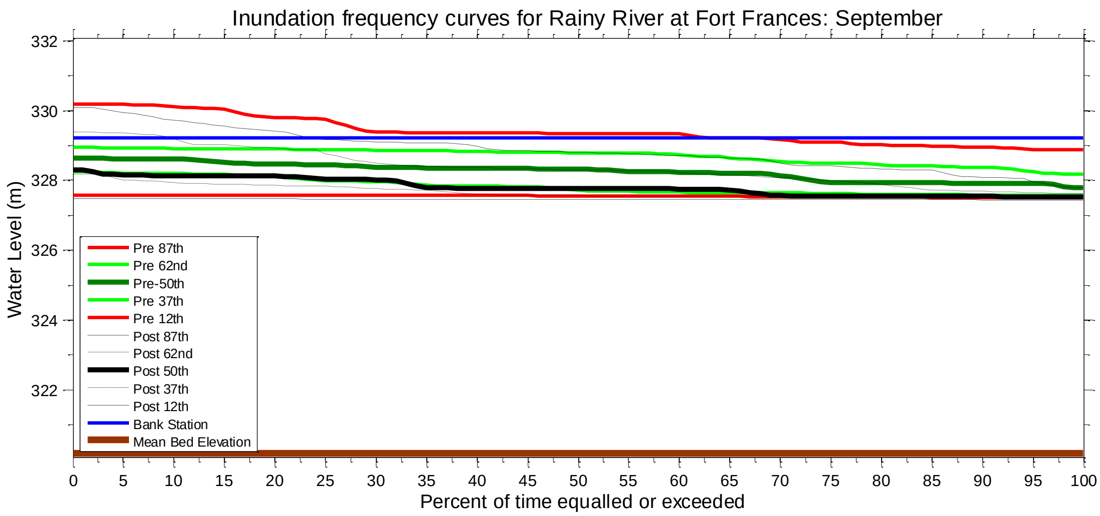

Frequency distribution curves for Rainy River at Fort Frances: July
Wetted Perimeter (m)
Percent of time equalled or exceeded
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station

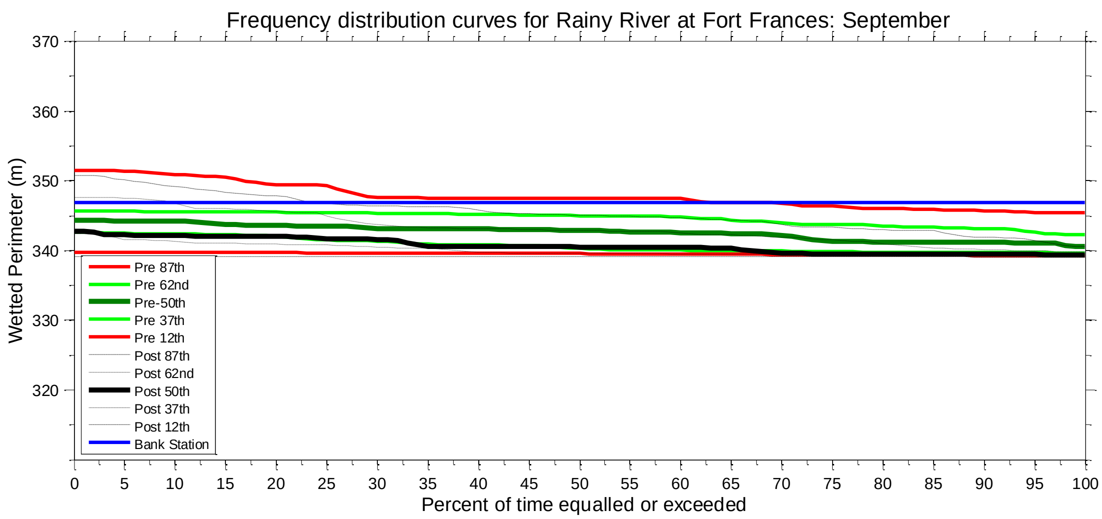

Between day water level range frequency curves for Rainy River at Fort Frances: July
Daily Water Level Difference (m)
Percent of time equalled or exceeded
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
10 cm
5 cm

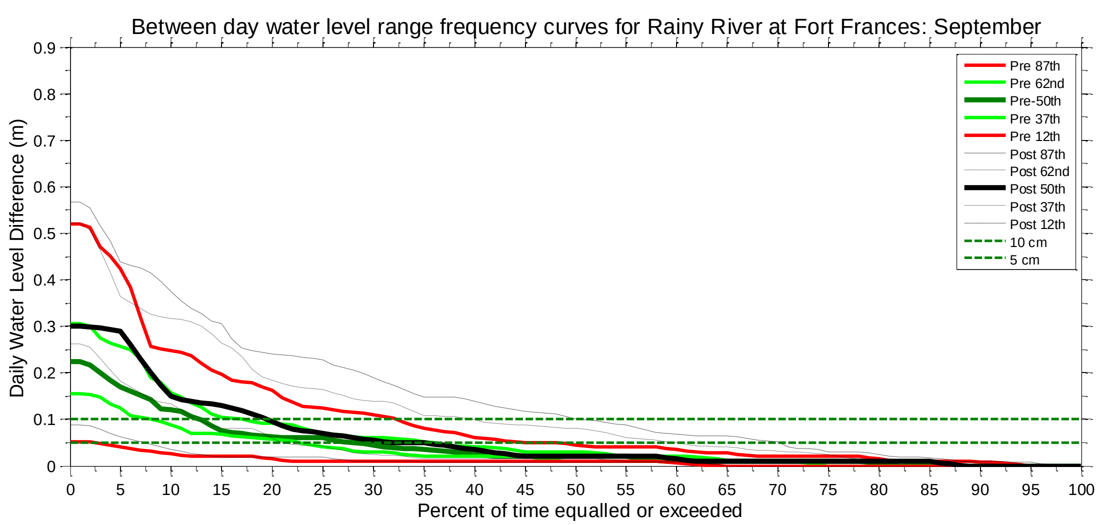

Inundation frequency curves for Rainy River at Fort Frances: August
Water Level (m)
332
330
328
326
324
322
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
Mean Bed Elevation
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded

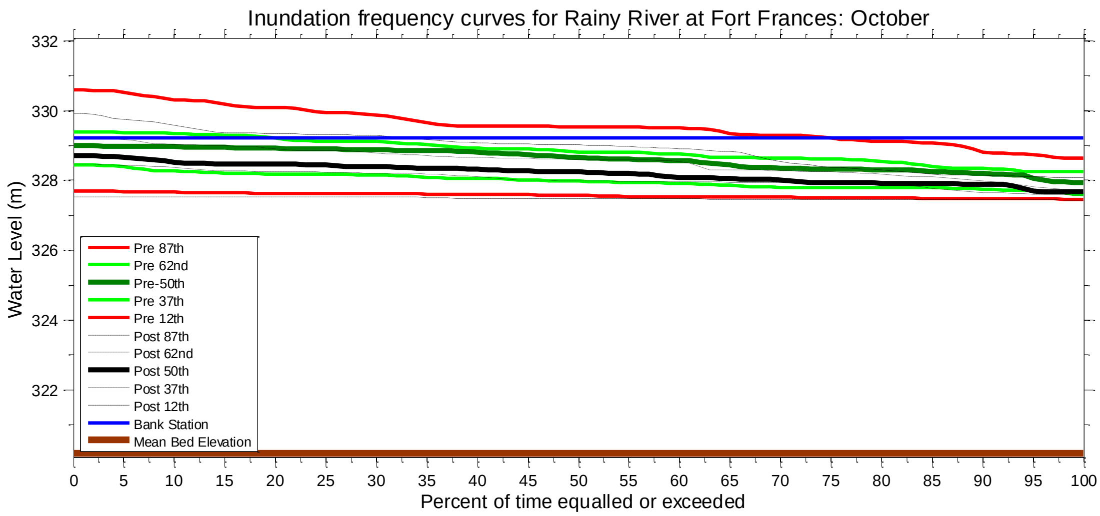

Frequency distribution curves for Rainy River at Fort Frances: August
Wetted Perimeter (m)
370
360
350
340
330
320
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded

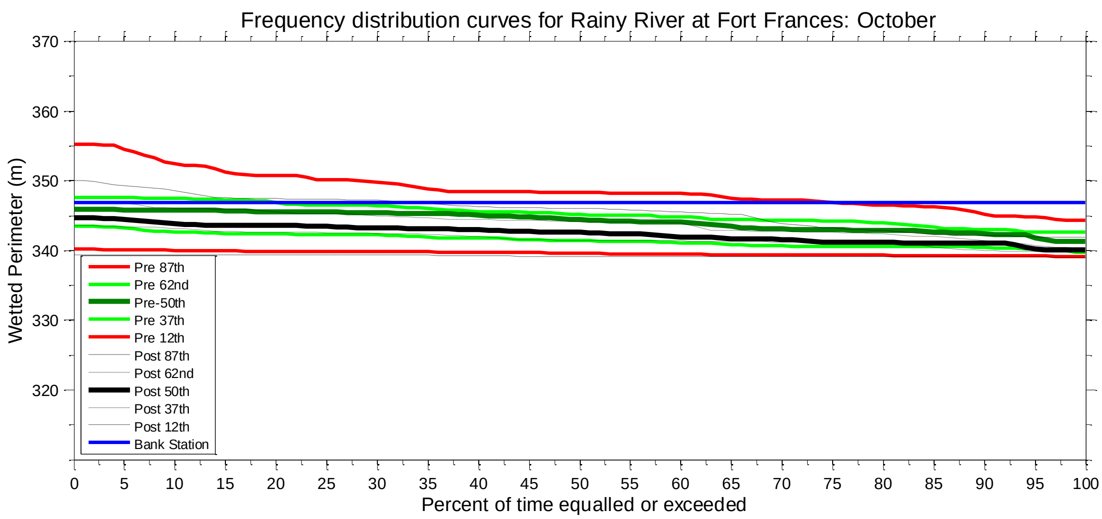

Between day water level range frequency curves for Rainy River at Fort Frances: August
Daily Water Level Difference (m)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
10 cm
5 cm
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded

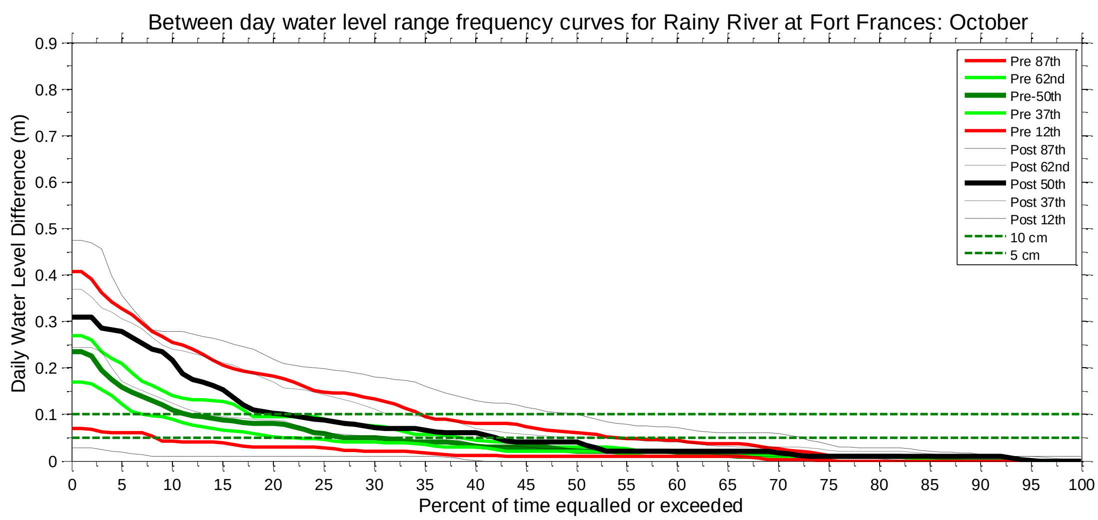

Inundation frequency curves for Rainy River at Fort Frances: September
Water Level (m)
332
330
328
326
324
322
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
Mean Bed Elevation
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded

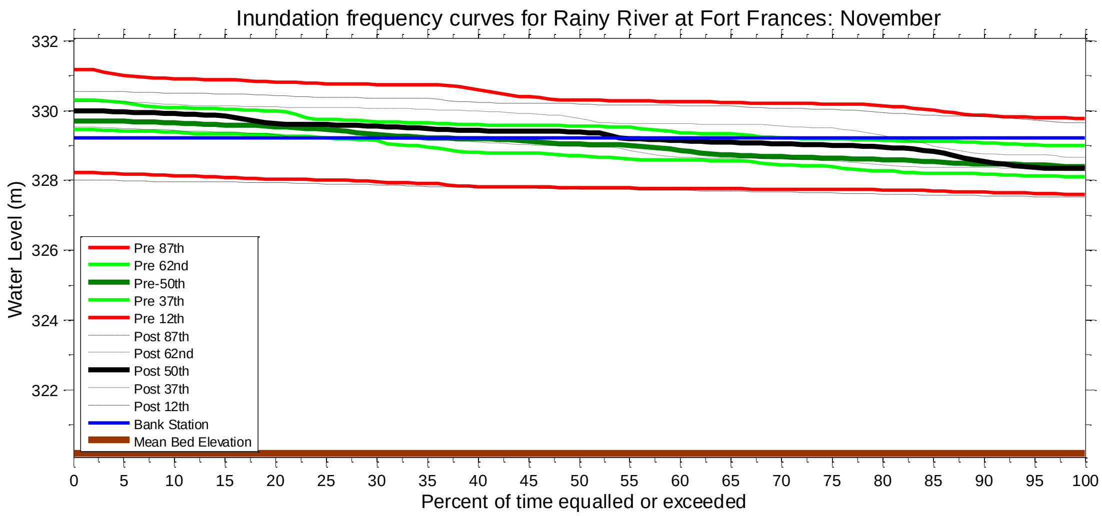

Frequency distribution curves for Rainy River at Fort Frances: September
Wetted Perimeter (m)
370
360
350
340
330
320
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded

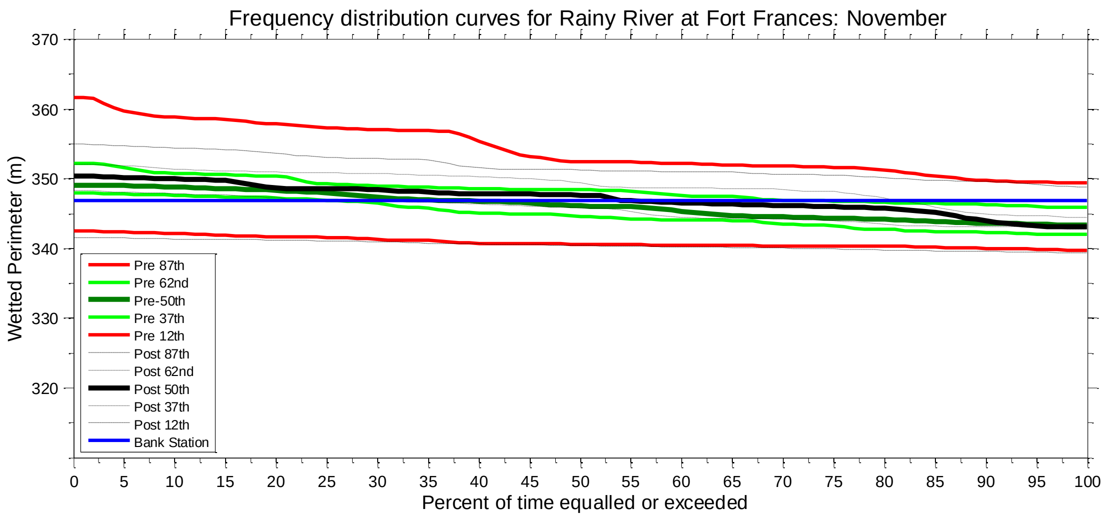

Between day water level range frequency curves for Rainy River at Fort Frances: September
Daily Water Level Difference (m)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
10 cm
5 cm
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded

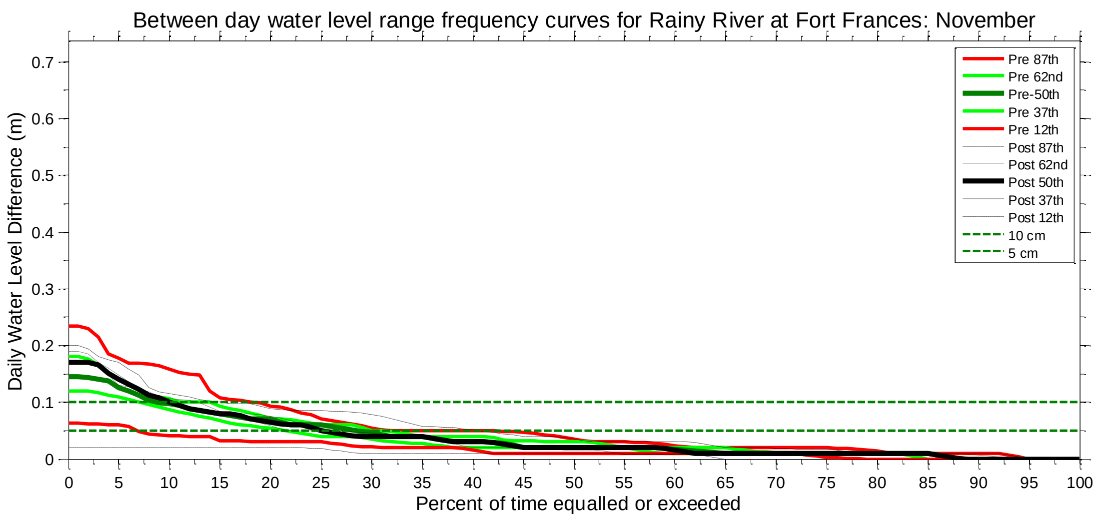

Inundation frequency curves for Rainy River at Fort Frances: October
Water Level (m)
Percent of time equalled or exceeded
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
Mean Bed Elevation

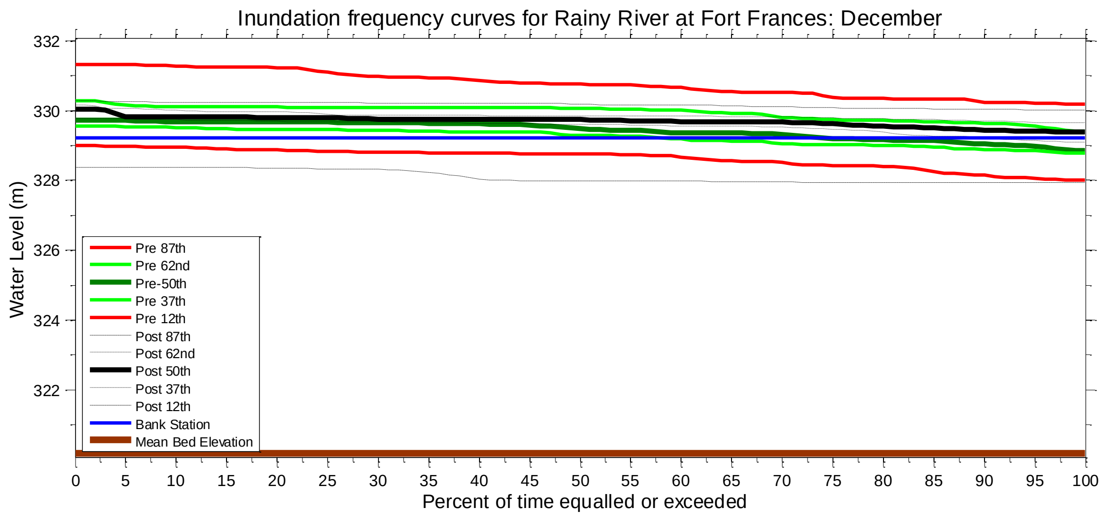

Frequency distribution curves for Rainy River at Fort Frances: October
Wetted Perimeter (m)
Percent of time equalled or exceeded
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station

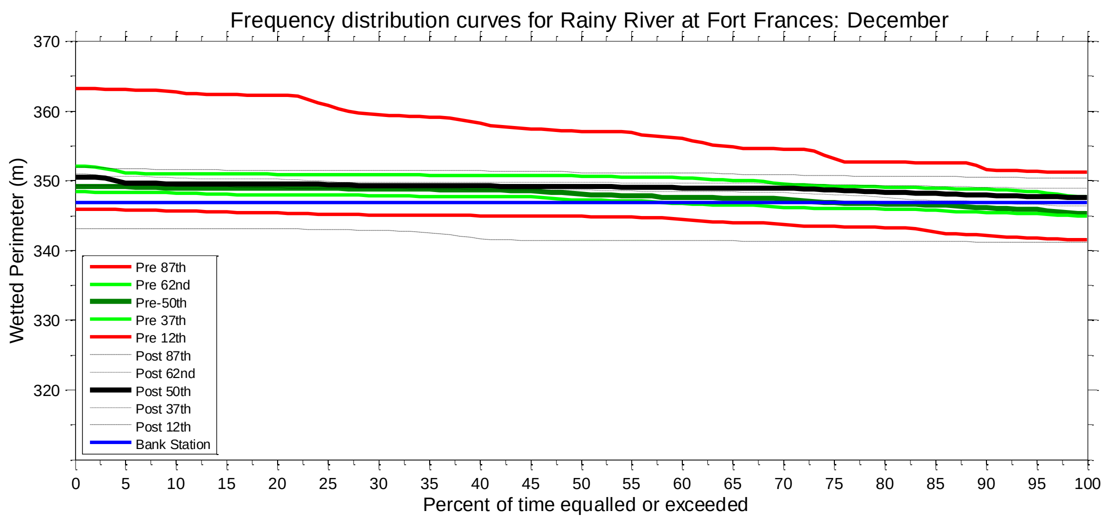

Between day water level range frequency curves for Rainy River at Fort Frances: October
Daily Water Level Difference (m)
Percent of time equalled or exceeded
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
10 cm
5 cm

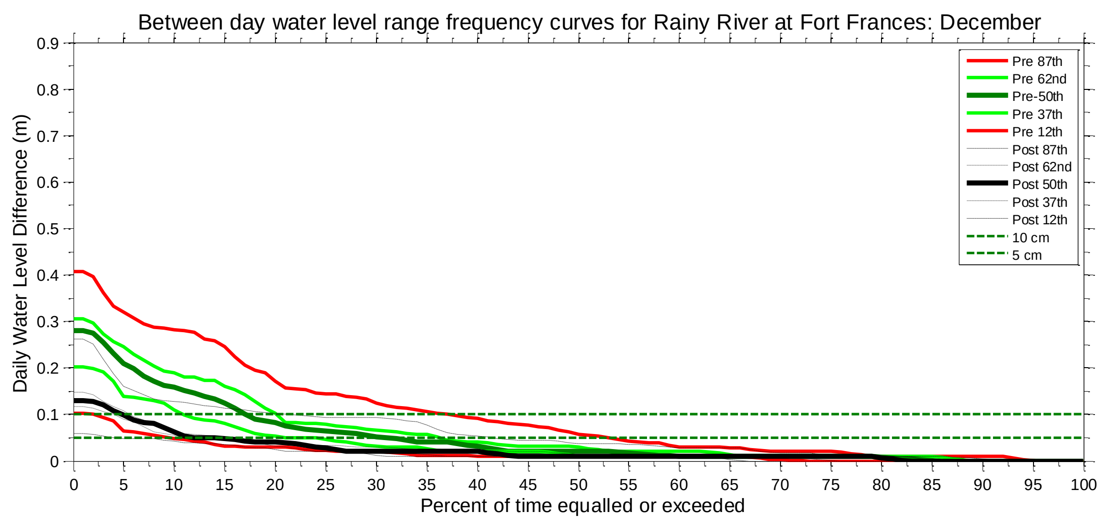

Inundation frequency curves for Rainy River at Fort Frances: November
Water Level (m)
332
330
328
326
324
322
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
Mean Bed Elevation
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded


Frequency distribution curves for Rainy River at Fort Frances: November
Wetted Perimeter (m)
370
360
350
340
330
320
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded


Between day water level range frequency curves for Rainy River at Fort Frances: November
Daily Water Level Difference (m)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
10 cm
5 cm
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Percent of time equalled or exceeded


Inundation frequency curves for Rainy River at Fort Frances: December
Water Level (m)
Percent of time equalled or exceeded
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station
Mean Bed Elevation


Frequency distribution curves for Rainy River at Fort Frances: December
Wetted Perimeter (m)
Percent of time equalled or exceeded
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
Bank Station


Between day water level range frequency curves for Rainy River at Fort Frances: December
Daily Water Level Difference (m)
Percent of time equalled or exceeded
Pre 87th
Pre 62nd
Pre-50th
Pre 37th
Pre 12th
Post 87th
Post 62nd
Post 50th
Post 37th
Post 12th
10 cm
5 cm