ENVIRONMENT CANADA

Namakan Chain of Lakes

Pinch Point Modelling

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LIST OF ABBREVIATIONS

1D	One-dimensional
2D	Two-dimensional
CGVD 28	Canadian Geodetic Vertical Datum of 1928
EC	Environment Canada
GIS	Geographic Information System
GPS	Global Positioning System
HEC-GeoRAS	Geographic information system add-in for HEC-RAS
HEC-RAS	Hydrologic Engineering Center – River Analysis System
IJC	International Joint Commission
LWCB	Lake of the Woods Control Board
LWS	Lake of the Woods Secretariat
NAVD 88	North American Vertical Datum of 1988
NGVD 29	National Geodetic Vertical Datum of 1929
USACE	United States Army Corps of Engineers
USC&GS 1912	United States Coast and Geodetic Survey Datum 1912
USGS	United States Geological Survey
UTM	Universal Transverse Mercator

1 INTRODUCTION

1.1 Background

The Namakan Chain of lakes are located along the Canada-US border of Ontario and Minnesota. The chain consists of a series of lakes connected by four narrow channels shown in Figure 1. Crane Lake and Little Lake Vermillion feed into Sand Point Lake through King Williams Narrows and Little Vermillion Narrows, respectively. The North and South ends of Sand Point Lake are separated by Harrison narrows. The outlet of Sand Point Lake connects with Namakan Narrows, which in turn flows into Namakan Lake.

Water travels from the Namakan system to Rainy Lake at three separate locations; the two dams at Kettle Falls, Gold Portage, and Bear Portage. Gold Portage and Bear Portage are both natural spillways. Water will spill from Namakan Lake through Gold Portage when the water level reaches 339.39 m (NAVD 1988). The spillway at Bear Portage is 1 metre higher; water begins spilling from Kabetogama Lake through Bear Portage at an elevation of 340.39 metres (Christensen et al., 2004). The dams at Squirrel Island and Kettle Falls are used to regulate water levels throughout the system according to the 2000 rule curve specified by the IJC shown in Figure 2.

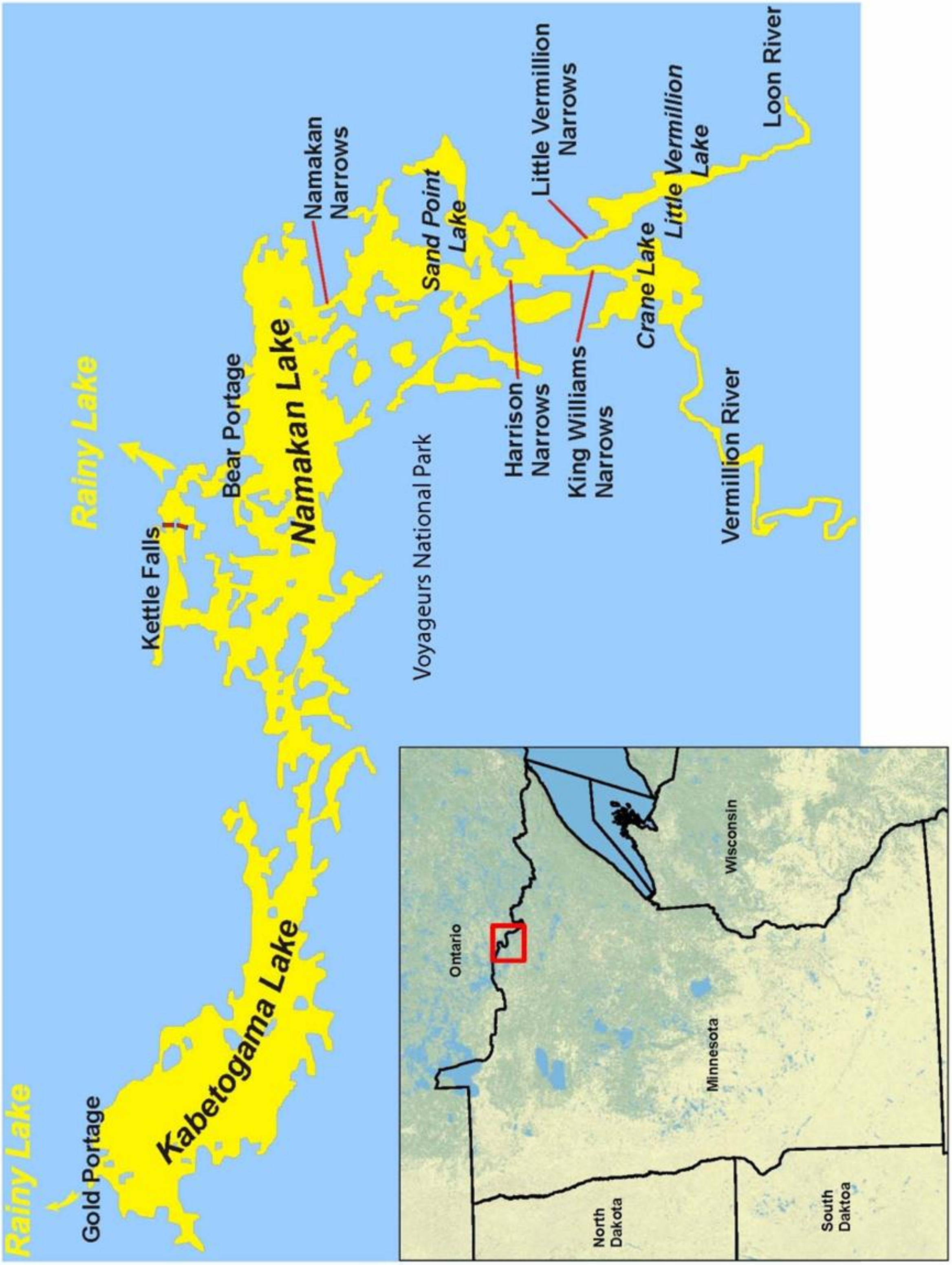
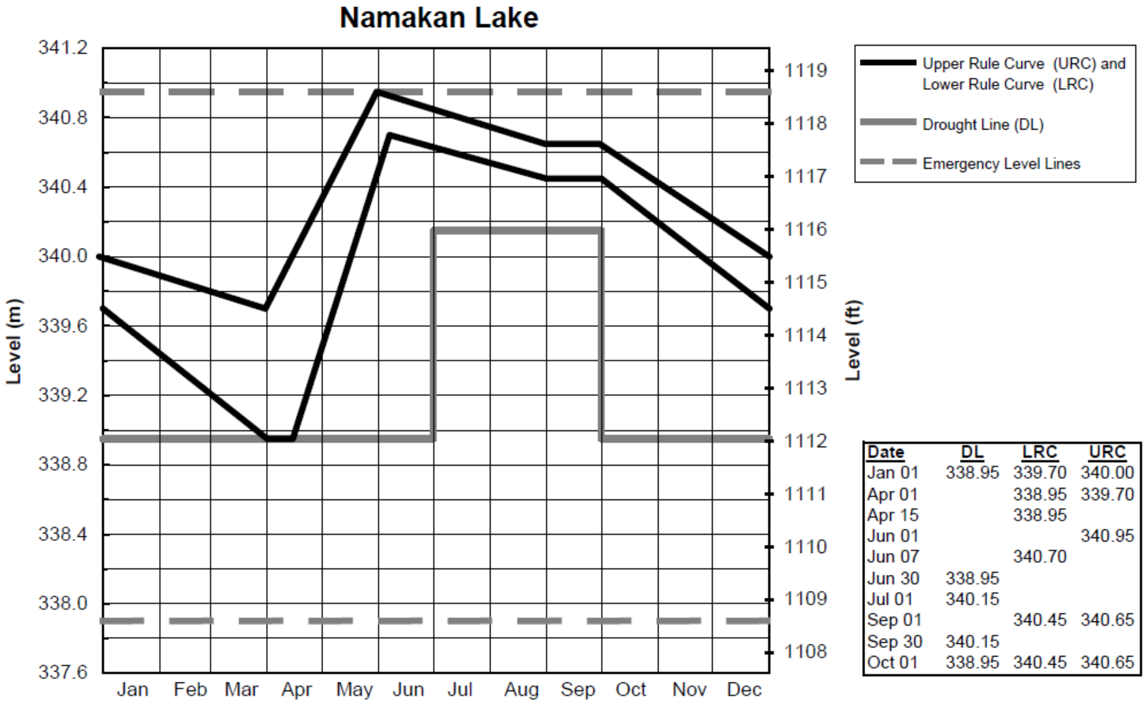


Figure 1: Namakan reservoir system



Date	DL	LRC	URC
Jan 01	338.95	339.70	340.00
Apr 01		338.95	339.70
Apr 15		338.95	
Jun 01			340.95
Jun 07		340.70	
Jun 30	338.95		
Jul 01	340.15		
Sep 01		340.45	340.65
Sep 30	340.15		
Oct 01	338.95	340.45	340.65

Figure 2: IJC Rule Curve from 2000 used to regulate water levels for Namakan reservoir system (IJC, 2001, p.18)

1.2 Project scope and objectives

The objective of this project was to develop a hydraulic model for the Namakan Chain of Lakes including Crane Lake, Sand Point Lake and Namakan Lake to help water managers regulating the Namakan water levels to better understand the hydraulics of the system. Specifically, the model would help water managers to understand the volume and timing of water flowing through the Chain of Lakes when the water level of Crane Lake is higher than Namakan Lake during spring freshet and at other times of the year.

1.3 Approach

The project involved the creation of a one-dimensional (1D) HEC-RAS model of the “pinch points” or narrows connecting Crane Lake, Sand Point Lake and Namakan Lake using bathymetry and discharge measurements collected in a previous International Watershed’s Initiative (IWI) funded project completed by the United States Geological Survey (USGS). The proposal focused on the pinch point channels because they were thought to restrict flow from upstream to downstream lakes. The model was to simulate a variety of water level conditions and be used to develop rating curves relating water levels and flows through the Chain of lakes. HEC-RAS was selected as the model to use for this system because the pinch points are generally straight with uniform in cross-sections. Water levels fluctuate over a large range of stage throughout the year, varying by more than two metres from winter minimums to late summer maximums. HEC-RAS is well suited to simulate these conditions, is computationally efficient, well documented, and has been used previously by Environment Canada and the USACE.

2 DATA PREPARATION AND MODEL CONSTRUCTION

2.1 Vertical datum conversions

Water level and bathymetry data for this project was obtained from several sources utilizing different vertical reference datums. All data was either provided or converted into a consistent vertical datum which was the United States Coast Guard and Geodetic Survey 1912 (USC&GS 1912) vertical datum. This is the datum utilized by the Lake of the Woods Secretariat, the official data custodians for the Rainy Lake and Lake of the Woods Watershed Board. Bathymetry and temporary water level data collected for this specific project was referenced to the NAVD 1988 vertical datum. Table 1 gives a summary of datum conversion factors used that are specific to the study area.

Table 1: Vertical Datum Conversions

Starting Datum	Ending Datum	Conversion
NAVD 1988	CGVD 1928	Subtract 0.42 m [a]
CGVD 1928	USC&GS 1912	Add 0.254 m [b]
NAVD1988	USC&GS 1912	Subtract 0.166 m [c]

[a]: Marc Veronneau personal communication (July 2012); NRCAN data from Francine Saumure for gauges in study area
[b]: Known local conversion (CHC, 2010; LWS, 2012)
[c]: a+b

2.2 Bathymetry Data

Bathymetric data for the model was obtained from two different sources; multi-beam surveys conducted by the USGS in 2011 and contour data obtained from the Minnesota Department of Natural Resources. Before merging this data to create the digital elevation model from which the hydraulic model was built, datum conversions and other processing was required. The following sections describe this process in detail.

2.2.1 2011 Multi-Beam Survey

A bathymetry survey of the pinch point channels in the Namakan chain was conducted in August 2011 by the USGS. King Williams Narrows, Little Vermillion Narrows, Harrison Narrows, and Namakan Narrows were all surveyed. Bathymetry was collected on a 50 cm grid using a RESON Seabat™ 7125 multibeam echosounder. The unit had a depth rating for measurements between 1.5 and 200 metres using a 400 kHz frequency and 128° swath width and was able to collect bathymetry at a 0.005 m resolution (Densmore et al., In press). Data was projected horizontally in Universal Transverse Mercator (UTM) zone 15N and was referenced vertically to the NAVD 1988 vertical datum. Further details of the survey are described in Table 2.

Table 2: 2011 bathymetry survey

Section	Number of Points
King Williams Narrows	1 564 332
Little Vermillion Narrows	2 702 068
Harrison Narrows	1 115 442
Namakan Narrows	1 059 579

2.2.2 Minnesota Department of Natural Resources (MinDNR) contour data

To create a continuous bathymetric surface for the model domain, contour data, obtained from the Minnesota Department of Natural Resources (MinDNR) website (http://deli.dnr.state.mn.us/index.html), was used to fill the gaps between the multi-beam surveys of each pinch point. A single digitized file of depth contours for Lakes throughout Minnesota was obtained which included depth contours at a 1.5 m (5 ft) interval. However, for the contours within the study area, most data was only reported at a 3 m (10 ft) contour interval. Contour data for the entire study area was available.

Inspection of the MinDNR contour data indicated the digitized dataset was a compilation of several surveys. This is illustrated in Figure 3, where overlapping contours are present in locations where surveys ended or started to allow for contour lines around a lake to connect. The MinDNR contour data was cleaned at the points where it was obvious contours from multiple surveys were merged together so contour lines followed the shoreline of the study area.

Depth contours are a function of a reference water level at the time a survey is completed; the water level affects the depth from surface to lake bottom, and therefore it impacts where contour lines are drawn. Bathymetric contours referenced as depths below the water surface were converted to elevations referenced to the USCGS vertical datum of 1912 using the water levels recorded at the time of the survey. These water levels were recorded on the contour maps obtained from the MinDNR. Contour maps that were developed for each lake survey were downloaded from the Minnesota DNR lake finder website (http://www.dnr.state.mn.us/lakefind/index.html). It is assumed these maps represent the original surveys that were digitized and merged together to create the MinDNR contour file for the entire system. When the MinDNR digital file was used, satellite imagery was incorporated to improve shoreline and island locations. This resulted in some changes to the contours compared to what was mapped in the original surveys (MinDNR, 2013b). The original contour maps that were downloaded each had a water level reference recorded on them indicating conditions that were present during each respective survey. Maps were obtained for each lake. Two maps were available for Kabetogama Lake so the most recent map was used to convert depth contours to elevations.

For Namakan and Sand Point Lake, depth contours were referenced to water levels at Kettle Falls Dam in USC&GS 1912 vertical datum. The maps reported a range of water levels at Kettle Falls observed during the survey; the midpoint of the range was used as the reference water level for the contours. Historical water levels for Namakan Lake at Kettle Falls were checked and verified with the reported levels on the maps of Namakan and Sand Point Lake that are described in Table A1. The dates and water levels listed for the surveys used to produce the maps matched with historical data for Kettle Falls Dam, indicating the main source of error introduced by the process of referencing water levels to bathymetric elevations were water level changes that occurred during the survey. As shown in Table A1, Namakan Lake water levels fluctuated 25.0 cm (0.82 ft) while it was surveyed, and Sand Point Lake water levels fluctuated 19.2 cm (0.63 ft). This indicates contour elevations have an additional 10 – 13 cm of uncertainty, depending on water levels during each survey day.

More uncertainty was introduced in the method to convert the Crane Lake contours to elevation data. The Crane Lake map was referenced to a single elevation at the Crane Lake gauge in April 1952. However, the water level was referenced to the top of the Crane Lake gauge and it was uncertain what elevation this point would have. An assumption was made that Crane Lake was the same level as Lake Namakan on April 7, 1952, and the daily water level at Kettle Falls was used to convert the depth contours to elevations. The head difference between Crane Lake and Lake Namakan at this time, and the fluctuations in water levels during the survey are sources of uncertainty added to the contour data when it is converted to a bathymetric elevation.

The Kabetogama map was referenced to a single elevation with no date. No metadata was found describing details of the survey, although the map appeared to be more recent in comparison to those for the other lakes. The elevation value of 339.85 m (1115 ft) was used for conversion to bathymetric elevation.

Further details of the elevation references provided by the hard copy maps are described in Table A1. Water levels used to convert depth contours for each lake to elevation data are listed in Table 3.

After the contours were prepared, polygons were drawn around Kabetogama Lake, Namakan Lake, Sand Point Lake, and Crane Lake. Polygons were joined in ArcGIS using the snapping function to allow clean separation of the lakes. The MinDNR contour data was clipped from these polygons to give a set of depth contours for each lake. The depth contours were then converted to elevation data using the reference water levels in Table 3. Fields for elevation in feet and elevation in metres were added to a contour shapefile for each lake.

Although the process of converting the MinDNR contour data to elevations for each lake in the study area is subject to potential error, it should be recognized that the contour data was only needed to connect the multi-beam bathymetry for each of the pinch points. The pinch points are the most shallow and narrow locations in the model and the bathymetry in these locations were expected to have a significant influence on flow through the system. In contrast, bathymetry in the lakes was not expected to have a significant impact on flow through the system.

Table 3: Reference water levels for MinDNR contour data

Lake	Gauge level used to convert depth contours (m)	Gauge level used to convert depth contours (ft)
Namakan	340.85	1118.27
Sand Point	340.84	1118.25
Kabetogama	339.85	1115.00
Crane	340.81	1118.15

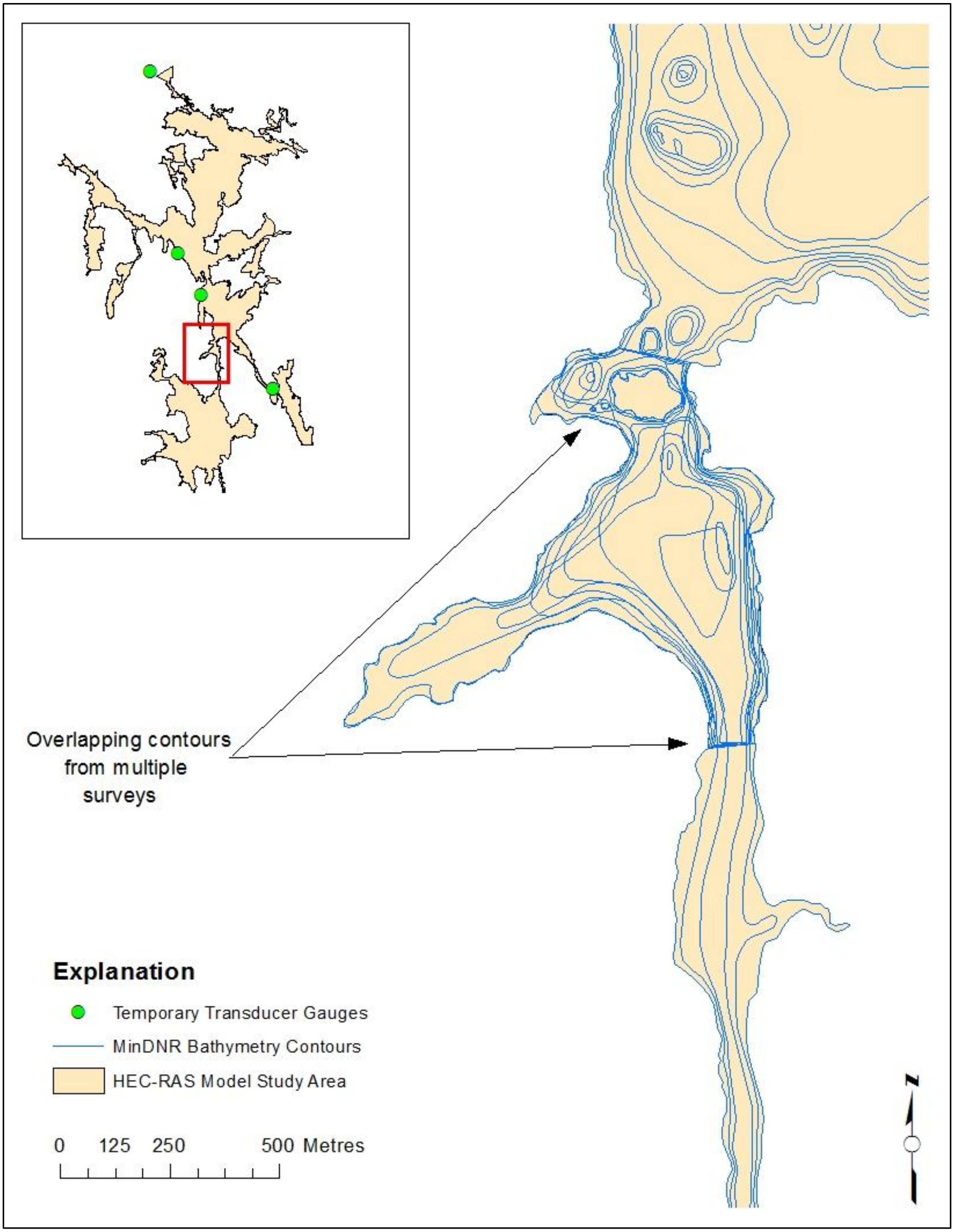


Figure 3: Example of overlapping depth contours from Kabetogama Lake and Namakan Lake surveys, UTM Zone 15 N

2.3 Water level and discharge data

Water level and discharge data are required to supply model boundary conditions and validate the model computations. These data were obtained from a number of sources as detailed in the following sections.

2.3.1 Discharge measurements

ADCP measurements were collected by the USGS during field visits on August 16, 2011, May 2, 2012 and June 26, 2012. Surveys were completed with a Rio Grande 600 KHz ADCP in 2011 and a Sontek River Surveyor M9 for the 2012 surveys. Transects in all four pinch point channels were collected. The measurements consisted of one pass of the boat across each transect. Because only one transect was completed at each cross-section location, there was uncertainty with respect to the accuracy of measurements. However, measurements made within the same pinch point did show some degree of agreement. The measurements during the August 2011 survey were taken when there was little or no difference in water level on Crane Lake and Namakan Lake. As a result, flow through the pinch points was negligible. Flow measurements indicated there was minimal movement of water from lake to lake in both upstream and downstream directions due to variable winds. As a result of the low flows and inconsistencies between measurements, the August 2011 discharge measurements were not used during the model calibration and simulation process.

Both sets of 2012 measurements were characterized by higher flows through the narrows and provided more useful datasets than the 2011 measurements. A summary of the discharge measurements collected 2012 is shown Table 4 and the transect locations are shown on Figure 4. The standard deviation reported in Table 4 is the standard deviation computed from all measurements within that pinch point.

Table 4: Namakan Chain ADCP measurements

Date	Location	Cross-sections measured	Average Q (m^3/s)	Standard Deviation
2012/05/02	King Williams	2	37.21	3.15
	Little Vermillion	3	12.91	6.26
	Harrison	1	50.70	N/A
2012/06/26	King Williams	3	45.63	2.02
	Little Vermillion	4	12.40	6.86
	Harrison	1	107.74	N/A
	Namakan	3	79.00	5.65

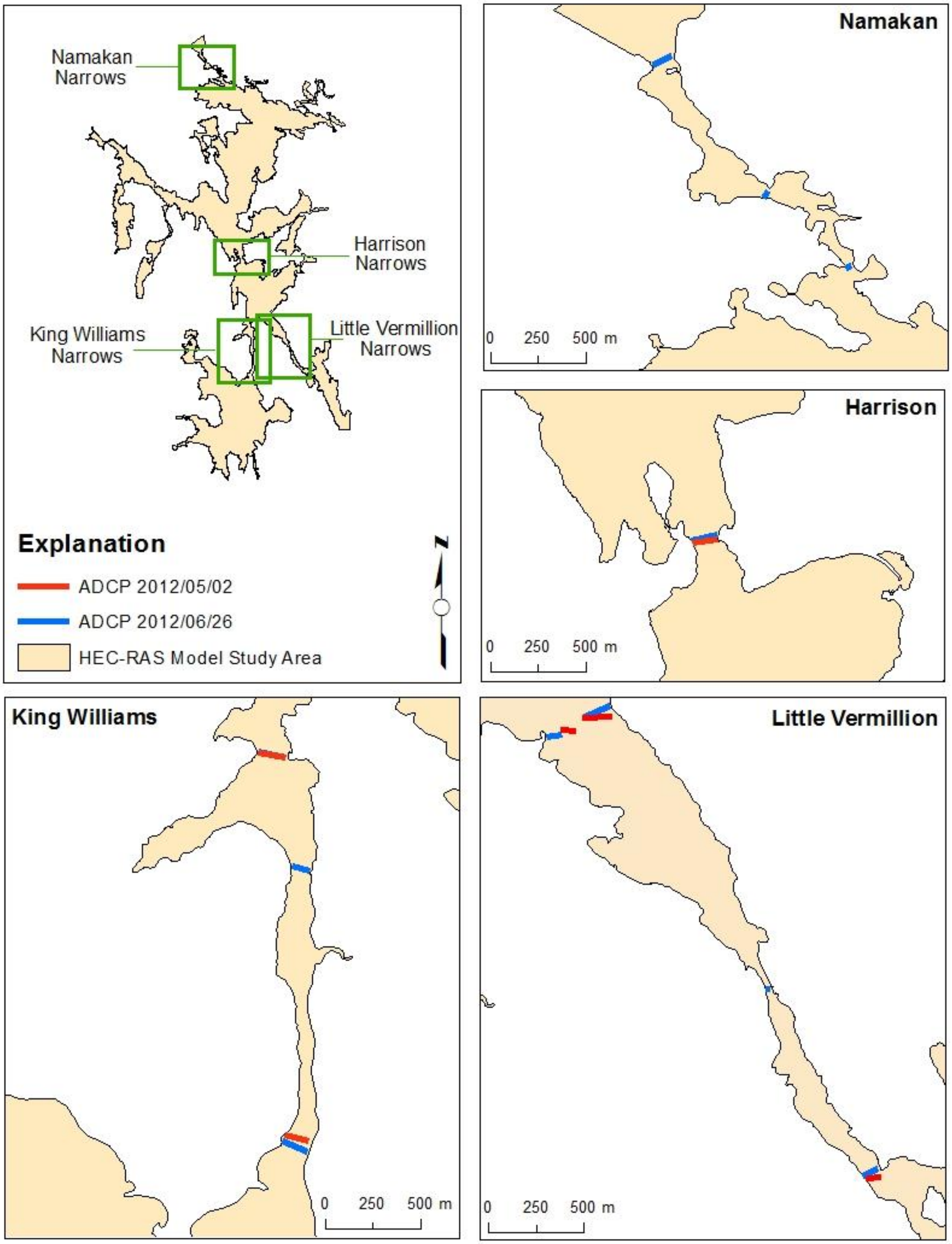


Figure 4: ADCP transects from 2012, UTM Zone 15 N

2.3.2 Water level observations

Water level data for the Namakan Chain of Lakes was obtained from “permanent” gauges that have been operated for many years and temporary gauges that were installed for two years to provide data for the development of the HEC-RAS model are shown in Figure 5. There are permanent water level gauges operated on Kabetogama Lake by the USGS, on Crane Lake operated by the United States Army Corps of Engineers (USACE), and at Squirrel Island on Namakan Lake operated by Environment Canada (EC) as described in Table 5. The official daily data records collected by the Lake of the Woods Secretariat are provided in Figures 6 and 7. Figure 6 shows Namakan Lake water levels for 2011-2012 with respect to the IJC rule curve. Further details of this data are shown in Figure 7, from April 2012 onwards, where Crane Lake levels are shown in comparison to Kabetogama Lake and Namakan Lake water levels.

All gauges record data referenced to the USC&GS 1912 vertical datum. Data for the Squirrel Island gauge was obtained from Environment Canada’s real-time website (http://www.wateroffice.ec.gc.ca/index_e.html). Squirrel Island data typically included two values each hour, one value at one minute past the hour, and a second value at a variable interval during the hour. An hourly time series was constructed for Squirrel Island with the values recorded one minute after each hour. Hourly Crane Lake data was downloaded from the USACE website (http://www.mvp-wc.usace.army.mil/dcp/). An important note is all water level data obtained from the permanent gauges during this modelling study were marked as provisional and are subject to change. As a result, model results and data analysis in this report and the supplemental data analysis report provided (Stevenson, 2013) are subject to potential error until the data is finalized. At the time this report was written, verified hourly Squirrel Island data was available up to March 3, 2012. The difference between preliminary and verified hourly Crane Lake data was unclear. In addition to the available water level records, a discharge gauge reporting daily data is operated by the USGS on the Vermillion River near Crane Lake.

Four temporary water level gauges (Ott Hydromet) were installed in the Namakan Chain to obtain boundary condition and calibration data for the model. Gauges were installed at Little Vermillion narrows, Sand Point Lake above Harrison narrows, Sand

Point Lake below Harrison narrows, and Namakan Lake. Prior to these gauges being installed there was no information available on the water level slope between Crane Lake and Namakan Lake. Loggers were installed in August 2011 and operated until they were removed in November 2011. They were again installed in May 2012 and operated until November of that year. Further information on the logger installation is available in Densmore et al. (In press). Stage and temperature data were logged at 15 minute intervals. Water levels collected at these gauges were referenced to the NAVD88 vertical datum and then converted to USC&GS 1912 vertical datum according to the conversions in Table 1 to allow for comparison with permanent gauge data. To differentiate between the two gauges on Namakan Lake, the permanent gauge 05PA013 will be referred to as “Squirrel Island” in this report and the temporary gauge will be referred to as “Namakan Lake” or “Namakan Lake transducer”. Installation locations and dates are described in Figure 5 and Table 6. Hourly time series of the temporary transducer measurements were created by selecting the fifteen minute value for the beginning of each hour.

Observed water levels at all gauges in the study area during the discharge measurements in May and June of 2012 are summarized in Table 7. All hourly data collected for modeling is shown in Figure 8. A significant point to note in Figure 8 is inconsistencies with agreement between gauges in the system at various times. The top panel of Figure 8 shows a period at the end of 2011 where Crane Lake levels are lower than Squirrel Island levels. Furthermore, the bottom panel shows the temporary Namakan transducer reads below the Squirrel Island level for almost all of 2012.

These hourly water level records were the main source of calibration and validation data available for model simulations. Although water level records were analyzed in further detail than what is included in this report, it was not possible to isolate potential error at individual gauges (Stevenson, 2013). The inconsistencies with agreement between gauges added a degree of uncertainty to the model simulations discussed below.

Table 5: Permanent gauges in study area

Gauge	Agency	Station Number	Vertical Datum
Crane Lake	USACE	CNLM5	USC&GS 1912
Squirrel Island (Namakan Lake)	WSC	05PA013	USC&GS 1912
Kabetogama Lake	USACE	GP0M5	USC&GS 1912
Vermillion River near Crane Lake*	USGS	05129115	N/A

*Disharge gauge

Table 6: Installation dates for temporary water level transducers. All transducers set to record on 15 minute interval. Collected water levels referenced to NAVD 1988.

	Period of Record	
Gauge	**2011**	**2012**
Little Vermillion Lake above Little Vermillion Narrows	2011/08/31 10:00 to 2011/11/01 13:15	2012/05/01 15:00 to 2012/06/26 17:30
Sand Point Lake below Harrison	2011/08/31 12:45 to 2011/11/02 12:00	2012/05/01 17:45 to 2012/06/26 15:45 to
Sand Point Lake above Harrison	2011/08/31 15:15 to 2011/11/02 10:15	2012/05/01 17:00 to 2012/06/26 19:30 to
Namakan Lake below Namakan Narrows	Not installed	2012/05/01 21:00 to 2012/06/26 13:30

Table 7: Observed water levels on Lake Namakan during discharge measurements. Daily averages shown for May 2 and June 26, 2012 measurements.

Gauge		May 02 2012 Water Level, m, USC&GS 1912	Hour	June 26 2012 Water Level, m, USC&GS 1912	Hour
Crane Lake	Avg	340.22	1-24	340.88	1-24
	Min	340.21	1	340.86	17
	Max	340.23	14	340.89	1
Little Vermillion	Avg	340.27	1-24	340.92	1-24
	Min	340.27	2	340.90	22
	Max	340.27	17	340.93	1
Sand Point Lake Above Harrison	Avg	340.22	1-24	340.88	1-24
	Min	340.22	1	340.87	22
	Max	340.23	13	340.90	1
Sand Point Lake below Harrison	Avg	340.23	1-24	340.88	1-24
	Min	340.22	1	340.86	22
	Max	340.23	24	340.90	1
Namakan Transducer	Avg	340.12	1-24	340.78	1-24
	Min	340.11	2	340.77	22
	Max	340.13	19	340.80	4
Squirrel Island	Avg	340.16	1-24	340.79	1-24
	Min	340.15	22	340.78	23
	Max	340.17	16	340.80	8

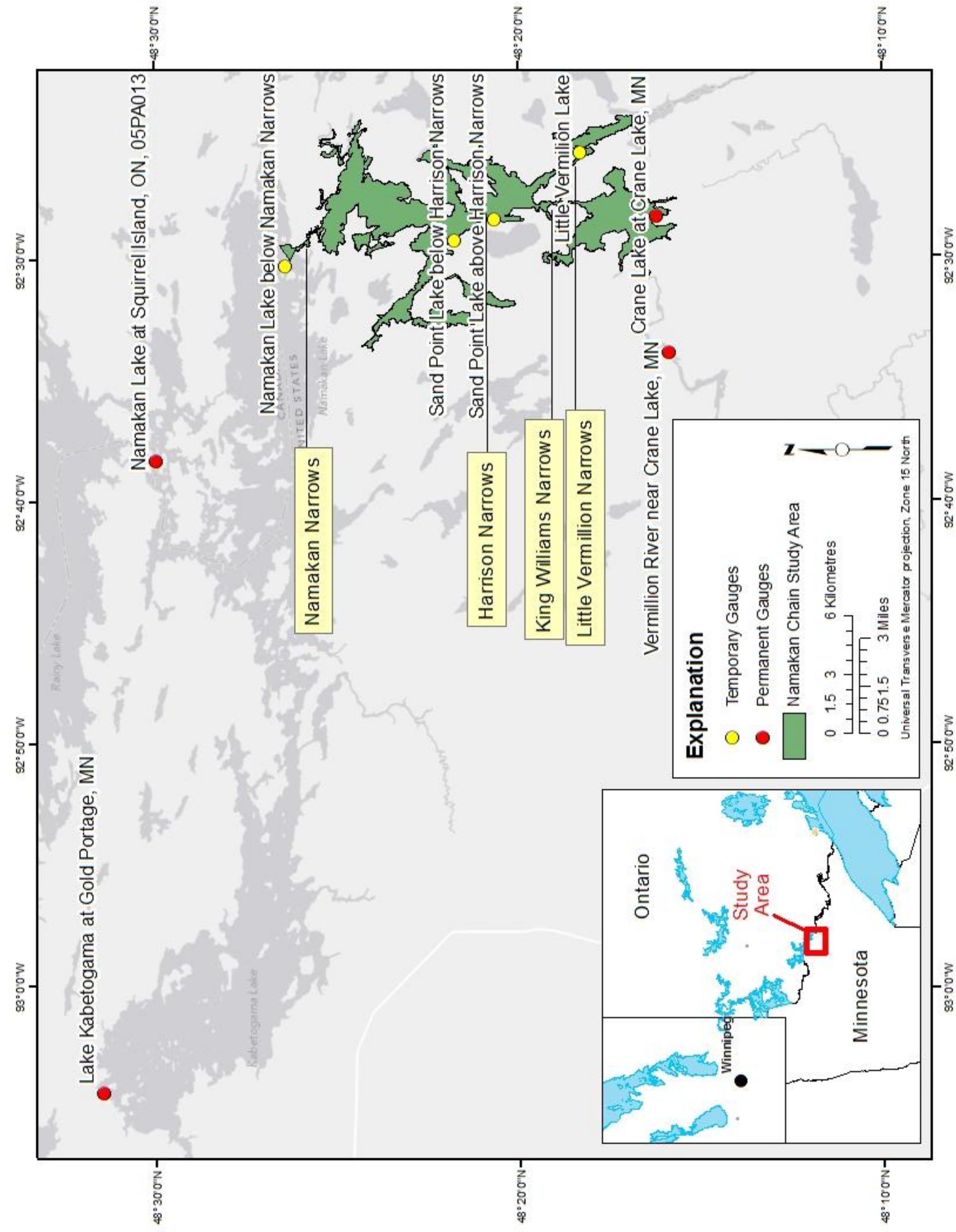


Figure 5: Namakan Chain Study Area and Gauge Stations

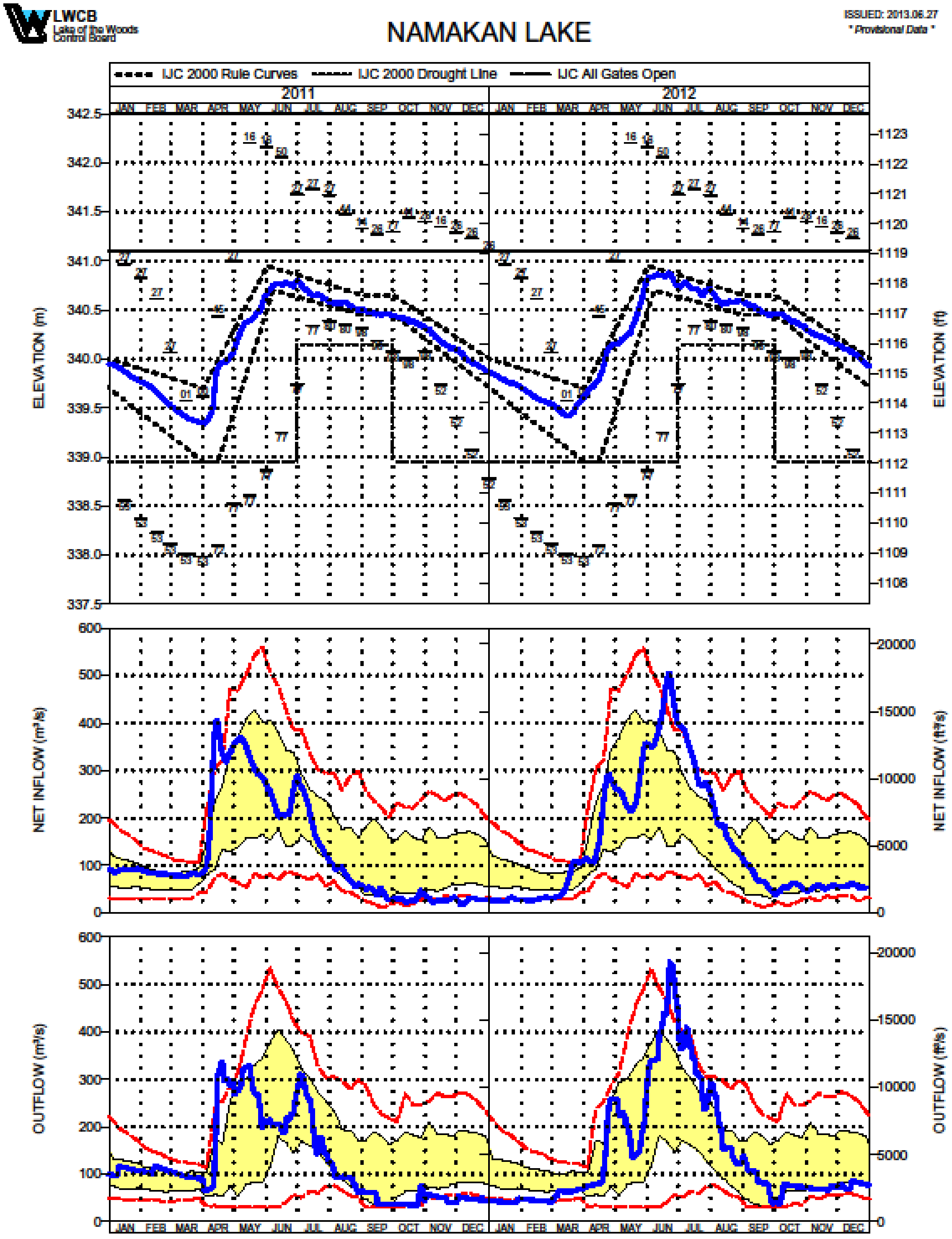


Figure 6: Water levels on Namakan Lake recorded by the Lake of the Woods Control Board for January 2011 to December 2012

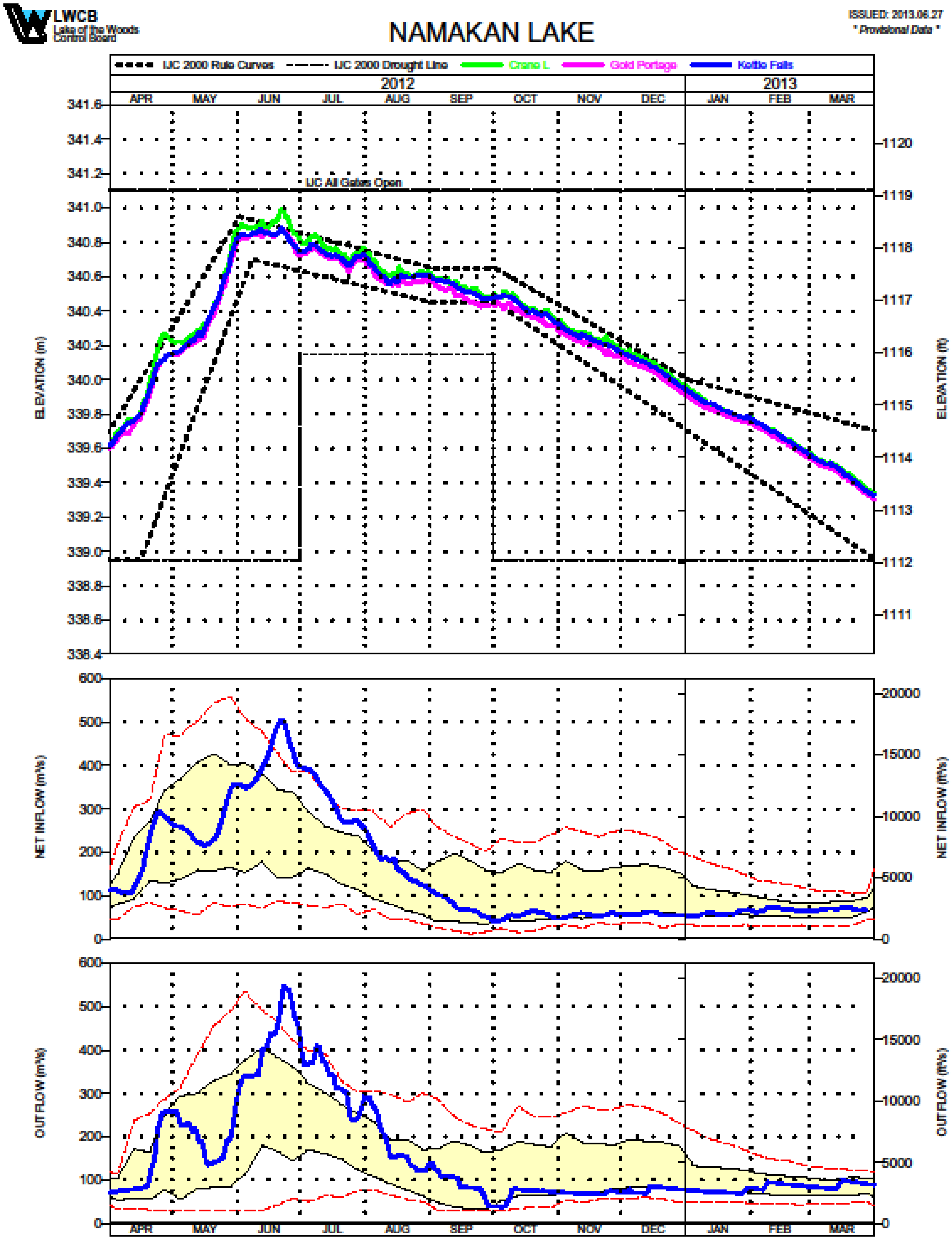


Figure 7: Water levels at Crane Lake, Kettle Falls, and Gold Portage for April 2012 to March 2013

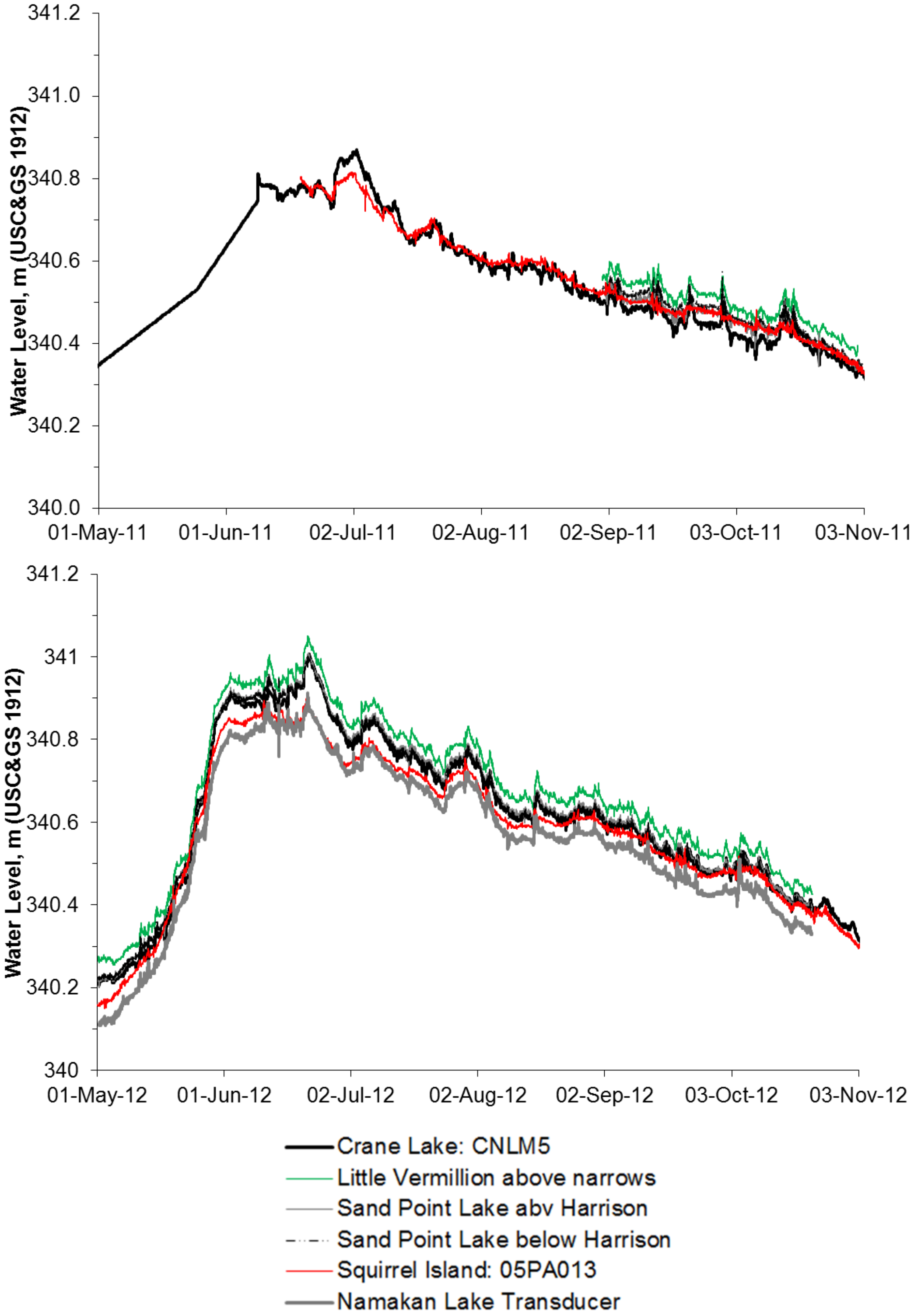


Figure 8: Hourly water level data collected during ice-free seasons of 2011-2012

2.4 HEC-RAS model geometry

The HEC-GeoRAS 10.0 add-in was used with ArcGIS 10.0 to develop a TIN surface for the model study area. The TIN was developed with elevation contours for Crane Lake, Sand Point Lake, Namakan Lake, and Little Vermillion narrows incorporated as softline fields, bathymetry data for each pinch point incorporated as masspoints, and an outline of the study area developed from the MinDNR contour data incorporated as a hardclip field. Polylines for banks, river line, flowpaths, and cross-sections were drawn in the UTM Zone 15 North projection.

After features were drawn, the geometry was exported to HEC-RAS and river reaches and cross-sections were named according to location. The ends of each cross-section were extended vertically to an elevation of 343.0 m to contain simulated flow. Cross-sections exported from HEC-GeoRAS with more than 500 points were filtered in HEC-RAS to allow the model to run. In addition, the raw bathymetry contained some pitch and roll errors, particularly for King Williams narrows. Obvious pitch and roll errors were removed to produce a more natural smooth cross-section. The example of cross-section 125 in King Williams narrows is shown in Figure 9.

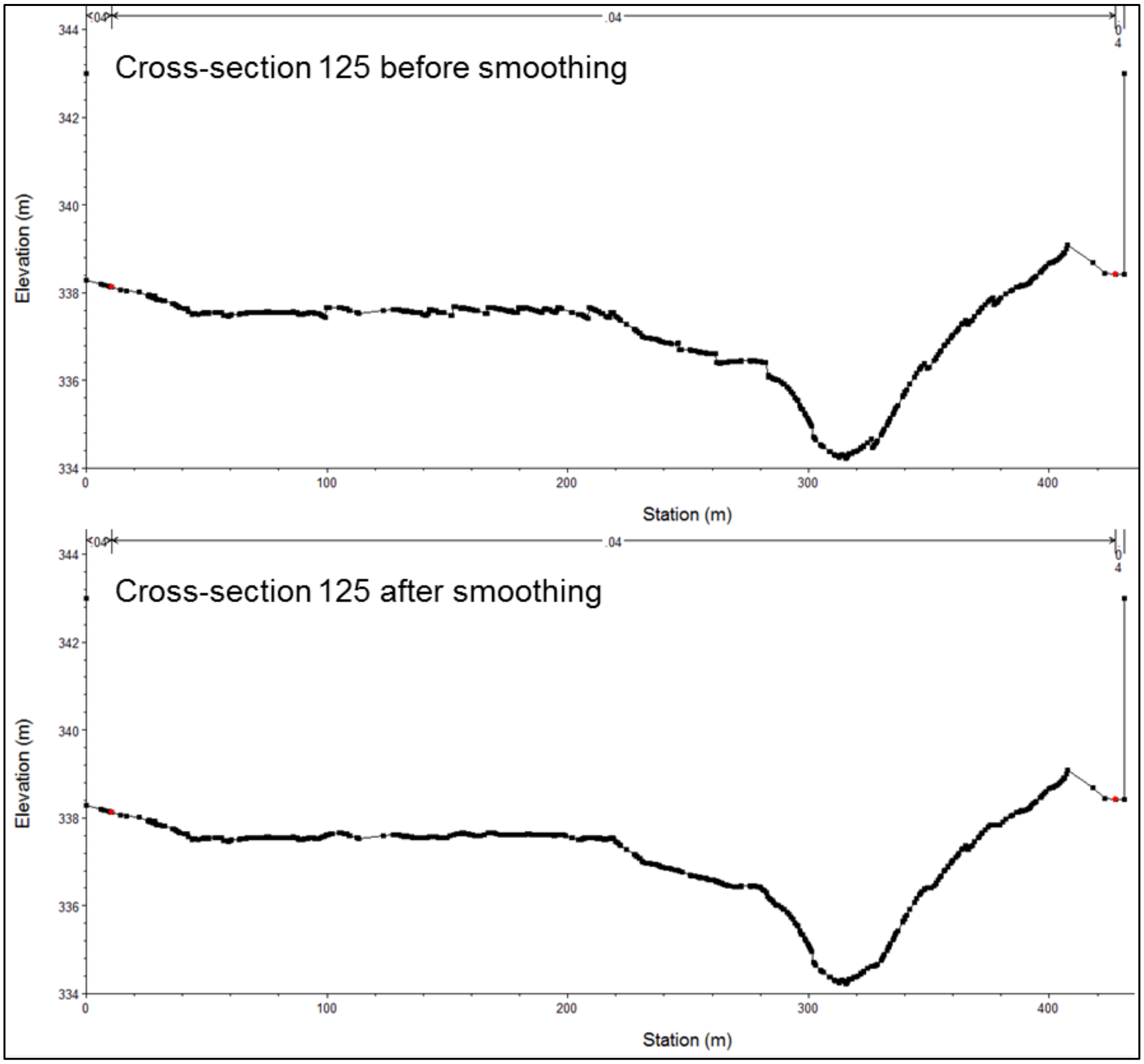
Multiple versions of the HEC-RAS geometry were developed and tested during the model development process in attempts to improve simulation results. The finalized geometry consisted of 245 cross-sections with a main channel starting at the upstream end of Crane Lake and ending at Namakan Lake. A separate channel for Little Vermillion narrows was included, along with three separate reaches to account for storage in Sand Point Lake. Further information on the river reaches and cross-section locations can be found in Tables 8, 9 and Figure 10.

Table 8: Summary of final model geometry

River Name	Model Reach	Number of Cross-Sections	Upstream Junction	Downstream Junction
Main	KingWilliams	58		1
Main	Lake1	4	1	2
Main	Below2	22	2	3
Main	Below3	4	3	4
Main	Below4	83	4	
LittleVermillion	LittleVermillion	50		1
Sand Point Lake	SP1	5		2
Sand Point Lake	SP2	9		3
Sand Point Lake	SP3	10		4

Table 9: Cross-sections corresponding to lakes and pinch points

Location	Model Reach	Cross-Sections
Crane Lake	KingWilliams	171-162
King Williams narrows	KingWilliams	161-114
Little Vermillion narrows	LittleVermillion	221-172
Harrison narrows	Below2	103-91
Namakan narrows	Below4	69-1
Sand point lake	Lake1	113-110
	Below2	109-104, 90-88
	Below3	87-84
	Below4	83-70
	SP1	231-222
	SP2	240-232
	SP3	231-222


Cross-section 125 before smoothing

Cross-section 125 after smoothing

Figure 9: Extension of cross-section ends to contain water surface profile at cross-section 125 in King Williams narrows. Top panel show pitch and roll errors in raw bathymetry. Bottom panel shows smoothed model cross-section to reduce pitch and roll errors.

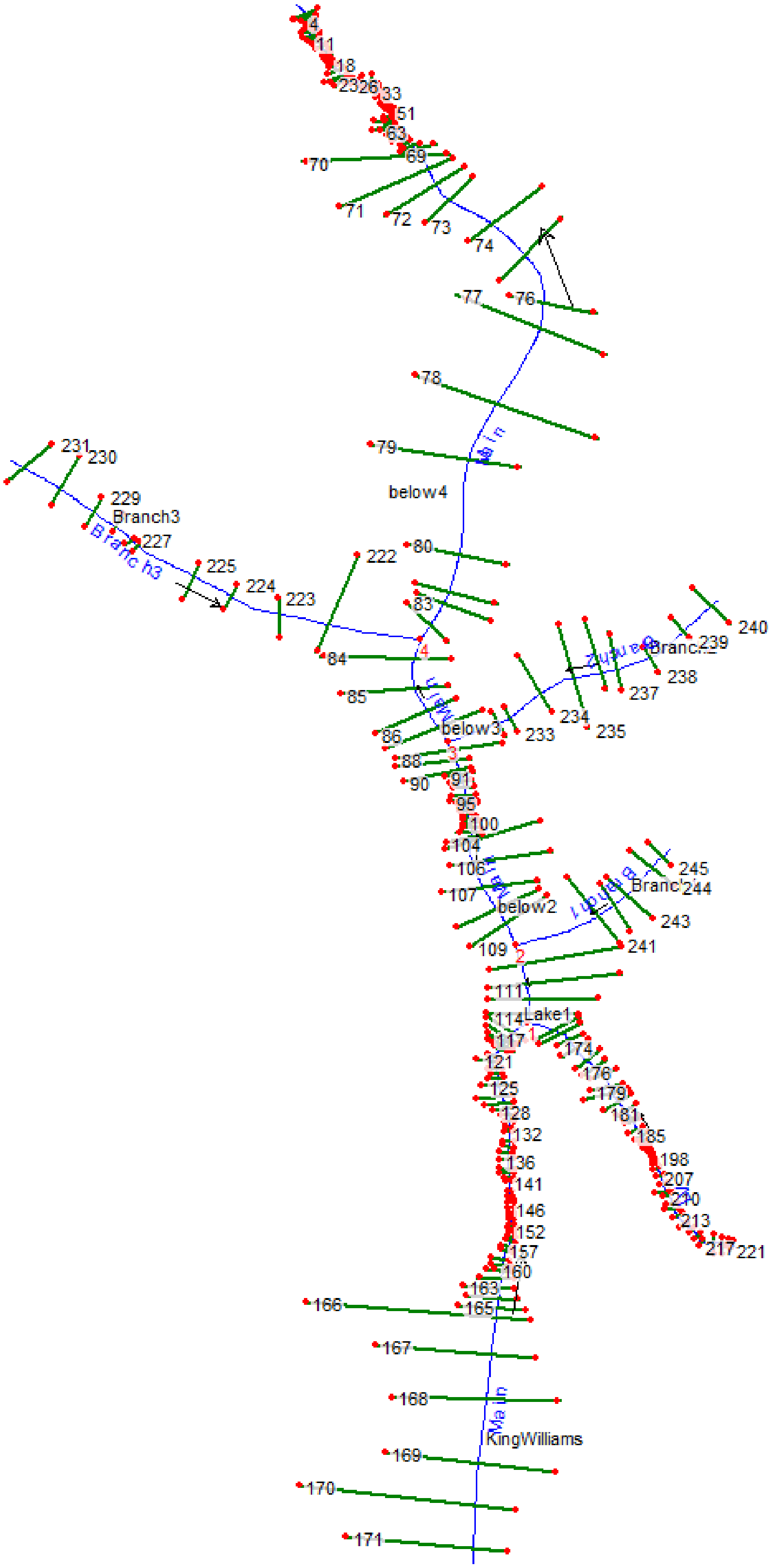


Figure 10: Final HEC-RAS model geometry

2.5 Manning's *n* and expansion/contraction coefficients

The HEC-RAS model requires the specification of two sets of parameters once the model geometry and boundary conditions have been established. These model parameters are the Manning's *n* roughness coefficients, and the expansion and contraction coefficients. Both of these parameters cannot be measured precisely and either need to be established using theoretical estimates or determined through a calibration process. Expansion and contraction coefficients allow the model to account for hydraulic losses at contracting and expanding cross-sections. These coefficients generally influence computed water levels to a lesser degree than Manning's *n* coefficients. The theoretical values of 0.3 for expansion and 0.1 for contraction losses were used for this model. Manning's *n* coefficients are typically estimated first by determining the bed type and selecting appropriate theoretical values. Refinement of these estimates is then accomplished through calibration where the Manning's *n* coefficients are varied and the model is executed repeatedly until the best match between computed and observed water levels is achieved.

The pinch point narrows are narrow, deep channels (see Figure 11) that connect the lakes shown in Figure 1. The shorelines are composed of large rock and boulders and are generally steep. The streambeds of all four narrows are likely comprised of boulders and cobbles although no grab samples were taken during field surveys in 2011 and 2012. The narrowest sections of each channel are approximately 30 metres in width although the pinch points are typically more than 100 metres wide. Theoretical estimates of Manning's *n* for the channels would range from 0.025 at a minimum to 0.06 maximum (Chow, 1959). Roughness values for these channels would be expected to be at the lower range due to the width of the channels, the moderate depths of the channels, the boulders and rock lining the shoreline and likely the subsurface and the lack of vegetation as observed late in August. A Manning's *n* of 0.03 was used as the initial estimate prior to attempting to establish a more accurate value through calibration.

Figure 11: Upstream end of Namakan narrows looking downstream. August 11, 2011

2.6 HEC-RAS Boundary Conditions

HEC-RAS requires boundary conditions to be specified at the upstream and downstream ends of all reaches for steady-state simulations when supercritical or mixed flow regimes are simulated (USACE 2010, pp.3-8). For steady-state computations, the discharge measurements in Table 4 provided upstream flow boundary conditions at King Williams narrows (cross-section 171) and Little Vermillion narrows (cross-section 221). The water level of Namakan Lake was used as the boundary condition at the downstream end of Namakan narrows (cross-section 1). Simulations were completed using both Squirrel Island and Namakan transducer data, although Squirrel Island was more frequently used. The design of the model required that boundary conditions also be specified at the upstream ends of the three reaches for Sand Point Lake shown in Figure 10 (cross-sections 231, 240, and 245). The upstream end of each lake reach was specified with a flow boundary condition to allow the model to simulate a water surface profile only constrained at the downstream end of the model. Physical measurements of flow through each lake reach did not exist, so estimated flows of 1, 5, 10, 15, and 25 m^3/s were tested to determine which scenarios provided the best matches with observed data. For steady-state simulations, flows were also specified at each junction as the sum of flows upstream of each reach.

3 MODEL SIMULATIONS

3.1 HEC-RAS steady-state simulations and model calibration

HEC-RAS steady-state simulations with the downstream boundary condition set at a constant level of 340.79 m and upstream inflows at Crane Lake and Little Vermillion are shown in Figures 12 and 13. Table 10 describes seven simulated flow conditions, PF1-PF7, where flow at Little Vermillion narrows was set to be 28% of flow at King Williams narrows, which was the approximate ratio observed during the ADCP measurements. Figure 12 shows simulations where the lake reach boundary conditions were set at 15 m^3/s and global roughness is varied. Figure 13 shows simulations with constant roughness of 0.035 with Sand Point Lake reach boundary conditions of 5, 10, and 25 m^3/s. For all scenarios in the left panels of Figure 12, the modelled head drop between Crane Lake and Lake Namakan ranged between 4 and 21 cm. Similar water level differences are shown between Little Vermillion and Lake Namakan in the panels on the right of Figure 12.

The ADCP measurements from 2012 (Table 4) recorded flows closer to the lowest flow scenario simulated in Figure 12, PF1. ADCP surveys from 2012 measured more flow than what was observed in August 2011. Therefore, it would be expected PF2-PF7 should all represent above-average flow conditions.

Figure 12 shows changing global roughness from 0.025 to 0.040 had had a more significant impact on simulation results for the high flow scenarios. When Sand Point Lake reach flow was 15 m^3/s, the observed water level at Crane Lake for PF1 increased approximately 4 cm when roughness increased from 0.025 to 0.040. For PF7, changing global roughness from 0.025 to 0.040 increased the simulated water level at Crane Lake by approximately 6 cm. However, as mentioned above, the PF7 flow scenario would likely represent abnormally high flow conditions.

Figures 14-15 show water surface profiles simulated by HEC-RAS in steady-state mode for the flow scenarios observed on May 2, 2012. Flow scenarios observed on June 26, 2012 are shown in Figures 16-17. The Crane Lake profiles on the left panels show observed water levels at Crane Lake, Sand Point Lake above Harrison narrows, Sand Point Lake below Harrison narrows, and Squirrel Island. The Little Vermillion profiles in the panels on the right show observed water levels at the Little Vermillion transducer, Sand Point Lake above Harrison narrows, Sand Point Lake below Harrison narrows, and Squirrel Island. Observed water levels shown in Figures 14-17 represent the daily average at each gauge. Observed water levels during ADCP discharge measurements on May 2 and June 26, 2012 are shown in Table 7.

The downstream boundary for the May 2, 2012 simulations in Figures 14 and 15 was set at a water level of 340.16 m, the daily average level reported at Squirrel Island. Likewise, the downstream water level boundary in Figures 16-17 was the Squirrel Island daily average on June 26 of 340.79 m. The flow boundary conditions used for these simulations at each point in the HEC-RAS model are described in Table 11; flow is conserved through the system where each junction in the model is the total flow from all upstream reaches.

The steady-state simulations in Figures 14-15 show the May 2 flow scenario; observed water levels are best predicted by Sand Point Lake reach flows between 10-15 m^3/s. The panels show increasing global roughness raises the water surface elevation profile. For global roughness of n=0.035, the observed water surface profile is predicted well when Sand Point Lake reach flow boundaries are set to 15 m^3/s. Observations are within 1 cm of observations at each gauge in the system.

In contrast to the May 2 simulations, water surface profiles simulated for the July 26 flow scenario do not match as well with observed data for the full range of parameters tested. Simulation results for the June 26 flow scenario are summarized in Figures 16-17. Setting Sand Point Lake reach boundary conditions to 25 m^3/s and roughness values between 0.050 – 0.060 provides the closest representation of observations. These values represent the upper limit of what could be expected for the system; such a high roughness value may not be representative of the bed conditions. As mentioned previously, observations during field measurements did not show conditions indicating river bed composition or vegetation growth which would substantiate such high roughness values. Furthermore, June 26 is still relatively early in the summer season and would not typically be a time of significant vegetation growth. Roughness values of 0.050-0.060 are likely too high to be representative of the channels in this system given the bed composition, lack of vegetative cover, and their respective widths and depths.

For the June 26 simulations, it should be noted how each specified boundary condition in Table 11 agrees with observed flows through Namakan narrows in Table 4. (Note, discharge measurements were not collected in Namakan narrows on May 2, 2012, which prevents a comparison of simulated and observed flows at this location for the first flow scenario.) The three ADCP transects on June 26 measured an average discharge of 79.0 m^3/s through Namakan narrows with a range between 72 – 82 m^3/s. Flow through Namakan narrows is specified in the steady-state model simulations at Junction 4; when flow through each Sand Point Lake reach is specified as 5-10 m^3/s, simulated flow through Namakan narrows is 73-88 m^3/s which provides the closest match with ADCP measurements for that day. However, the closest match with observed water levels for the June 26 scenario was found when the Sand Point Lake reach flows were set to 25 m^3/s. This results in a flow through Namakan narrows, specified at Junction 4, of 133 m^3/s which is well above the observed average of 79 m^3/s for June 26 2012. Although HEC-RAS simulations were able to replicate the observed water surface profiles for the June 26 2012 flow scenario, the required parameter settings used values above those that would represent true conditions in the system, where roughness was set between 0.050-0.060 and Sand Point Lake Reach boundary conditions were set at 25 m^3/s.

The observed data in Figures 14-17 show little head difference between Crane Lake and Sand Point Lake, only indicating a water level drop through Namakan narrows. Based on the observed data alone, the two-steady-state flow scenarios for May 2 and June 26 indicate a flat profile for Crane Lake and Sand Point Lake up to the beginning of Namakan narrows. This does not agree with physical observations during ADCP measurements, where flow in excess of 30 m^3/s was measured through King Williams narrows on May 2 and June 26, 2012. If the water levels on Crane Lake and Sand Point Lake were truly the same for May 2 and June 26, 2012, little flow through King Williams narrows would have been measured by the ADCP. In addition, model simulations in Figures 12-17 consistently show a distinct head drop through King Williams narrows.

Observations in Figure 8 show Crane Lake and Sand Point Lake reported similar water levels for most of 2012. Daily values show the reported Crane Lake water levels were below what was observed at the temporary water level gauges for the duration of the 2011 installation and the majority of 2012. Based on the fact that water flows from Crane Lake to Sand Point Lake (downhill), these observed water level profiles are not possible as they would generally result in flow from Sand Point Lake to Crane Lake. While it is possible that water could flow from Sand Point Lake to Crane Lake over short periods when the levels of both lakes are equal and there are strong atmospheric disturbances, these instances are rare. Observed and recorded flow through King Williams narrows and model simulation results indicate there is an error in vertical leveling that exists either at the permanent Crane Lake gauge or the temporary gauges, or a combination of both gauges for the data obtained for 2011-2012. Reported water levels and sources of uncertainty from all data sources are discussed in more detail in section 5.3.

Because of the differences between the May 2 and June 26 steady-state flow scenarios, it was unclear whether the 1D model was capable of accurately simulating flow through the system. The model simulated observed conditions well for the May 2 scenario, but did not perform as well for the high water scenario of June 26. In addition, Crane Lake water levels were not consistent with what would be expected; observations did not show a head drop through King Williams narrows which was consistently present in model simulations.

Table 10: Boundary conditions for steady-state simulation scenarios PF1-PF7

Scenario	Flow at King Williams (m^3/s)	Flow at Little Vermillion (m^3/s)	Water Level at Lake Namakan (m)
PF1	45	13.0	340.79
PF2	55	15.9	340.79
PF3	65	18.8	340.79
PF4	75	21.7	340.79
PF5	85	24.6	340.79
PF6	95	27.4	340.79
PF7	105	30.3	340.79

Table 11: Flow boundary conditions for May 2 and June 26, 2012 steady-state simulations

Location	May 2, 2012 Scenario (m^3/s)				June 26, 2012 Scenario (m^3/s)			
Crane Lake	37				45			
Little Vermillion narrows	13				13			
Sand Point Lake reach 1	5	10	15	25	5	10	15	25
Sand Point Lake reach 2	5	10	15	25	5	10	15	25
Sand Point Lake reach 3	5	10	15	25	5	10	15	25
Junction 1	50	50	50	50	58	58	58	58
Junction 2	55	60	65	75	63	68	73	83
Junction 3	60	70	80	100	68	78	88	108
Junction 4	65	80	95	125	73	88	103	133

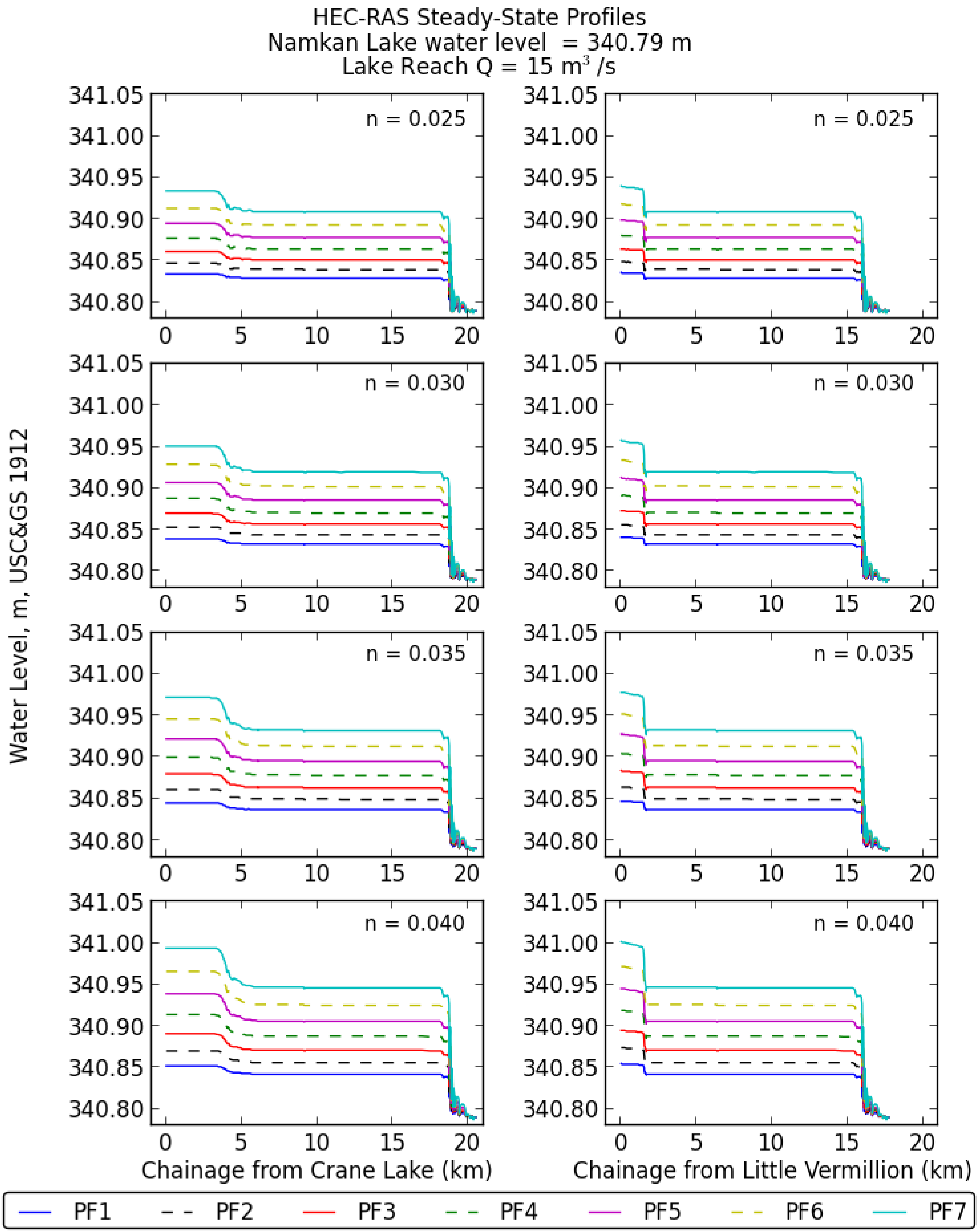


Figure 12: River profiles simulated with HEC-RAS for various roughness conditions. Downstream water level set at 340.79 m for all simulations. Sand Point Lake reach flow set at 15 m^3/s.

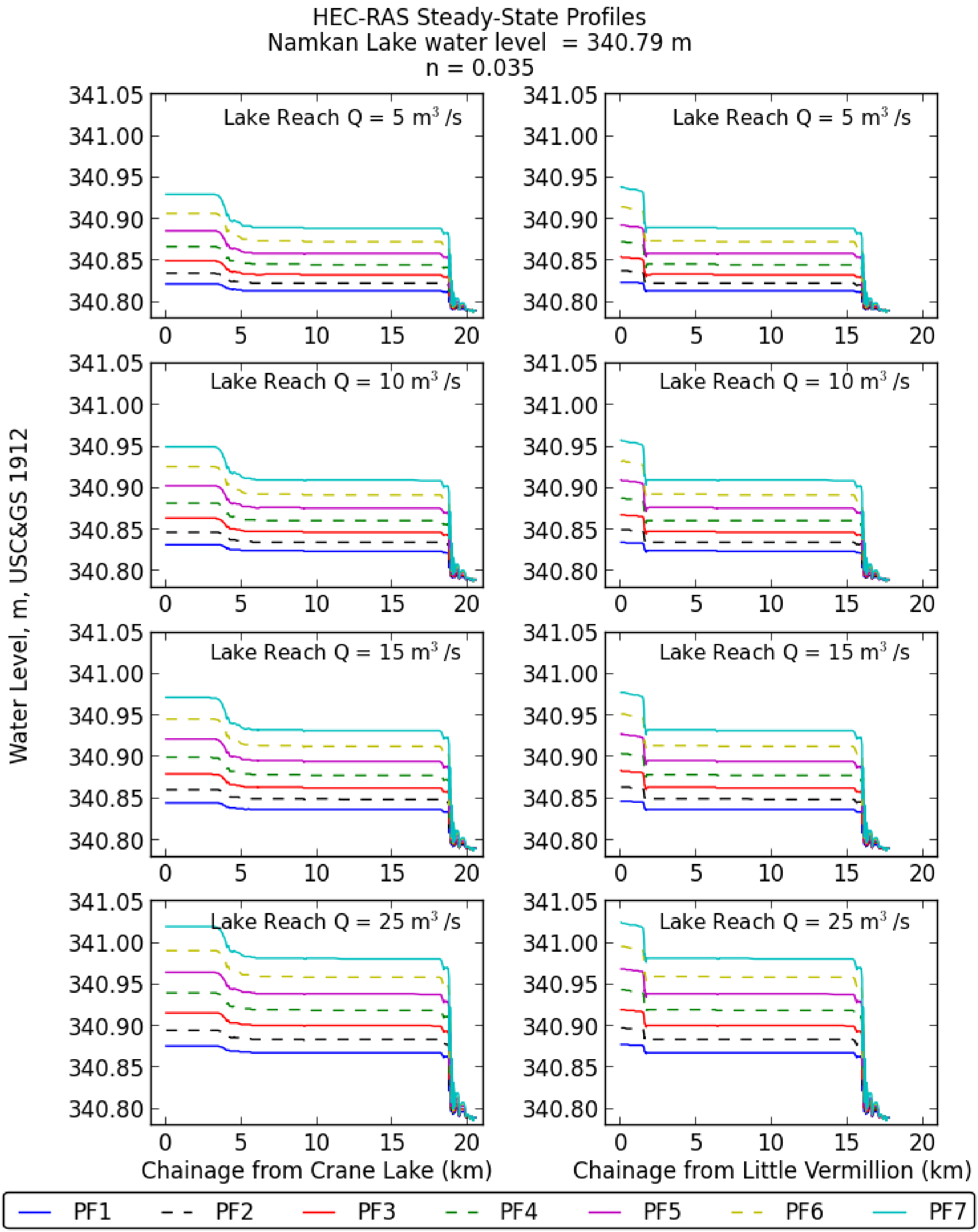


Figure 13: River profiles simulated with HEC-RAS for various Sand Point Lake reach flows. Downstream water level set at 340.79 m for all simulations. Roughness set at *n* = 0.035.

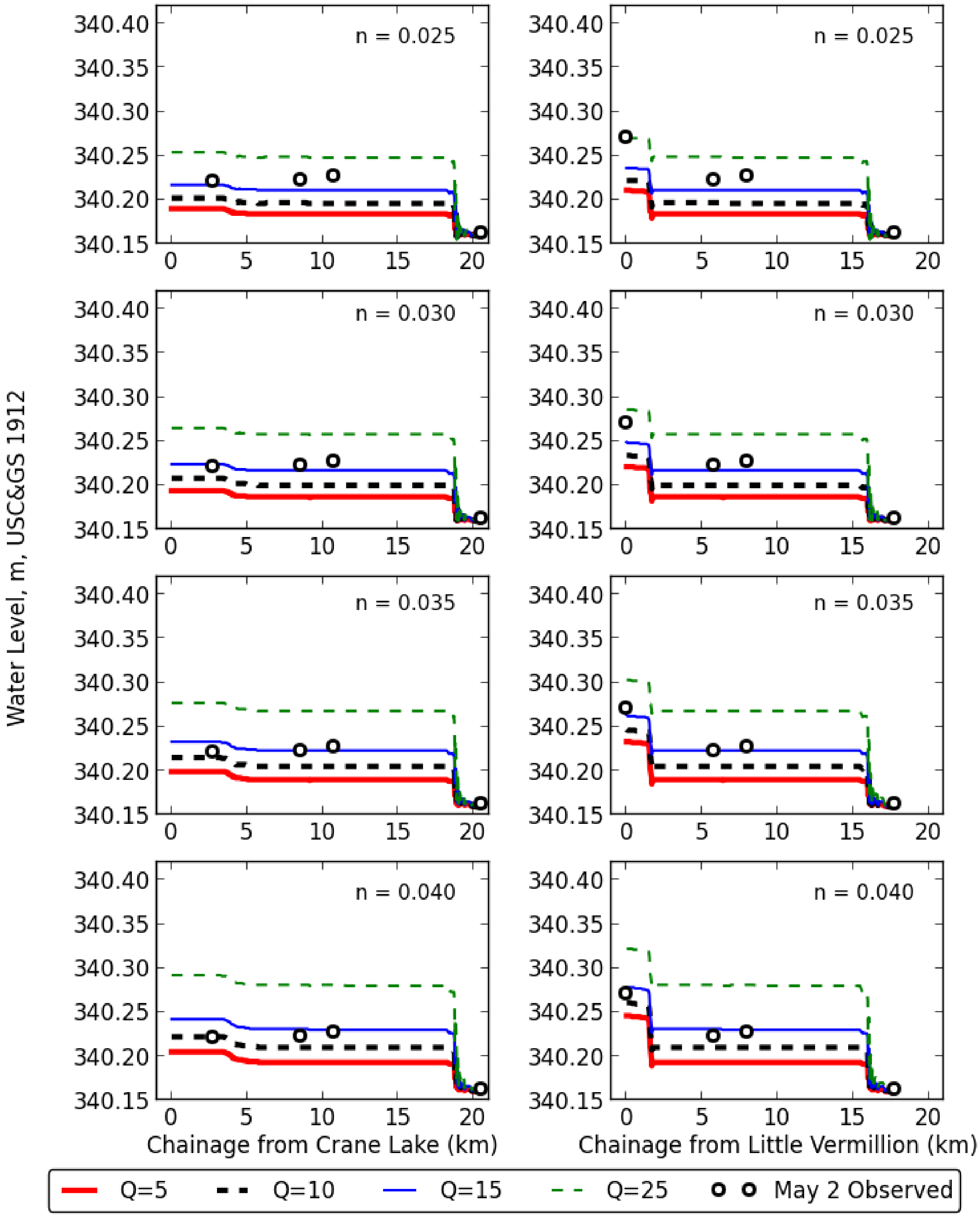


Figure 14: Steady state simulations of May 2 2012 flow scenario where roughness is varied. Boundary conditions at King Williams = 37 m^3/s, Little Vermillion = 13 m^3/s, and Lake Namakan = 340.16 m. Left panels show water surface profile from Crane Lake, right panels show profile from Little Vermillion narrows. Flow at lake reaches set at Q=5, 10, 15, 25 m^3/s.

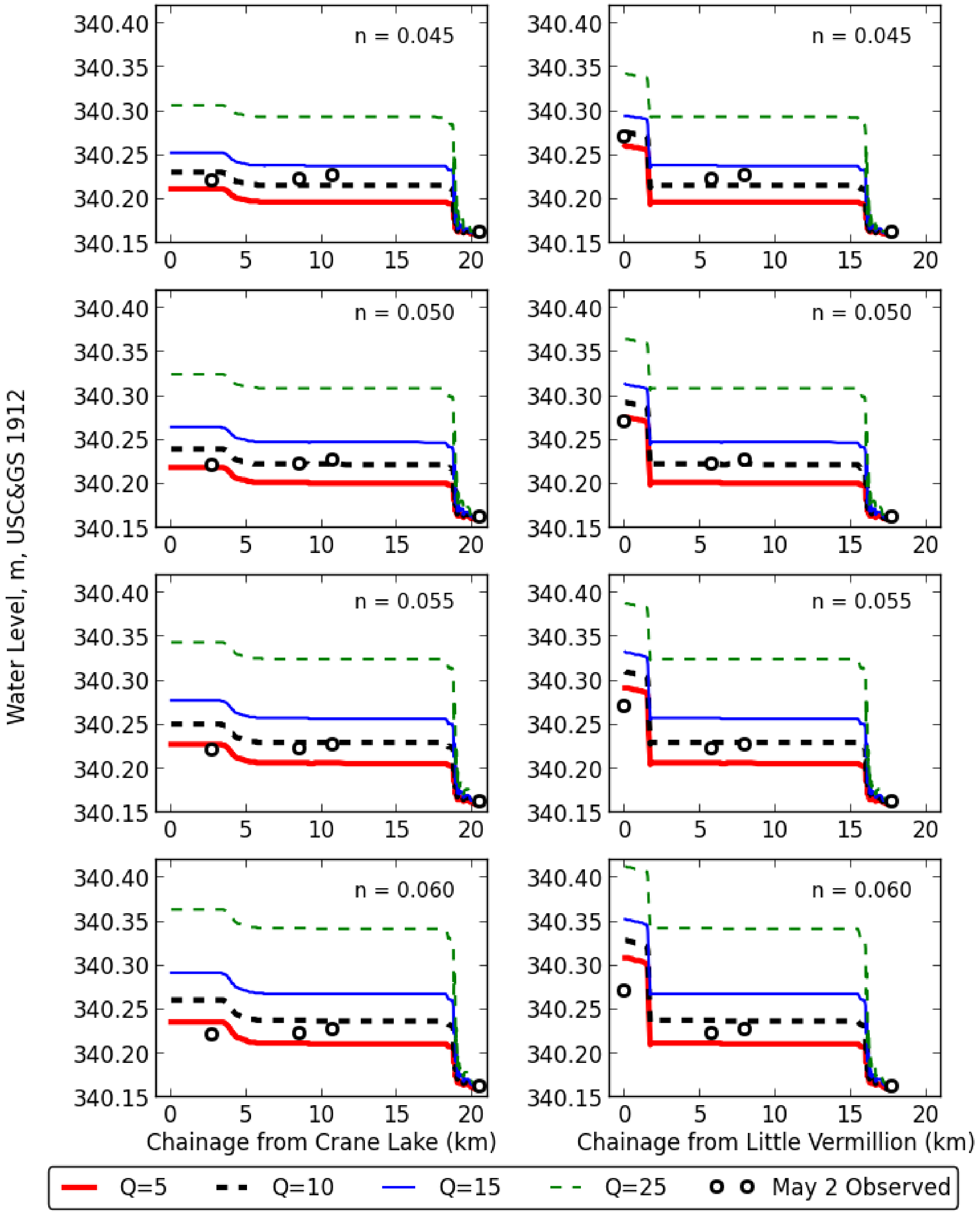


Figure 15: Steady state simulations of May 2 2012 flow scenario where roughness is varied. Boundary conditions at King Williams = 37 m^3/s, Little Vermillion = 13 m^3/s, and Lake Namakan = 340.16 m. Left panels show water surface profile from Crane Lake, right panels show profile from Little Vermillion narrows. Flow at lake reaches set at Q=5, 10, 15, 25 m^3/s.

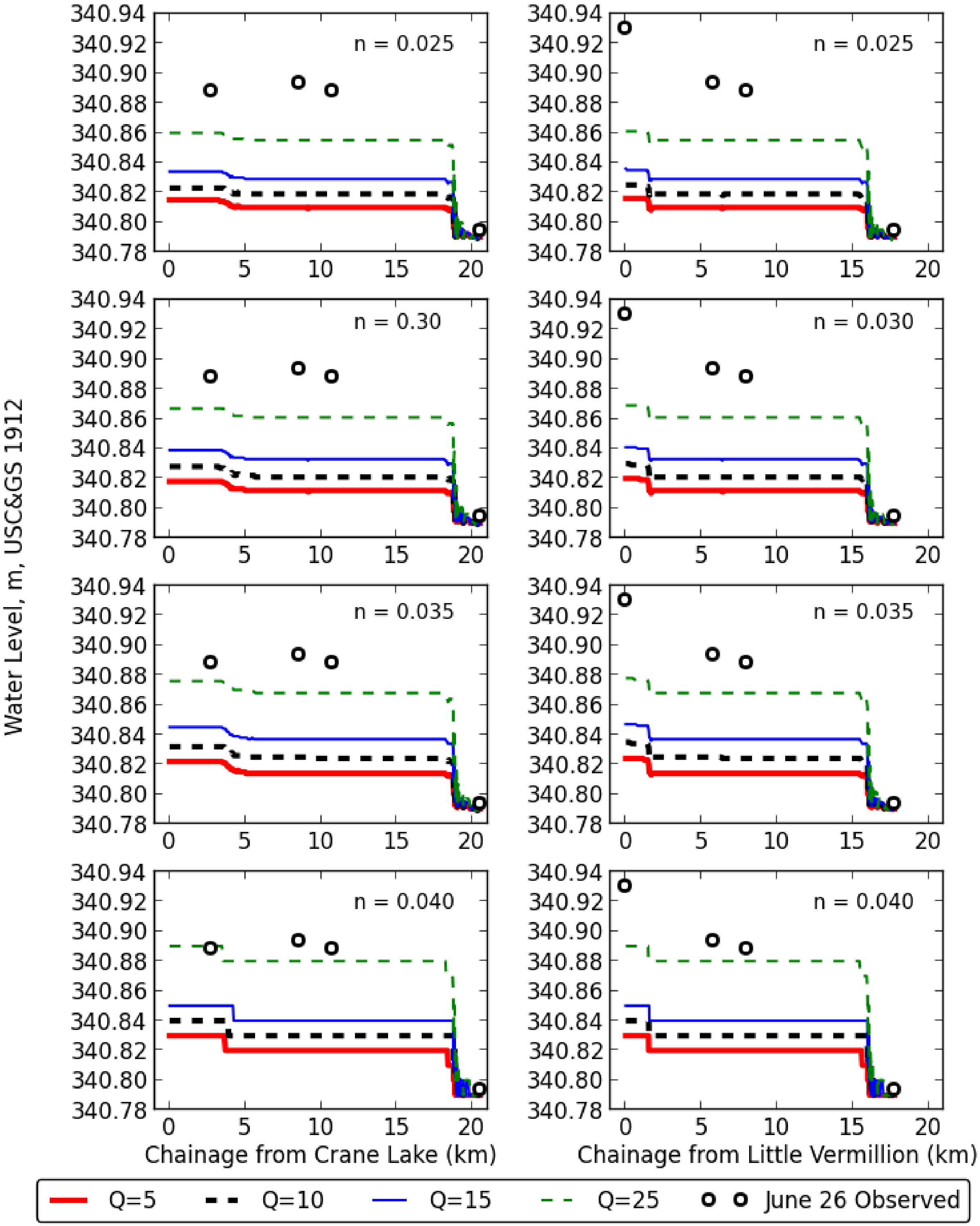


Figure 16: Steady state simulations of June 26 2012 flow scenario where roughness is varied. Boundary conditions at King Williams = 45 m^3/s, Little Vermillion = 13 m^3/s, and Lake Namakan = 340.79 m. Left panels show water surface profile from Crane Lake, right panels show profile from Little Vermillion narrows. Flow at lake reaches set at Q=5, 10, 15, 25 m^3/s.

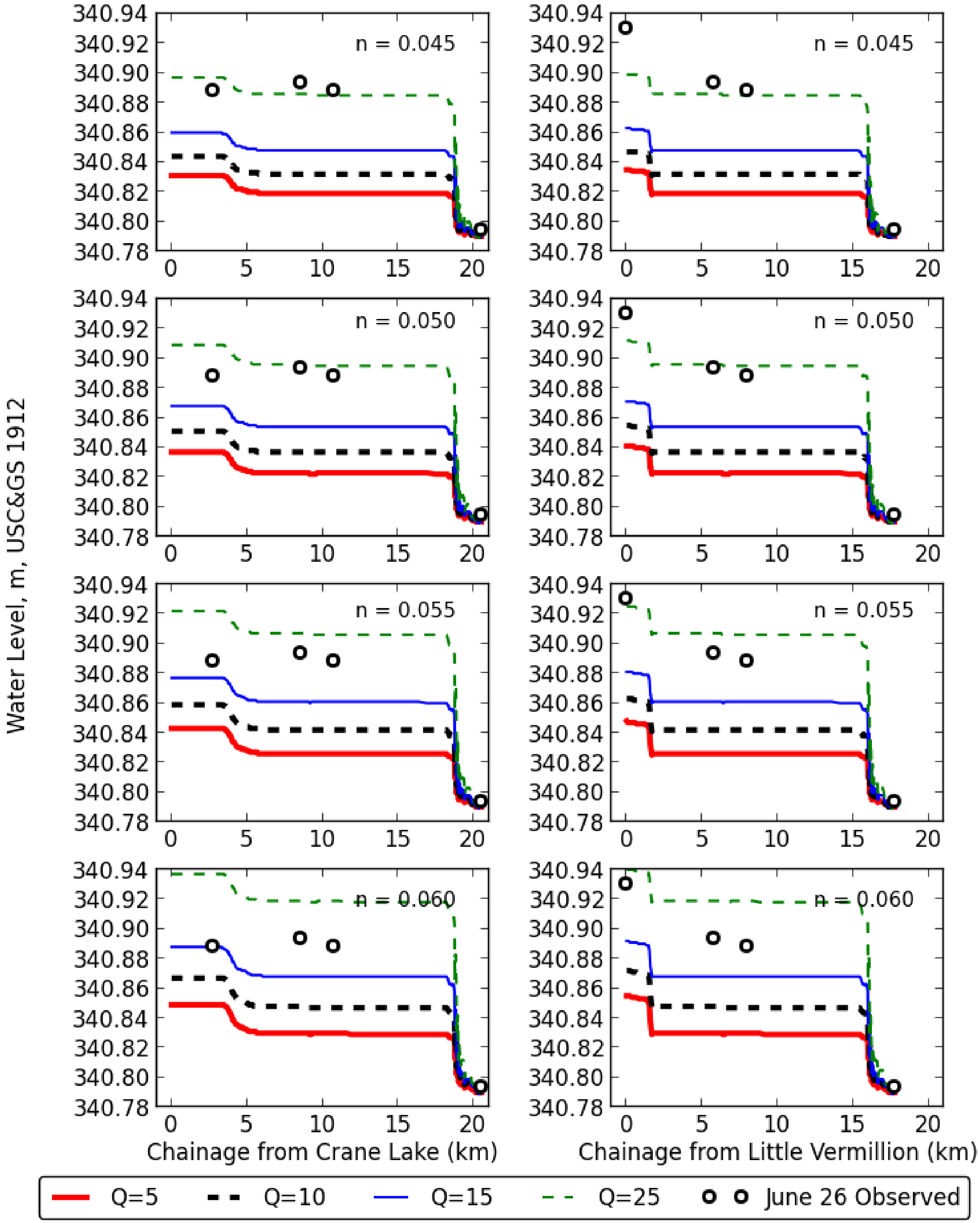


Figure 17: Steady state simulations of June 26 2012 flow scenario where roughness is varied. Boundary conditions at King Williams = 45 m^3/s, Little Vermillion = 13 m^3/s, and Lake Namakan = 340.79. Left panels show water surface profile from Crane Lake, right panels show profile from Little Vermillion narrows. Flow at lake reaches set at Q=5, 10, 15, 25 m^3/s.

3.2 Unsteady flow simulations

The HEC-RAS model was also executed in unsteady-state mode to provide further analysis of model performance. Unsteady-state simulations were completed for the summer of 2012 using available observations of flow and water level in the system. The flow measured at the USGS discharge gauge on the Vermillion River (05129115) was used as the upstream boundary condition for Crane Lake. The other upstream boundary condition at Little Vermillion Narrows was set to a value of the water level reported at the temporary transducer at that location, and the downstream water level was set to the level reported by the Squirrel Island gauge. Ideally, a flow boundary condition would be specified for Little Vermillion Narrows but there was insufficient observation data to do so. All three reaches in Sand Point Lake were set to a constant flow of either 5, 10, or 15 m^3/s. The Vermillion River gauge reports data on a daily time step. Thus, daily values for all water level records were used and the model was simulated at a daily interval. Figure 18 shows the daily discharges simulated through each pinch point during the simulations as well as the upstream discharge boundary condition at Crane Lake. Figure 19 shows the difference between the simulated and observed water levels. Head drop observed between upstream gauges and Squirrel Island for the simulation period is shown in Figure 20.

The panels in Figure 18 show increasing roughness lowers the flow through Little Vermillion narrows required by the model to meet the specified water level. For all roughness scenarios, the simulated flow through King Williams narrows was almost identical to the upstream boundary condition for Crane Lake. The ADCP measurements in Table 4 indicated flow through Little Vermillion Narrows was on the order of 1/3 of the total flow through King Williams narrows. Although reliable discharge measurements were only collected for two days, it is assumed that flow through Little Vermillion narrows is typically always less than flow through King Williams narrows. Figure 18 indicates simulated flow through Little Vermillion narrows was greater than simulated flow through King Williams narrows until global roughness is increased to a value of 0.060. As mentioned in section 3.1, global roughness is not expected to be as high as 0.050-0.060 based on the lack of weed growth and channel bottom characteristics observed during field surveys.

Furthermore, the unsteady simulations in Figures 18 and 19 never show a period when flow through the system reduces to negligible amounts when head drop through the system is minimal. Observed water levels between September and October 2012 in Figure 20 show the entire Namakan Chain is close to a static level, which is expected to result in minimal flow through the system. However, due to the structure of the model geometry and the use of flow boundary conditions for the Sand Point Lake reaches, the unsteady simulations in Figure 18 show significant flow through Harrison and Namakan narrows during this time (even for high roughness values), indicating there is a problem with the unsteady simulations.

Figure 19 shows multiple instances when simulated water levels diverged significantly from observed water levels, where simulated water levels on Crane Lake and Sand Point Lake were lower than observations. Several spikes in residual water level are shown in Figure 19; these spikes correlate with times when upstream water levels become elevated above the downstream end of the system, which is shown in Figure 20. This indicates that the current set up of the model and boundary conditions utilized are insufficient to characterize the system appropriately. More observations of water levels and discharge are needed to understand how water levels rise and fall in the system.

A comparison of simulated and observed discharges for unsteady flow simulations in Figures 18-19 is summarized in Figure 21. The plots compare ADCP discharge for May 2, 2012 and June 26, 2012 to the corresponding daily value simulated during the unsteady flow model runs. Figure 21 shows increasing global roughness towards 0.050-0.060 minimize the difference between simulated and observed discharge through each pinch point, with the exception of Harrison narrows on June 26. It should be noted the measured flow in Harrison narrows for June 26 was 107.74 m^3/s, a value well-above the discharges measured in the other pinch points on that day. Furthermore, there was less than 1 cm of difference between the June 26 daily water levels at the Sand Point Lake transducers above and below Harrison narrows; the minimal head drop indicates flow through Harrison narrows should be small. This measurement was a single transect at one location and it is possible this value is not reflective of average conditions that day. Temporary wind effects or other measurement error may have caused this value to be higher than the daily average flow through Harrison narrows.

Unsteady simulations were also completed with the same boundary conditions described above where the Vermillion River discharge time series was multiplied by a constant factor in an attempt to raise simulated water levels on Crane Lake. Figures 22 and 23 show simulations where global roughness was set at 0.035, Sand Point Lake reach boundary conditions were set at 5 m^3/s, and the Crane Lake boundary condition was set at 100%, 200%, 300%, 400%, and 500% of the Vermillion River discharge gauge. Similar simulation results are shown in Figures A1 and A2 for cases where the Sand Point Lake reach flows were set at 10 m^3/s. Results show that increasing flow into Crane Lake can reduce water level residuals throughout the system. However, the flows required to close the gap between simulated and observed water levels are well in excess of the ADCP measurements from May 2 and June 26 2012. Figure 24 shows the difference between observed and simulated discharges for simulations when flow is increased at Crane Lake. Although increasing the Crane Lake boundary condition was shown to reduce water level residuals in Figures 23 and A2, setting the Crane Lake boundary condition to 300-500% of the Vermillion River discharge results in flows through the system which are much greater than what is observed.

The results from the unsteady flow simulations indicate the HEC-RAS model simulates water levels and discharges through the system reasonably well when Crane Lake and Sand Point Lake are not significantly elevated above Namakan Lake. However, the model was not capable of replicating the water surface profile when observations show Crane and Sand Point Lakes elevated above the downstream end. Simulation results showed the amount of inflow into Crane Lake to allow the profile to rise enough to match observations resulted in flows through each pinch point which were higher than observations from ADCP measurements.

To help isolate sources of error in the simulations and to verify HEC-RAS results, a two-dimensional RMA2 model was built and executed for a number of scenarios to allow comparison with the HEC-RAS model. These results are discussed in the next sections.

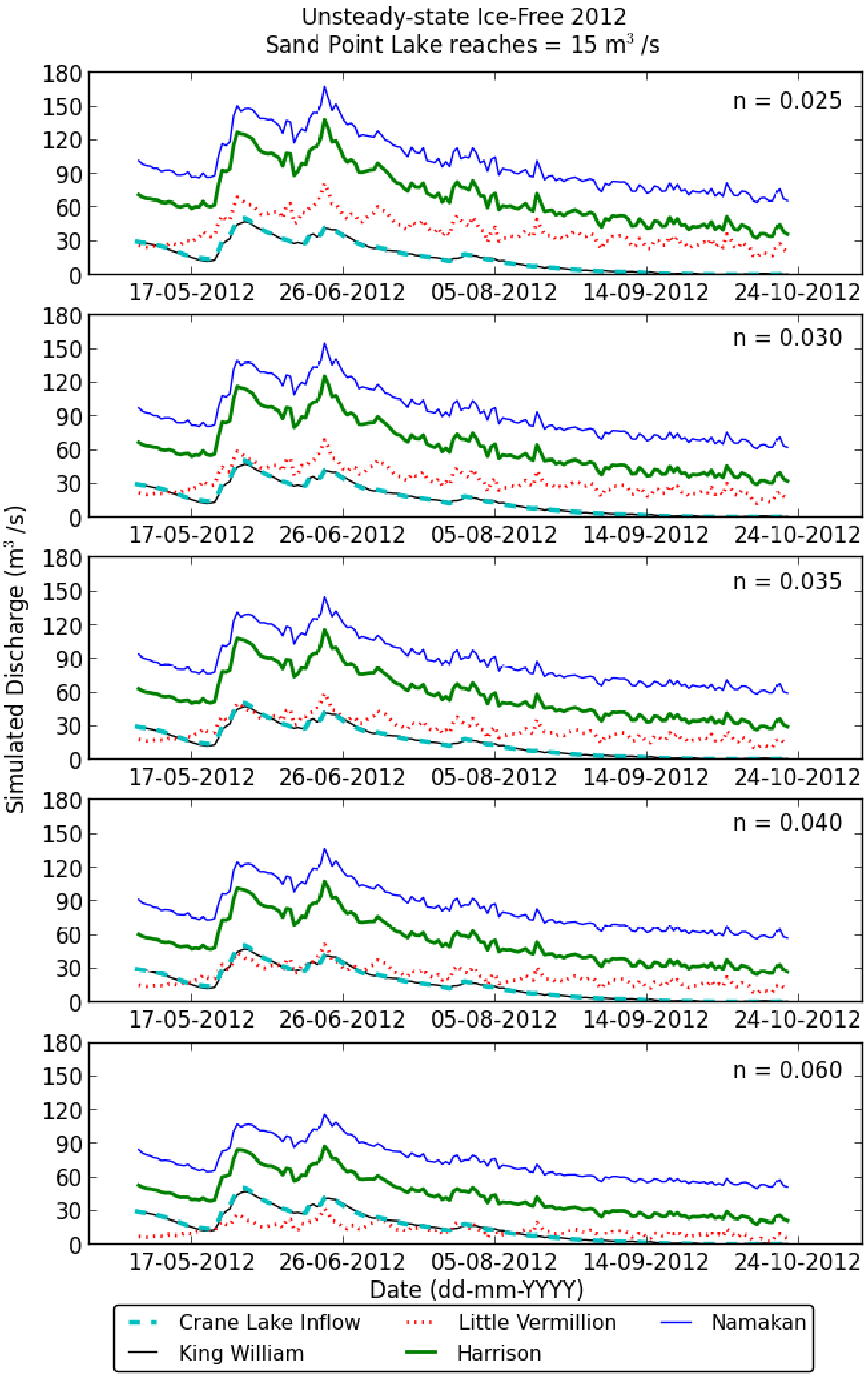


Figure 18: Daily discharge simulated through each pinch point during 2012. Downstream boundary set to Squirrel Island water level, upstream boundary at Little Vermillion set to temporary transducer water level, upstream boundary at Crane Lake set to USGS discharge gauge measurements.

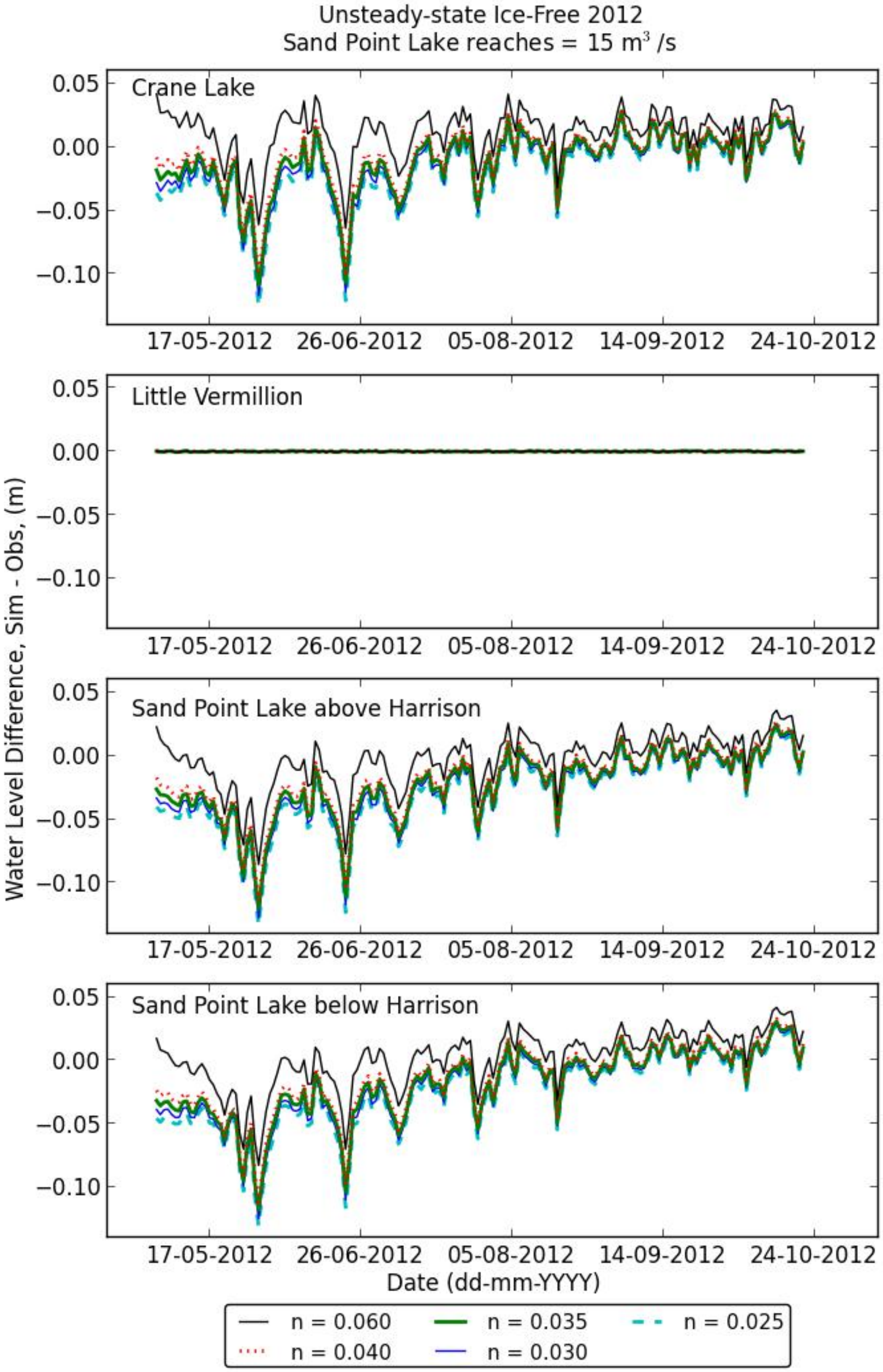


Figure 19: Water level residuals from unsteady-state simulations for 2012. Downstream boundary set to Squirrel Island water level, upstream boundary at Little Vermillion set to temporary transducer water level, upstream boundary at Crane Lake set to USGS discharge gauge measurements.

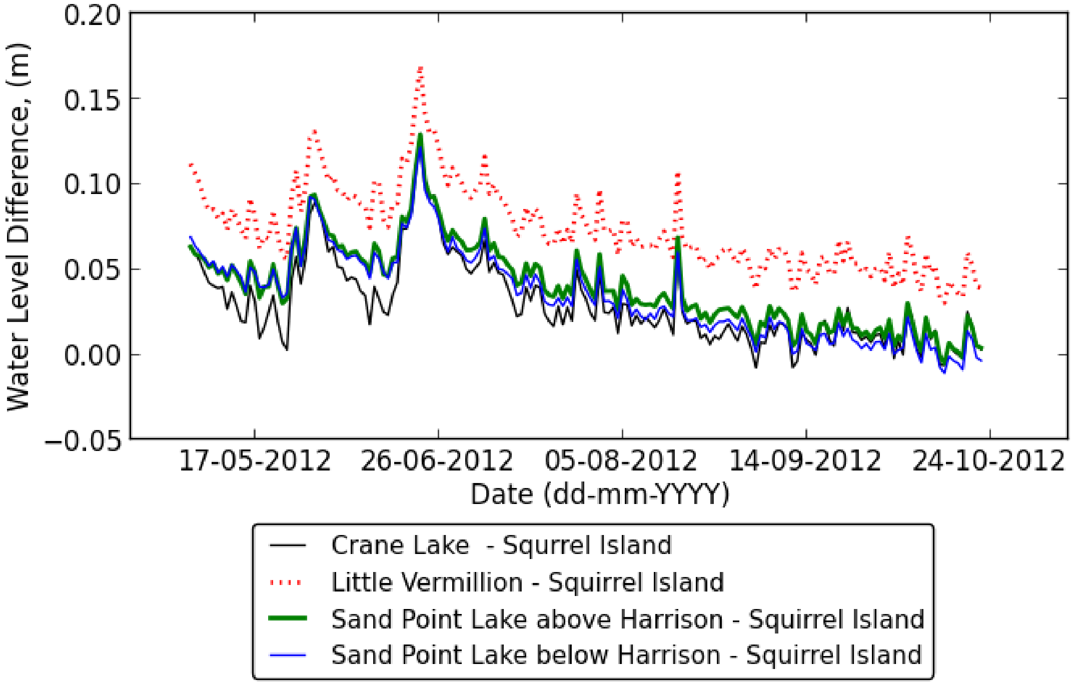


Figure 20: Daily water level head drop observed between upstream gauges and Squirrel Island.

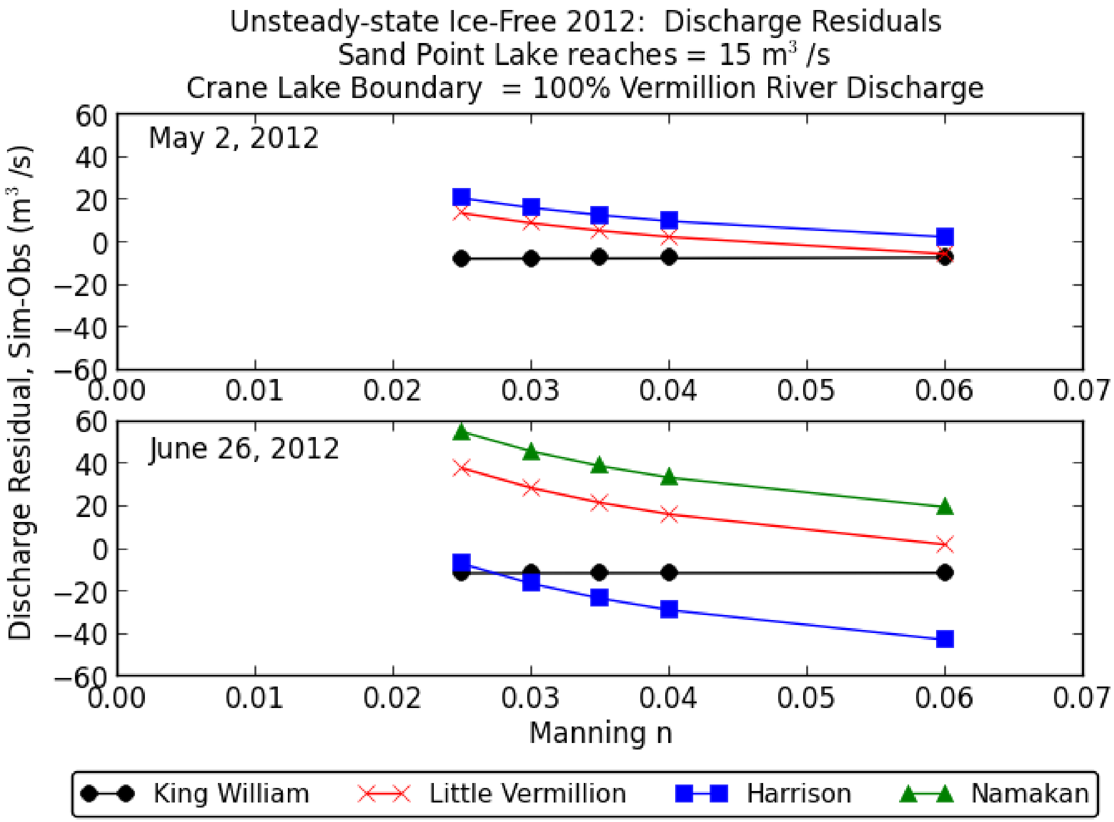


Figure 21: Effect of roughness on discharge residuals when unsteady simulation results are compared to May 2, 2012 and June 26, 2012 ADCP measurements.

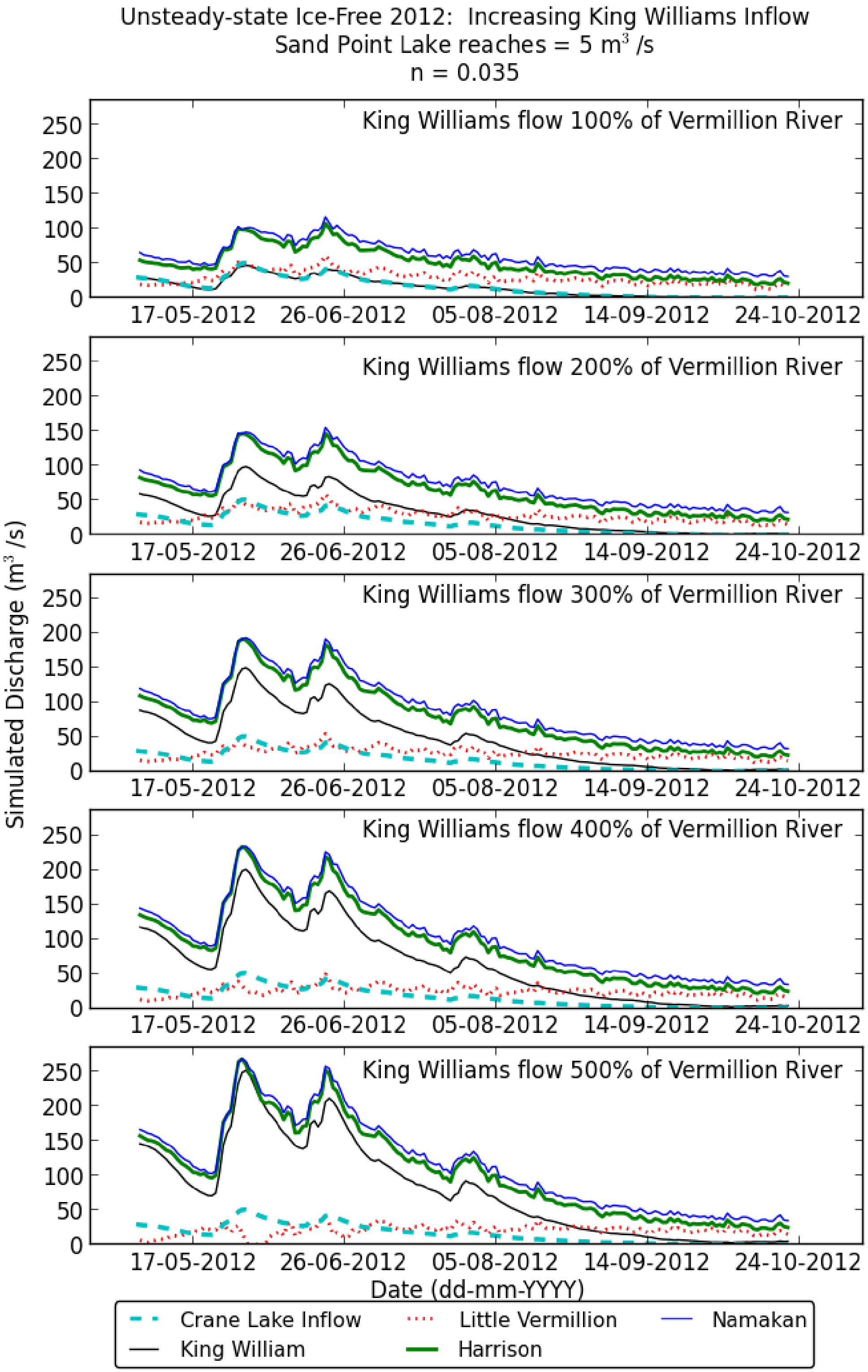


Figure 22: Daily discharge simulated through each pinch point during 2012 for Sand Point Lake reach flow of 5 m^3/s. Downstream boundary set to Squirrel Island water level, upstream boundary at Little Vermillion set to temporary transducer water level, upstream boundary at Crane Lake set to percentage of Vermillion River discharge gauge measurements.

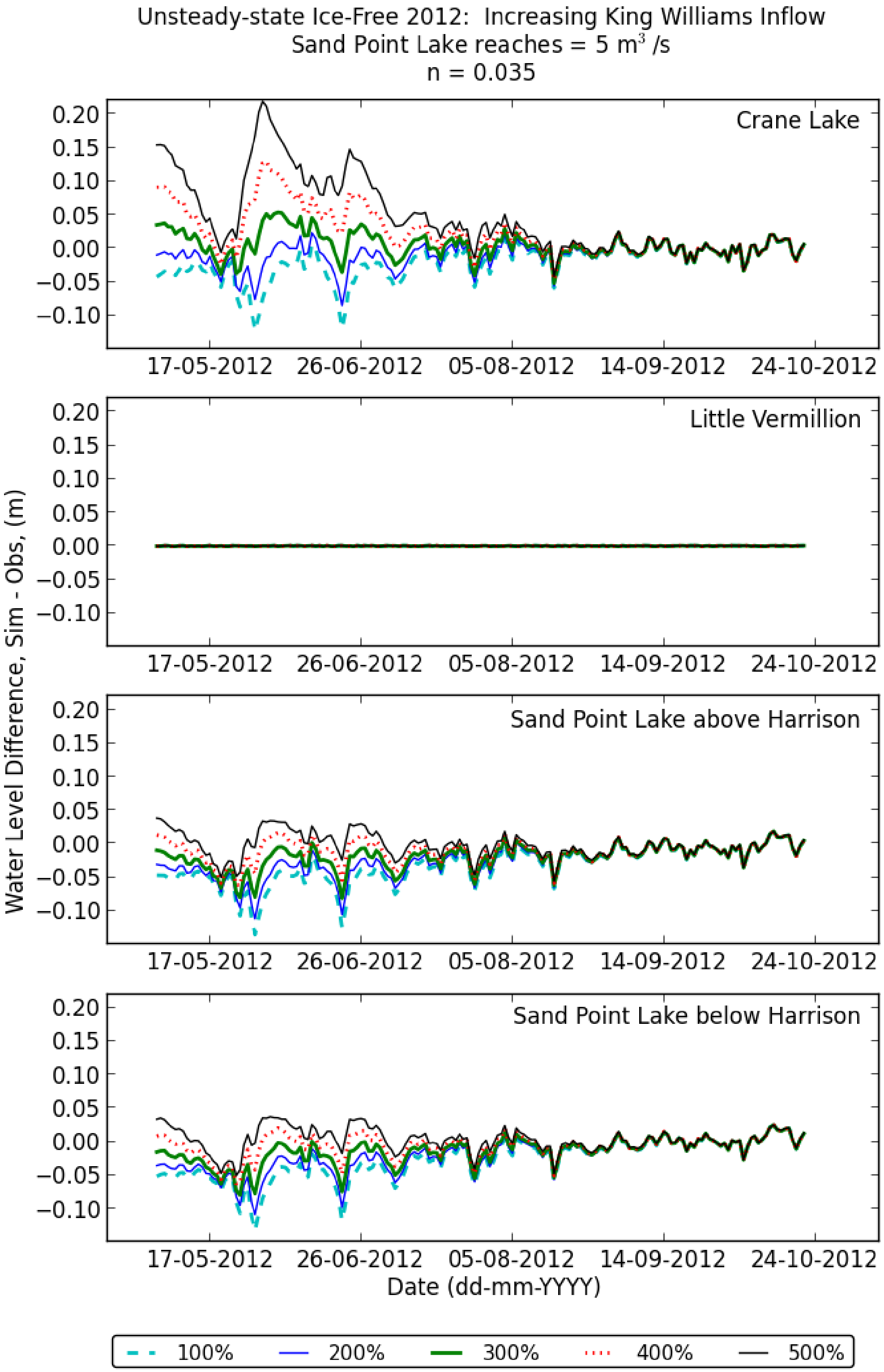


Figure 23: Water level residuals from unsteady-state simulations for 2012. Downstream boundary set to Squirrel Island water level, upstream boundary at Little Vermillion set to temporary transducer water level. Upstream boundary at Crane Lake set to percentage of USGS discharge gauge measurements – 100%, 150%, 200%, 250%, 300%.

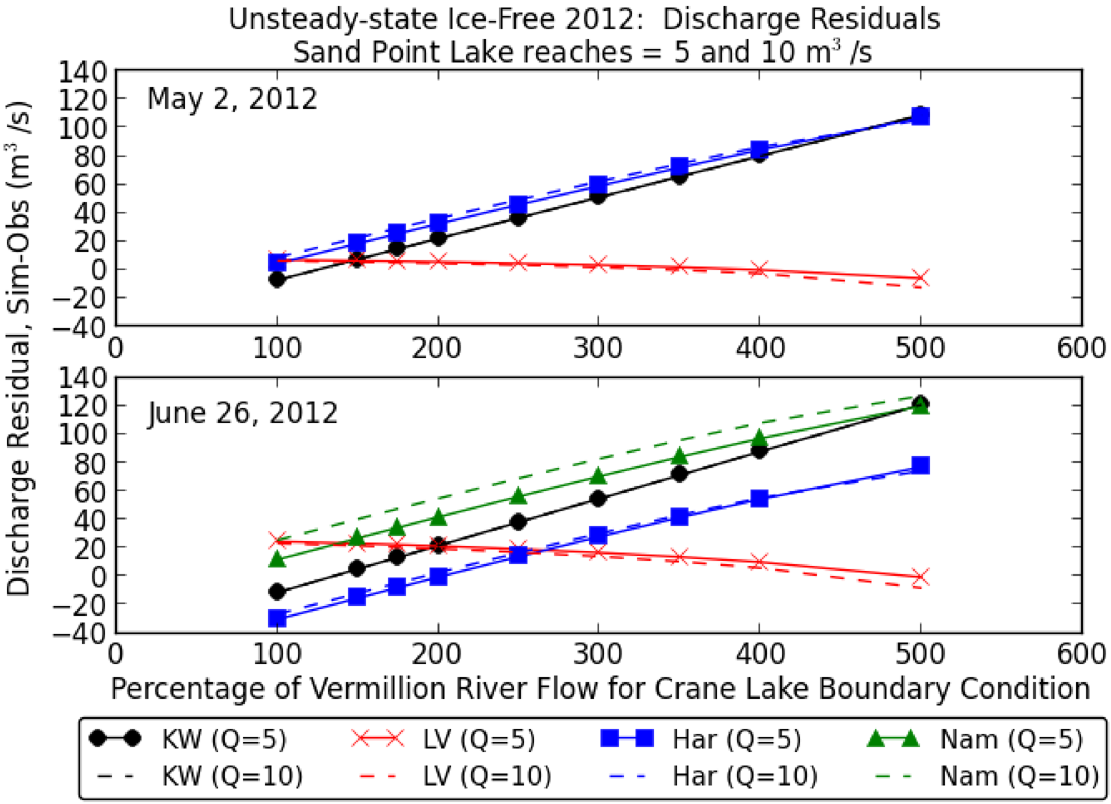


Figure 24: Unsteady simulation results when increasing flow at Crane Lake boundary condition by a percentage of Vermillion River time series. Global roughness = 0.035. Solid lines for cases when Sand Point Lake reach boundary conditions set to 5 m^3/s, dotted lines for cases when Sand Point Lake reach boundary conditions set to 10 m^3/s.

4 RMA2 MODEL

The main source of concern with setting up the HEC-RAS model geometry was including appropriate assumptions to account for storage in each of the lake areas. The study area is a system of reservoirs connected by pinch point channels; properly accounting for storage in the lakes is a critical component of modelling flow through the system. Results from initial HEC-RAS simulations discussed above showed divergence between simulated and observed water levels for periods when Crane Lake was elevated above Namakan Lake, where the model was simulating less head drop through the system than what was observed at water level gauges.

An RMA2 model was developed in parallel with the HEC-RAS model to verify the1D model was capable of accounting for storage in the lake areas. RMA2 is a two-dimensional hydrodynamic model developed by the Resource Management Associates and maintained for many years by the U.S. Army Corps of Engineers. It has been widely used in hydrodynamic modeling applications (Donnell et al., 2011). The two-dimensional (2D) model was quickly built to provide a validation of whether the storage and flow junctions in Sand Point Lake were appropriate. The 2D model does not require the specification of boundary conditions on Sand Point Lake or the proportion of flow at reach junctions. It was hypothesized that the boundary conditions required at the upstream ends of the three lake reaches in the HEC-RAS model were introducing error into the simulation results. Physical measurements to verify flow from each lake for the HEC-RAS simulations were not available; as a result, Sand Point Lake reach boundary conditions had been set based on estimates of what types of flows from these reaches would be plausible. Furthermore, the lack of calibration and validation data available for the study area limited the amount of analysis that could be completed with HEC-RAS. Development of a 2D model was desirable to provide a more robust metric of model comparison beyond the two steady-state flow scenarios for May 2 and June 26, 2012.

4.1 RMA2 geometry and boundary conditions

The RMA2 model mesh consisted of 24 732 quadratic triangular elements and 52 783 nodes. Element size in the lake areas were set to 100 m, while the grid was refined to an element size of 25 m in the pinch point channels. The same pinch point channel bathymetry and shoreline files that were used to develop the TIN used with HEC-GeoRAS was used for the RMA2 model. The MinDNR contour data was converted to points before it was included In the RMA2 geometry. Figure 25 shows the elevation of mesh elements and the corresponding side profile of the study area. Further details of the 2D mesh elements are shown in Figure 26. The RMA2 model also requires the specification of roughness parameters and eddy viscosity coefficients or Peclet numbers that need to be determined through calibration. For this model, global roughness was set at values ranging from 0.025 to 0.04 and a Peclet Number of 20 was utilized.

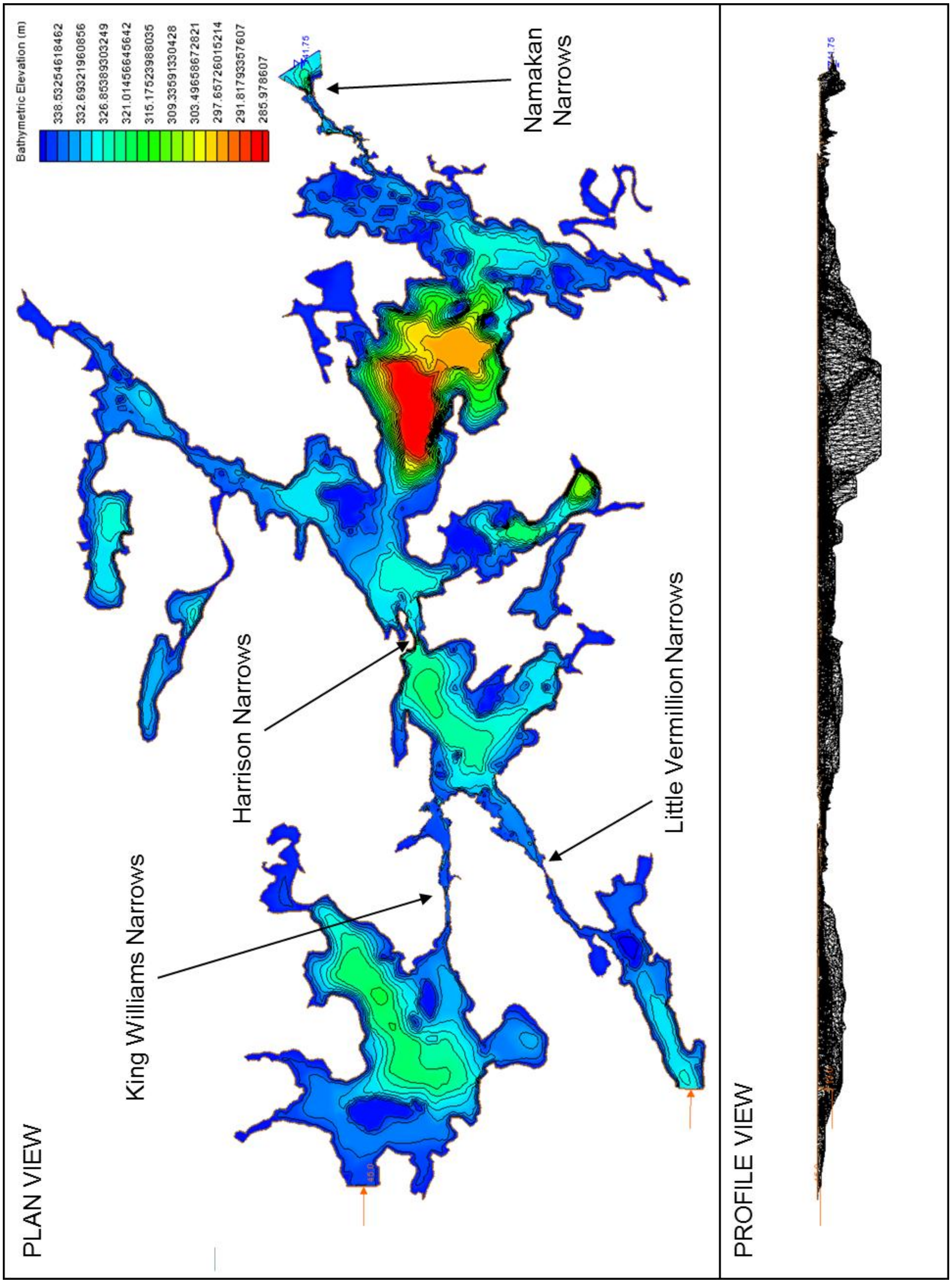


Figure 25: RMA2 model geometry with elevation contours of model grid in USC&GS 1912 vertical datum. Bottom panel shows elevation profile of study area.

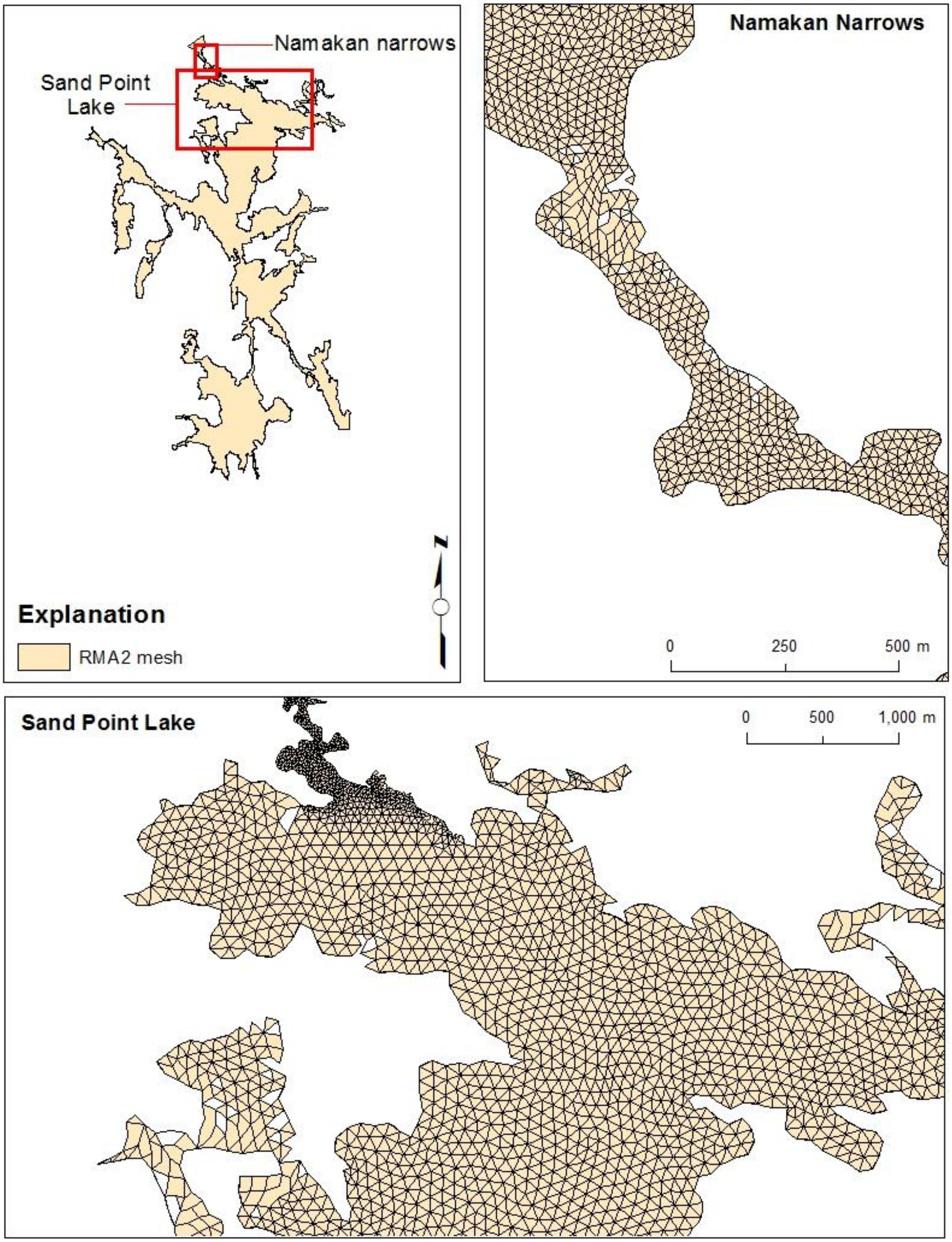


Figure 26: RMA2 mesh developed with SMS 11.0, UTM Zone 15 N

4.2 RMA2 simulations

For all simulations, a global Manning's roughness value was applied to the entire model, similar to the approach used with the HEC-RAS model. Roughness values of 0.025, 0.030, 0.035, and 0.04 were used for simulations. The RMA2 model was not calibrated as the purpose of the simulations was limited to verification of the HEC-RAS output. The downstream boundary condition was the level of Namakan Lake used for HEC-RAS simulations. Upstream flow boundary conditions were varied based on the assumption flow through Little Vermillion narrows was always 29% of flow through King Williams narrows. Simulations began with the observation scenario from June 26, 2013 of 45 m^3/s at King Williams narrows and 13 m^3/s at Little Vermillion narrows and increased flow at King Williams narrows in increments of 10 m^3/s as shown in Table 10.

Figure 27 shows the RMA2 simulation results. The left panels show simulated water level profiles from Crane Lake through King Williams narrows to Namakan Lake, while the right panels show simulated profiles through Little Vermillion narrows through to Namakan Lake. Model nodes showing the water surface profile were selected based on the location of HEC-RAS cross-sections and an approximate centerline of each reach. Figure 27 shows roughness did not have a major influence on water surface profiles for the low flow conditions simulated. For the highest flow scenario, PF7, changing global roughness from 0.025 to 0.040 increased the simulated water level at Crane Lake by approximately 3 cm. Less change was observed at the downstream end of the system, where the increase in roughness from 0.025 to 0.04 caused approximately a 2 cm increase in water levels at the downstream end of Sand Point Lake. The impacts of changing roughness were more pronounced at the upstream end of Little Vermillion narrows, where the change of from 0.025 to 0.040 for PF7 caused an increase in water level of 4 cm. The Little Vermillion profiles show a small increase in water levels from upstream to downstream at low roughness values in one short section of the reach slightly downstream of Little Vermillion narrows. The reason for this is there is an abrupt constriction in the Little Vermillion narrows that causes velocities to rise significantly at the constriction. The velocity head increases significantly at the restriction causing the water levels to fall abruptly at this section. A short distance downstream, the channel widens again and velocities decrease quickly causing the water levels to rise again. This phenomena is not as evident when larger roughness values are utilized in the model because velocities are smaller due to the increased roughness. Froude numbers remain below 1 throughout this section at all times so there is not a critical flow control section.

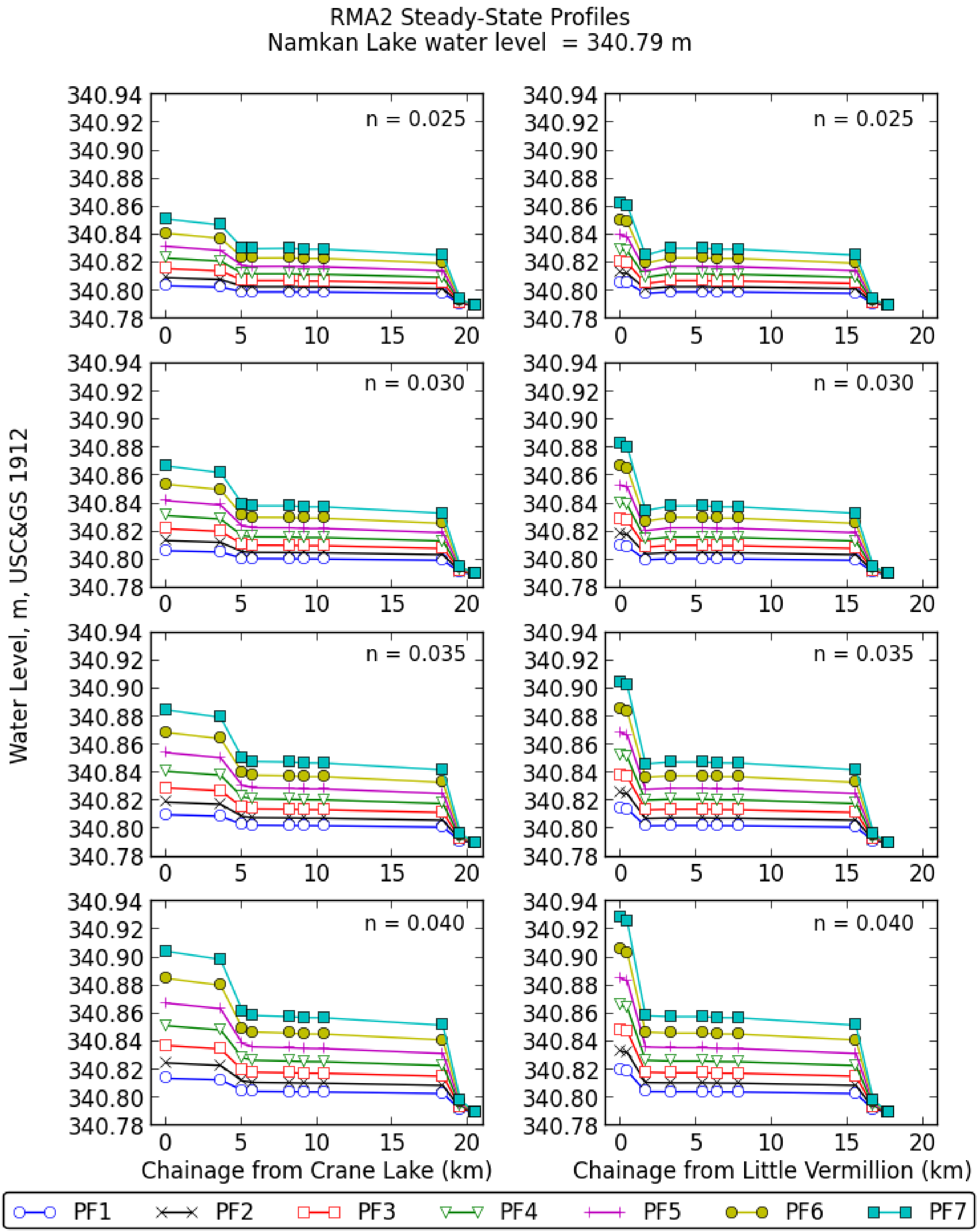


Figure 27: River profiles simulated with RMA2 for various roughness conditions. Downstream water level set at 340.79 m for all simulations. RMA2 profiles extracted from simulated water levels at 10 model nodes.

4.3 Comparisons of HEC-RAS and RMA2 simulations

RMA2 simulation results are compared to HEC-RAS simulations in Figures 28 and 29 when global roughness in the RMA2 model was set to 0.035. Figure 28 provides the water surface profile simulated from Crane Lake while Figure 29 describes the water surface profile from Little Vermillion. Simulations of PF1-PF7 from Table 10 are shown in each panel where HEC-RAS water surface profiles simulated for Sand Point Lake reach boundary conditions of Q = 1, 5, 10, 15, and 25 m^3/s are shown by each line and water surface elevations simulated by RMA2 are shown by the teal points. Figures A3-A8 summarize the same model comparison for global roughness values of 0.025, 0.030, and 0.040.

Direct comparison of the HEC-RAS and RMA2 simulations indicates the RMA2 under-predicted HEC-RAS water surface profiles for global roughness values of 0.025-0.040, particularly for the higher flow conditions in PF3-PF7. The gap between RMA2 and HEC-RAS simulations increased as boundary condition flow increased. The results in Figures 28-29 and A3-A8 indicate the HEC-RAS simulations match closest with RMA2 when Sand Point Lake reach flows are set to negligible values of 1 m^3/s. Figure 30 compares the HEC-RAS and RMA2 profiles simulated from Crane Lake to Namakan Lake when the Sand Point Lake flow boundary conditions are 1 m^3/s. Profiles simulated by HEC-RAS are shown in the left panels while RMA2 profiles are shown in panels on the right. Both models simulate a head drop through King Williams narrows and Namakan narrows, with no head drop observed through Harrison narrows. The RMA2 simulations show slightly less head drop through the entire system than the HEC-RAS simulations do. A direct comparison of simulated water levels at selected model locations is shown in Figure 31; the difference between simulated water levels at HEC-RAS cross-sections and the nearest corresponding RMA2 model node is plotted in each panel, where the panels on the left show chainage from Crane Lake, while the panels on the right show chainage from Little Vermillion narrows. Figure 31 shows the difference between simulated HEC-RAS and RMA2 water levels was less than 1 cm for PF1, while the difference between simulated water levels in the two models increases to approximately 3 cm for PF7.

RMA2 simulations predicted water surface profiles that were slightly lower than those predicted by HEC-RAS, particularly for the higher flow conditions in PF3-PF7. The RMA2 model showed general agreement with HEC-RAS; results indicate the HEC-RAS geometry provides a reasonable representation of the Namakan Chain system. This suggests the decision to use reaches to account for storage in Sand Point Lake in the HEC-RAS model was an accurate assumption. RMA2 results indicate the best match with HEC-RAS for steady-flow scenarios would be to set the Sand Point Lake reach boundary flow conditions to negligible values. This contrasts with the steady-flow HEC-RAS simulations which showed higher reach boundary conditions of 15-25 m^3/s in HEC-RAS provided the best fit with observed data. It should be noted that the RMA2 model was developed quickly with the purpose of providing a validation of the HEC-RAS simulations and therefore minimal effort was invested in attempts to improve or calibrate simulation results. Further to this point, the RMA2 model was not simulated in unsteady mode for two reasons; (1) RMA2 does not handle large fluctuations in water levels well due to the way wetting and drying conditions are specified and (2) detailed 2D modeling was beyond the scope of work for this project.

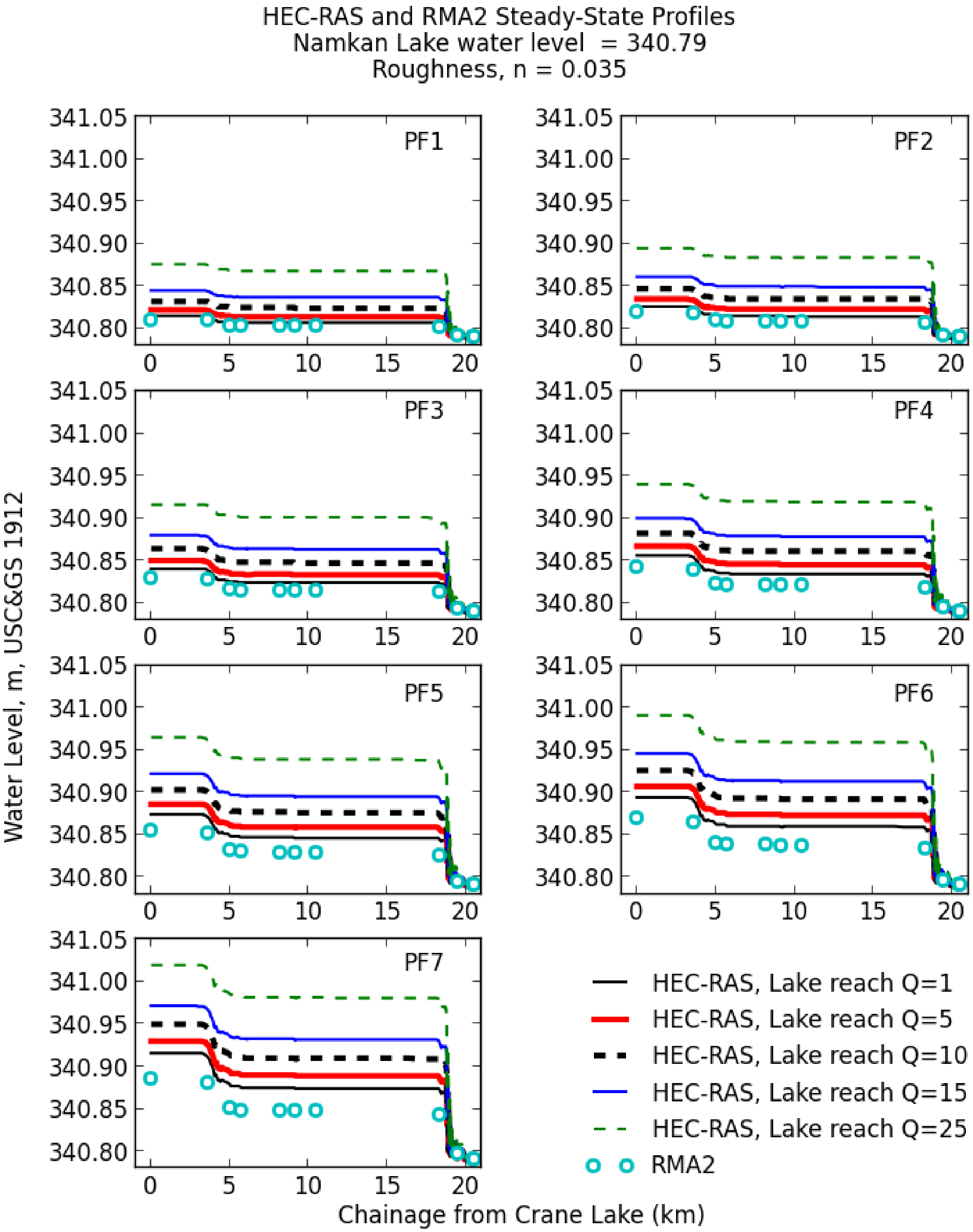


Figure 28: Water surface profiles from HEC-RAS and RMA2 steady-state simulations from Crane Lake to Namakan Lake, roughness = 0.035. HEC-RAS boundary conditions for lake reaches = 5, 10, 15, and 25 m^3/s.

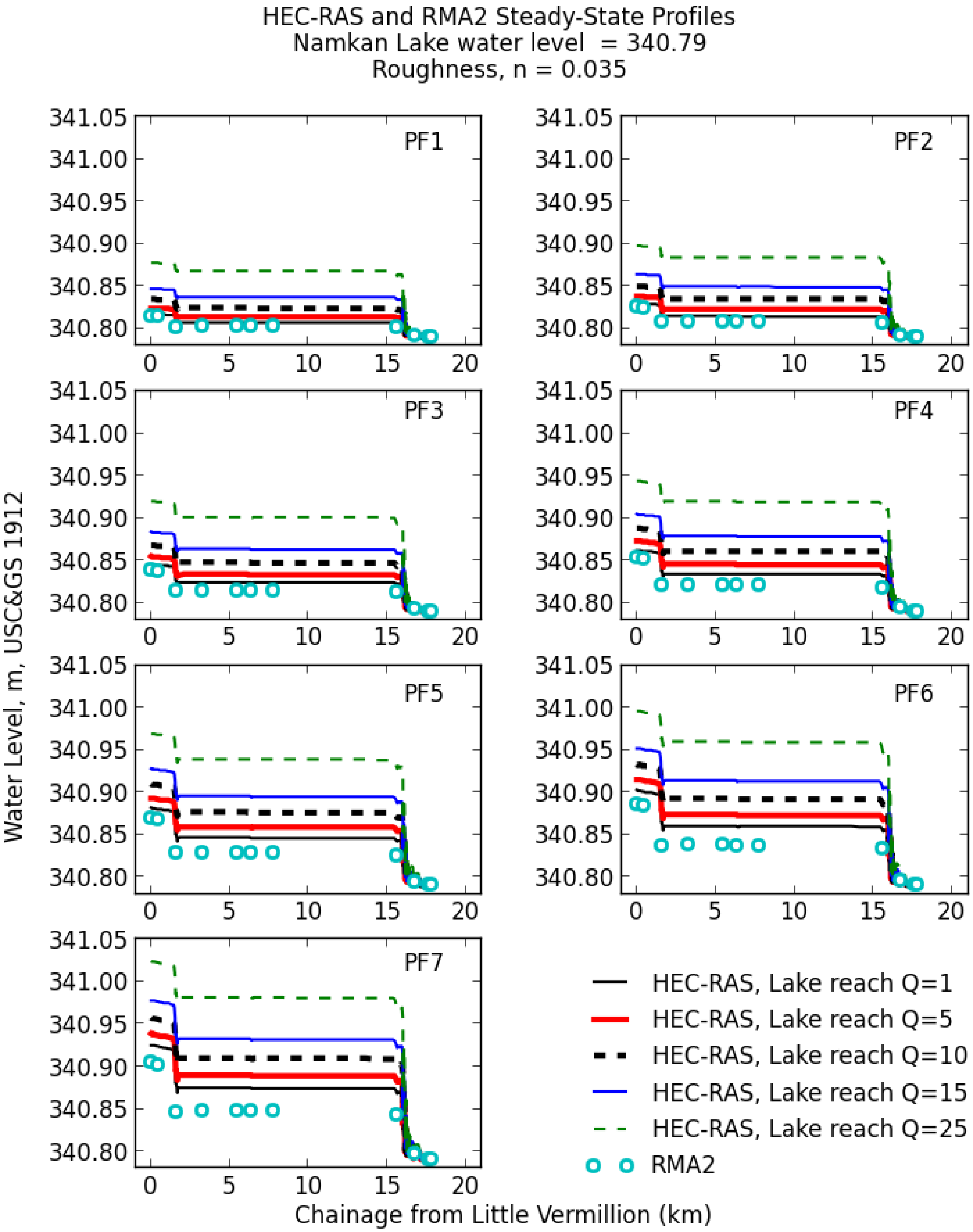


Figure 29: Water surface profiles from HEC-RAS and RMA2 steady-state simulations from Little Vermillion to Namakan Lake, roughness = 0.035. HEC-RAS boundary conditions for lake reaches = 5, 10, 15, and 25 m^3/s.

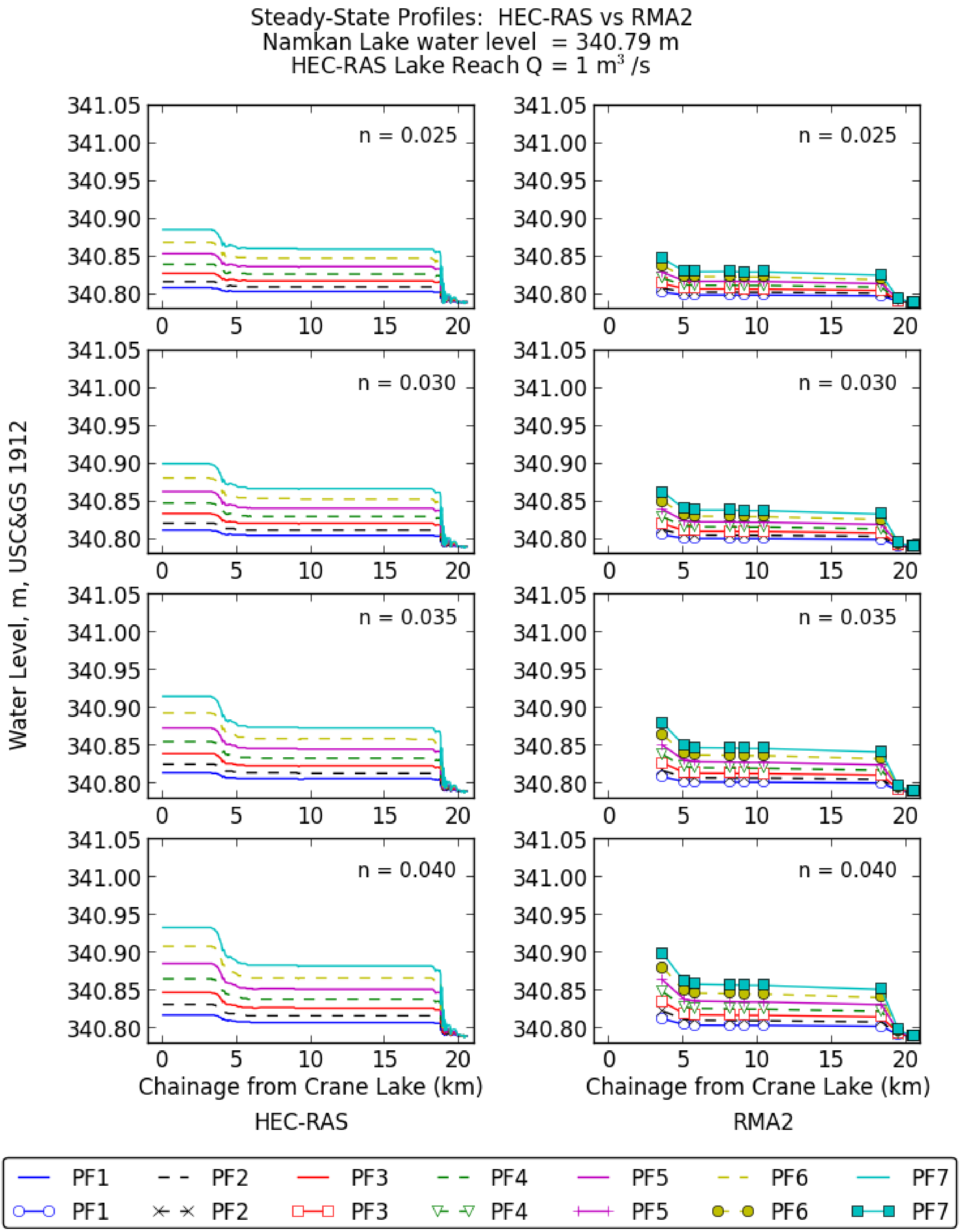


Figure 30: Comparison of steady-state profiles simulated by HEC-RAS and RMA2. Downstream water level set to 340.79 for all simulations. HEC-RAS simulations used flow boundary condition of 1 m^3/s for lake reaches. RMA2 profiles extracted from simulated water levels at 10 model nodes.

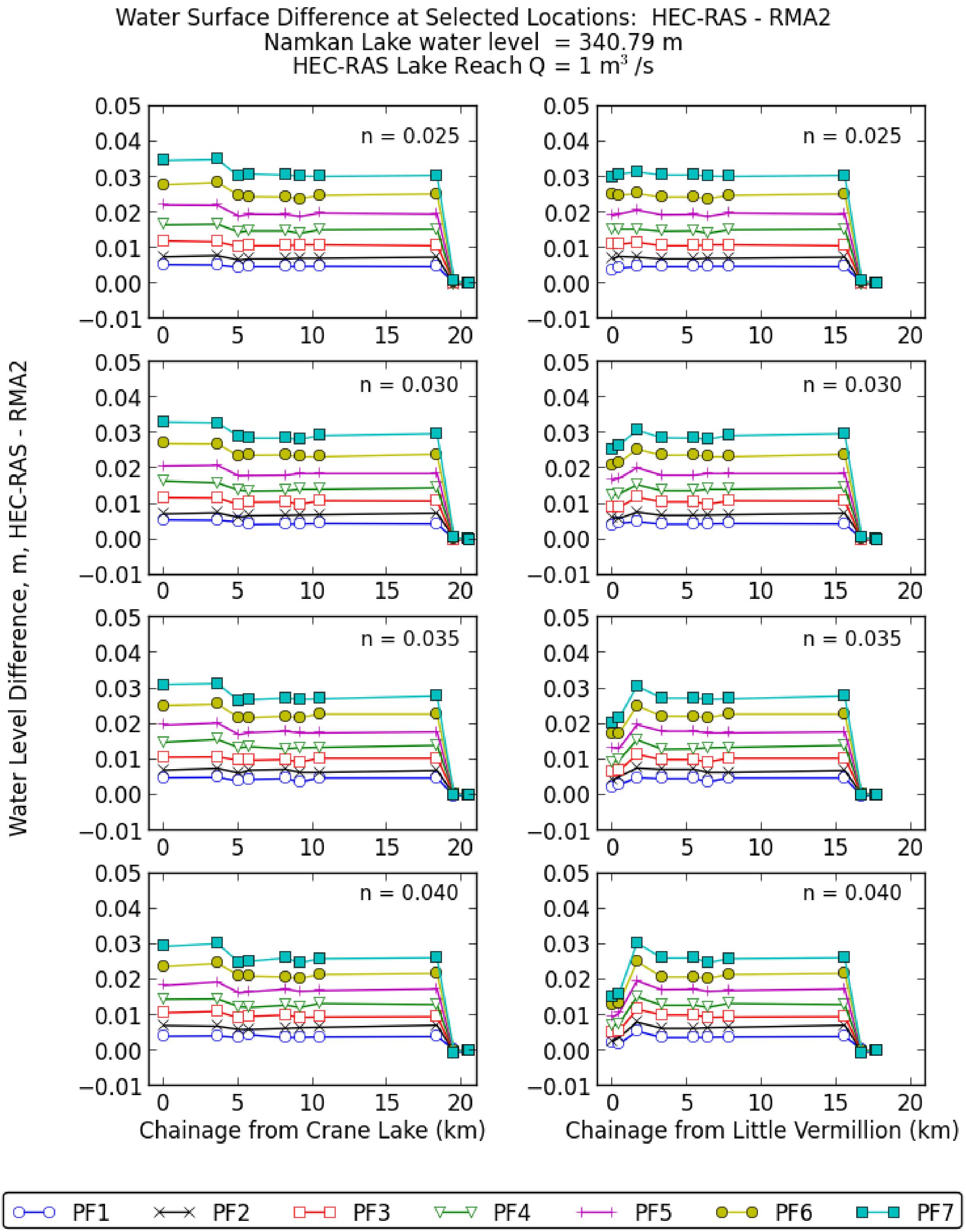


Figure 31: Comparison of steady-state profiles simulated by HEC-RAS and RMA2. HEC-RAS water levels simulated at 10 cross-sections selected and compared to RMA2 water levels at nearest corresponding nodes.

5 DISCUSSION AND CONCLUSIONS

5.1 Troubleshooting to improve model performance

The HEC-RAS model was developed in multiple stages, producing several sets of preliminary geometry which were tested. Early models did not incorporate reaches to account for storage in Sand Point Lake, or incorporated a series of sensitivity tests on model geometry. Investigations included adjusting the elevations of reaches and cross-sections up and down, adjusting cross-section end points to be extended at an angle rather than directly vertical, and splitting up individual pinch point channels as stand-along models to focus only on discharge through each reach. However, some of the initial sensitivity testing was conducted with model geometry exported from HEC-GeoRAS in the WGS 1984 Web Mercator coordinate system (rather than UTM Zone 15 N), which produced HEC-RAS geometry that was projected incorrectly, and therefore the results from these sensitivity tests were not included in this report.

The unsteady-state HEC-RAS simulations discussed above used a discharge boundary condition for Crane Lake based on the USGS Vermillion River gauge and water level boundary conditions at Little Vermillion narrows and Namakan Lake. Attempts were made to develop a discharge boundary condition for Little Vermillion narrows based on an area-ratio method to allow unsteady simulation to use discharge boundaries for the entire upstream end of the model. However, it was not possible to find a combination of drainage basins where the contributing area to Little Vermillion narrows was on the order of 1/3 of the contribution area to Crane Lake; as mentioned above, ADCP measurements in Table 4 showed the ratio of discharge between these two locations to be close to 1:3 for the May and June 2012 measurements. The ADCP measurements, while apparently valid measurements of discharge, may not be consistent with the typical flow conditions in the system. These measurements are only brief snapshots in time and need to be augmented with additional measurements in order to gain a good understanding of the flow through the system and the relative ratios of the flows contributed from Crane Lake and Little Vermillion River to Sand Point Lake.

5.2 Accuracy of bathymetry

The multi-beam bathymetry data collected in each of the pinch point channels was analyzed in comparison to contour data from LakeMaster^{TM}, a division of Johnson Outdoor Marine Electronics (JOME). JOME provided contour data to the IJC to be used to update the stage and volume curves for Rainy and Namakan Lakes. Comparisons of the JOME bathymetry to the multi-beam bathymetry collected for this model were completed. This analysis did not show any consistent bias or vertical offset in the bathymetry data for any of the pinch points; contour elevations showed an even distribution of points above and below the multi-beam bathymetry points for all pinch point channels. Further details are described in Stevenson (2013).

The LakeMaster contour data was not analyzed with respect to the MinDNR contour data because of the large interval between contours of the MinDNR data (5 – 10 ft depth intervals) which prevented a meaningful analysis. LakeMaster contours were not included in the HEC-RAS model.

5.3 Limitations due to discharge and water level data deficiencies

A key obstacle to the development of a good model was the limited amount of discharge data available for model calibration and validation and apparent vertical leveling inconsistencies with the temporary and permanent water level gauges. Only two sets of reliable ADCP discharge measurements collected on May 2, 2012 and June 26, 2012 were available for calibration and validation. This lack of data combined with the low velocities simulated through the system and the consequently minor model response to changes in the roughness parameter prevented a detailed model calibration. As a result, global roughness applied to all model cross-sections were tested, rather than calibrating each reach to a unique value.

The likelihood that water level data is subject to vertical leveling error at some or all of the gauges in the study area also posed a significant barrier to detailed model assessment and calibration. As reported by Stevenson (2013), detailed analysis of each water level time series and consideration of field survey results did not provide conclusive evidence of which specific gauges were subject to vertical leveling error and the amount of error that existed in each dataset. Consequently, a true assessment of the skill of the HEC-RAS model was not possible and analysis was restricted to generalized comparisons to observed data and profiles simulated by the RMA2 model.

5.4 Froude numbers

Model simulations showed that Froude numbers in the pinch point channels were generally low due to the low velocities in the channels. These low Froude numbers indicate that there are no single cross-sections that provide hydraulic controls in the channels.

5.5 Steady-state simulations

Steady-state simulations were conducted to determine: (1) the model sensitivity to different parameters; (2) provide a general calibration of model roughness and values for the Sand Point Lake reach boundary conditions; and (3) assess model performance against observed for flow scenarios on May 2, 2012 and June 26, 2012.

Adjusting global roughness for the model from 0.025 – 0.040 in Figure 12 was found to increase water levels simulated at the upstream end of the model by 1-6 cm. This indicated the model was sensitive to large changes in global roughness, although it may not be possible to provide a detailed calibration of individual reaches.

In addition to hypothetical flow scenarios, steady-state simulations with the HEC-RAS model were also completed for two scenarios in May and June 2012 that corresponded with ADCP measurements. The May 2 flow scenario in Figures 14-15 showed that setting global roughness to 0.035 and Sand Point Lake reach flows to 15 m^3/s provided a good match within 1 cm of observed water levels. The June 26 flow scenario summarized in Figures 16-17 indicated high roughness values in the range of 0.050-0.060 and flow boundaries at Sand Point Lake of 25 m^3/s were required to allow provide a match between simulated and observed water levels. These values likely represented higher roughness and flow into Sand Point Lake true conditions. The large differences in parameter values for the two calibration scenarios indicated the model was not able to robustly predict a wide range of flow conditions.

The observed data for both steady-state flow scenarios did not show a head drop through King Williams narrows. However, HEC-RAS and RMA2 simulations always showed a discernible water level difference between Crane Lake and Sand Point Lake in the range of 1-5 cm. This indicated there may be a vertical leveling issue at the Crane Lake gauge and/or temporary gauges.

Steady-state simulations with the RMA2 model produced water surface profiles that were slightly lower than those simulated with HEC-RAS. The closest agreement with the HEC-RAS model was when flow specified at the Sand Point Lake reach boundary conditions was set to 1 m^3/s. Although the analysis produced with the RMA2 model was limited, results suggested it may not be appropriate to set the Sand Point Lake reach boundary conditions at elevated levels.

5.6 Unsteady-state simulations

Unsteady flow simulations were completed to assess model sensitivity to different parameters and to compare simulated water levels and discharges with observed values. Simulations were completed for the ice-free period of 2012. Flow into Crane Lake was set to discharge from the USGS Vermillion River gauge and the water level at Little Vermillion was set to observed values at the temporary gauge. The downstream boundary condition for these simulations was the observed water level at Squirrel Island. Results showed the model was capable of predicting observed water levels when there was little head drop through the system. However, when observations at Crane Lake, the Little Vermillion gauge, and Sand Point Lake were significantly higher than Squirrel Island, the model under-predicted upstream water levels (see Figures 18-21). These results were consistent with the steady-flow results, where the model predicted close agreement between simulated and observed water levels for the May 2 scenario when there was little head drop between Crane Lake and Namakan Lake, but required an unrealistic parameterization for the June 26 scenario when Crane Lake water levels were elevated. Furthermore, flow simulated through Little Vermillion narrows was higher than flow from the Vermillion River discharge gauge (for roughness of 0.025-0.035) which was not consistent with observed measurements. High roughness values (0.050-0.060) minimized the differences between simulated and observed water levels and flows (Figures 19 and 21), with the exception of flow through Harrison narrows on June 26, 2012.

Simulations were also completed when the inflow into Crane Lake was multiplied by a constant factor in an attempt to raise simulated water levels on Crane Lake (Figures 22-24). Results showed that increasing the flow into Crane Lake by 300-500% of the discharge measured at the Vermillion River gauge reduced differences between simulated and observed water levels, but resulted in flows through each pinch point that were higher than observations.

Based on the steady and unsteady-state simulation results, setting global roughness to 0.035 and Sand Point Lake reach boundary conditions to 15 m^3/s provided the best overall fit between simulated and observed values. However, a lack of calibration and validation data prevented a more detailed calibration beyond general comparisons. In addition, the divergence between simulated and observed water levels when Crane Lake becomes elevated above Namakan Lake indicates the current model cannot accurately predict conditions in the Namakan Chain system.

5.7 Limitations of 1D model in comparison to 2D

Model comparisons showed setting the RMA2 slightly under-predicted water levels in comparison to the HEC-RAS model. Detailed analysis of the 2D RMA2 model is beyond the scope of this project although further work with this or another 2D model could provide more information about the Namakan reservoir system. In particular, running a 2D model in unsteady-state mode to provide a direct comparison with HEC-RAS results would be beneficial to understand whether the 2D mesh handles storage in the lake areas differently than the HEC-RAS model.

6 RECOMMENDATIONS

1. Discrepancies between observed water levels at permanent gauges and temporary water level gauges are a major barrier to a detailed modelling study of the Namakan Chain of lakes. Although further work on the model is possible, uncertainty with respect to the accuracy of vertical leveling at each gauge location must be reduced first. The Namakan Chain of Lakes system is typically flat and the differences between Crane Lake and Namakan Lake are small, necessitating that vertical leveling has to be extremely accurate within the system

in order to be able to provide the data required to build a hydraulic model. It is recommended that high resolution vertical leveling surveys of the three water level gauges on the Namakan Chain system be undertaken to confirm the relationships between the three gauges. It would be a good idea to have continuously operated GPS instruments installed on these gauges and operated simultaneously for a period long enough to have high confidence in the vertical positioning of these gauges and the relative differences between the gauges at various times in the year. If temporary gauges are installed again upstream and downstream of the pinch point channels, high level vertical positioning is required to tie these measurements to the permanent water level gauges. Tying temporary water level gauges to the permanent gauges in the system is a challenge because of a lack of permanent vertical monuments. At a minimum, better knowledge of vertical positioning for the Crane Lake and Squirrel Island gauges alone would aid any efforts to tie temporary gauges to these locations.

2. It is also recommended that regular ADCP discharge measurements be taken in the Namakan Chain of Lakes in all branches in the spring when Crane Lake water levels are typically higher than Namakan Lake. More measurements are required to increase understanding of the flows in the system and the relative ratios between each of the pinch points in the system. This data is also critical for further development of a hydraulic or hydrodynamic model. The two sets of measurements collected in 2012 are a good start but additional measurements are needed to improve understanding of the system and provide sufficient data for model calibration and validation. A larger set of ADCP discharge measurements would allow for a detailed calibration of roughness for each model reach, rather than the generalized global roughness calibration described in this report. Furthermore, standard USGS and Environment Canada measurement practices where multiple transects are completed over a minimum time interval are recommended to reduce uncertainty with respect to collected data.

3. Future ADCP discharge measurements should be accompanied by water level measurements at Crane Lake, the upstream end of Little Vermillion narrows, both ends of Sand Point Lake, and Namakan Lake. An ideal scenario would be to collect water levels at each location through the installation of temporary transducers for future ice-free seasons and supplement this data with ADCP measurements similar to what was done in 2012. However, if this degree of data collection were not possible, instantaneous water level measurements during ADCP collection times are needed to provide model calibration and validation scenarios.

4. Further work with a 2D hydrodynamic model using unsteady state conditions may provide insight on the storage volumes and releases in each of Namakan Chain reservoir. A 2D model would be more appropriate for simulating flow though the Namakan Reservoir system in comparison to a 1D model. The complexity of the system combined with the need to use fewer boundary conditions with a 2D model make it a more reliable and practical tool for understanding flow through the chain of lakes. Although further sensitivity analysis with the 1D HEC-RAS model is possible, a 2D model is subject to fewer uncertainties with respect to model geometry and future efforts may be better placed with another 2D model.

5. The amount of flow into Namakan Lake from Namakan narrows can be back-calculated based on the change in storage in Namakan Lake, outflows through Kettle Falls Dam, and inflow from Lake La Croix. However, it is not possible to determine supplies to Crane Lake, each end of Sand Point Lake, and Little Vermillion narrows based on this data. Efforts in this project to use the Vermillion River discharge gauge and local drainage basins to estimate inflows for each lake in the system did not successfully correlate estimates with observed ADCP measurements. An alternative to area-ratio methods would be to use a hydrologic model to estimate supplies to each lake in the hydraulic model domain.

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APPENDIX

Table A1: Reference water levels from survey maps for MinDNR depth contours

Lake	Date	Water Level	Text from map
Namakan	July 20 ,1973	1117.86 ft	“During mapping, Lake Namakan water levels, which are controlled by the Kettle Falls Dam varied between 1117.86 on July 20, 1973, and 1118.68 feet above mean sea level on August 22, 1974”
	Aug 22, 1974	1118.68 ft	
Sand Point	July 5, 1975	1118.56 ft	“During mapping, Sand Point Lake water levels, which are controlled by the Kettle Falls Dam, varied between 11117.93 feet above mean sea level on July 17, 1975 and 1118.56 feet above mean sea level on July 5, 1975”
	July 17, 1975	1117.93 ft	
Kabetogama (newer)		1115.00 ft	“Elevations obtained from DNR division of waters”
Kabetogama (older)	Not given	11120 ft	Approximate high water level
	Not given	1110 ft	Approximate low water level – contours referenced to this level
Crane			“BM – water level gage at Handberg Resort Water level 26.5 inches below top of gauge 7/4/52” Map dated “4-52”

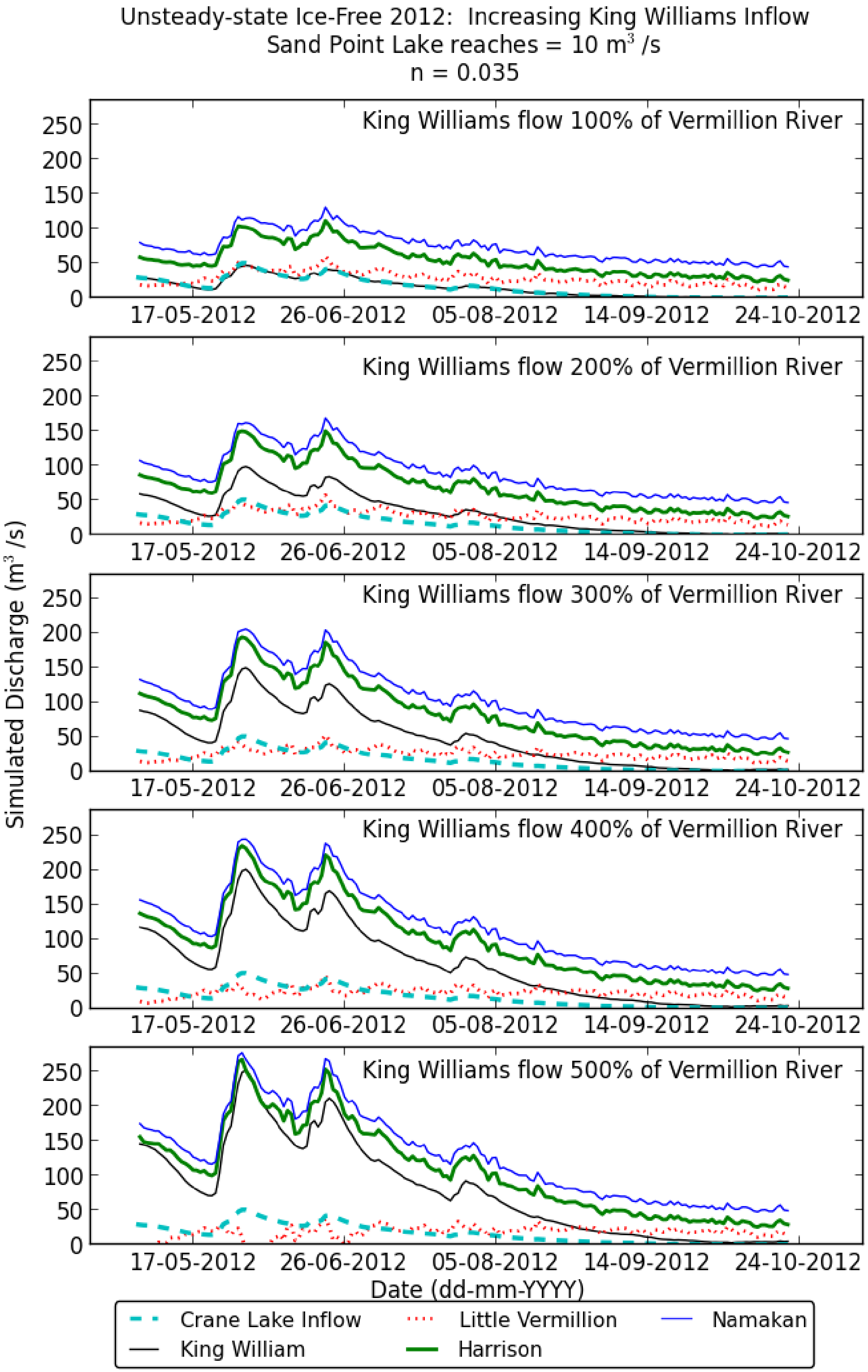

Figure A1: Daily discharge simulated through each pinch point during 2012 for Sand Point Lake reach flow of 10 m^3/s. Downstream boundary set to Squirrel Island water level, upstream boundary at Little Vermillion set to temporary transducer water level, upstream boundary at Crane Lake set to percentage of Vermillion River discharge gauge measurements.

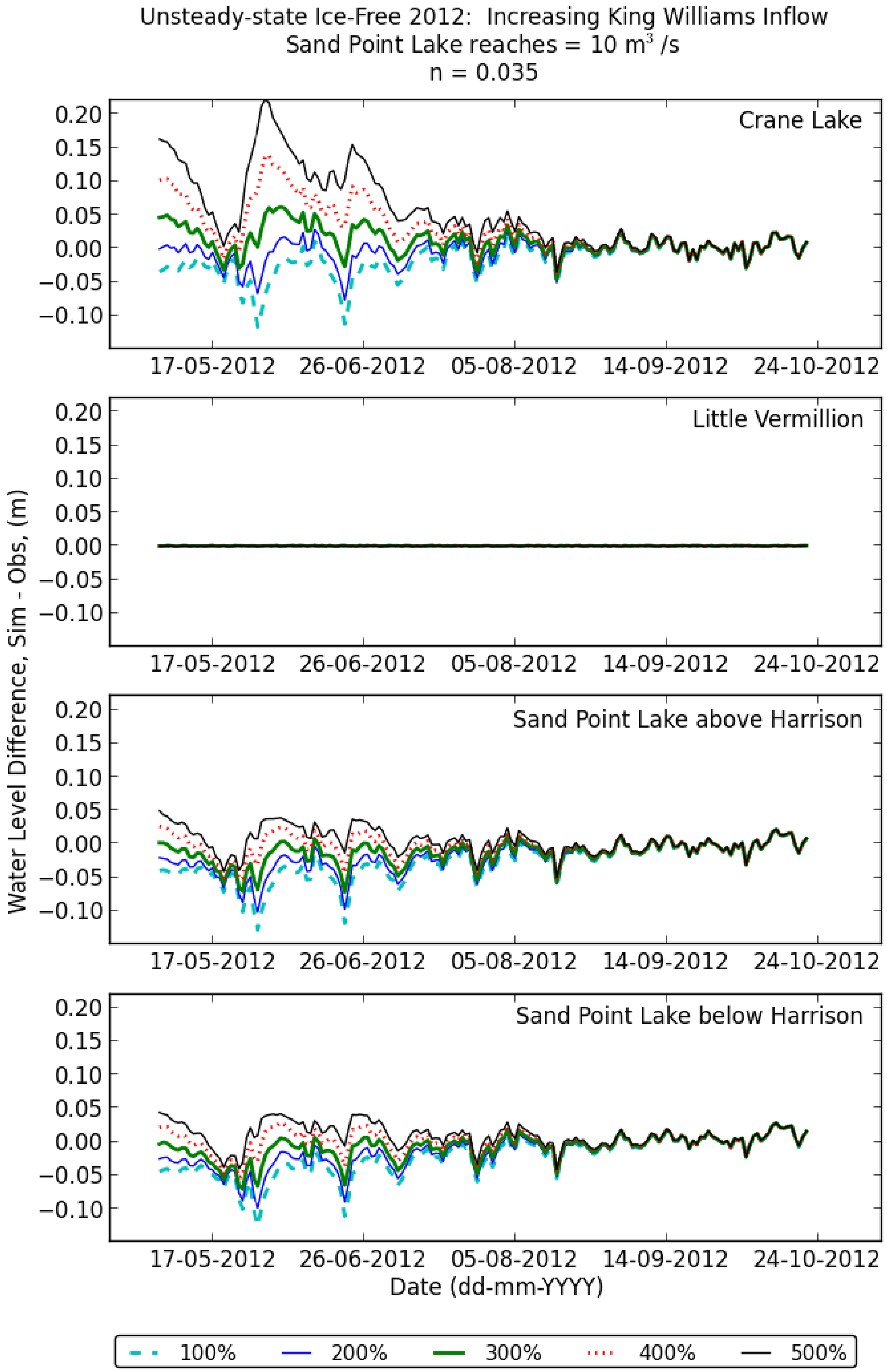

Figure A2: Water level residuals from unsteady-state simulations for 2012. Downstream boundary set to Squirrel Island water level, upstream boundary at Little Vermillion set to temporary transducer water level. Upstream boundary at Crane Lake set to percentage of USGS discharge gauge measurements – 100%, 150%, 200%, 250%, 300%.

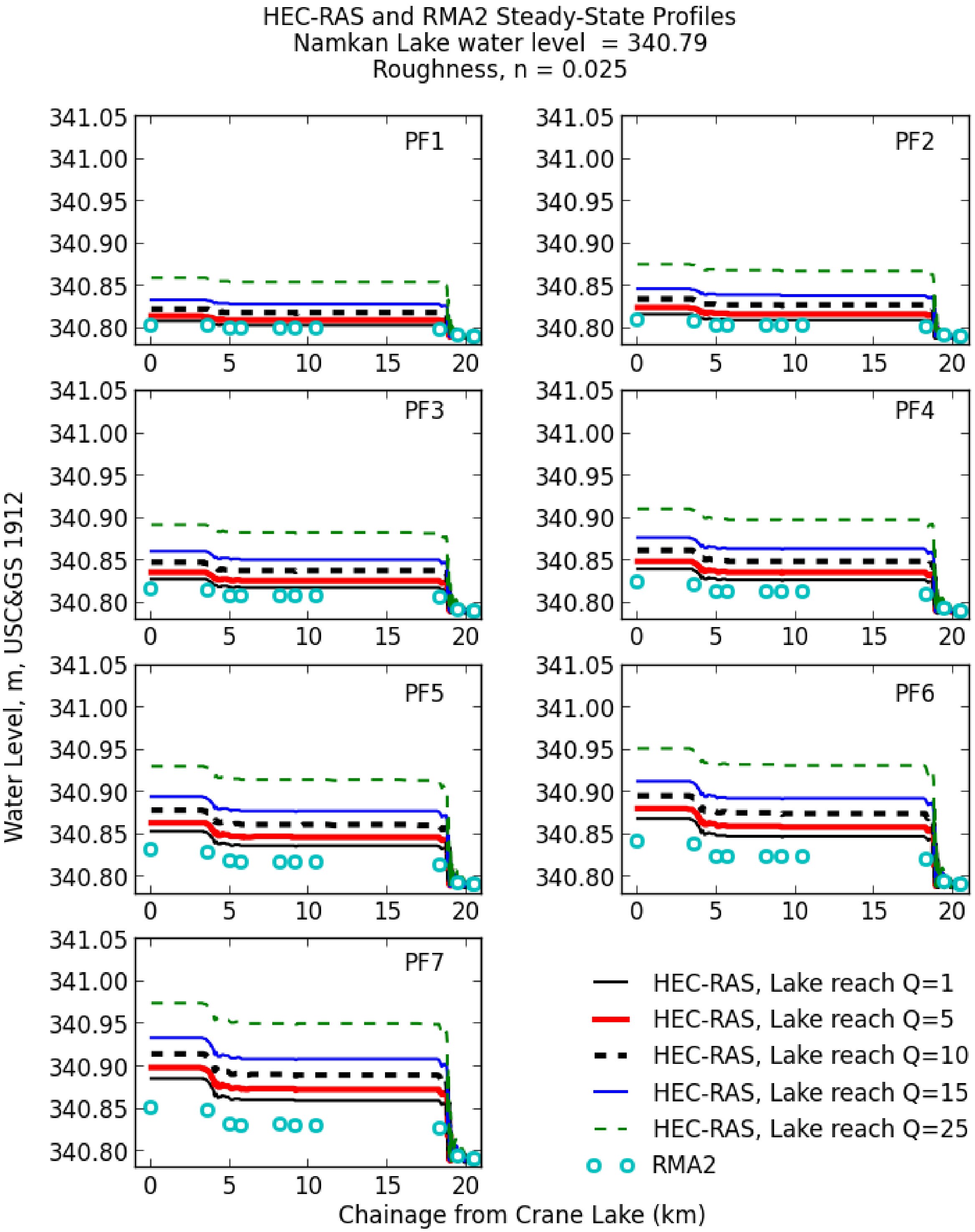

Figure A3: Water surface profiles from HEC-RAS and RMA2 steady-state simulations from Crane Lake to Namakan Lake, roughness = 0.025. HEC-RAS boundary conditions for lake reaches = 5, 10, 15, and 25 m^3/s.

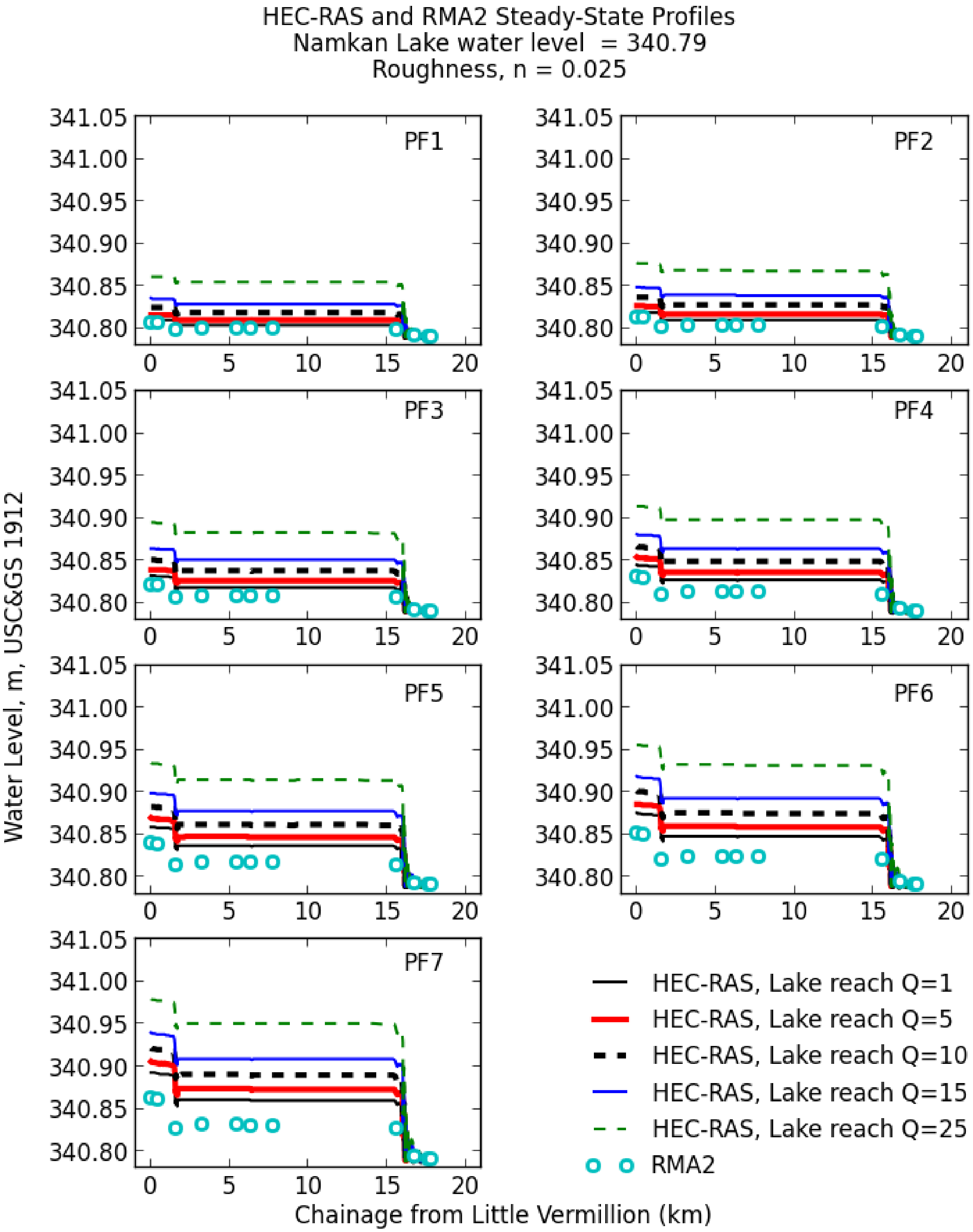

Figure A4: Water surface profiles from HEC-RAS and RMA2 steady-state simulations from Little Vermillion to Namakan Lake, roughness = 0.025. HEC-RAS boundary conditions for lake reaches = 5, 10, 15, and 25 m^3/s.

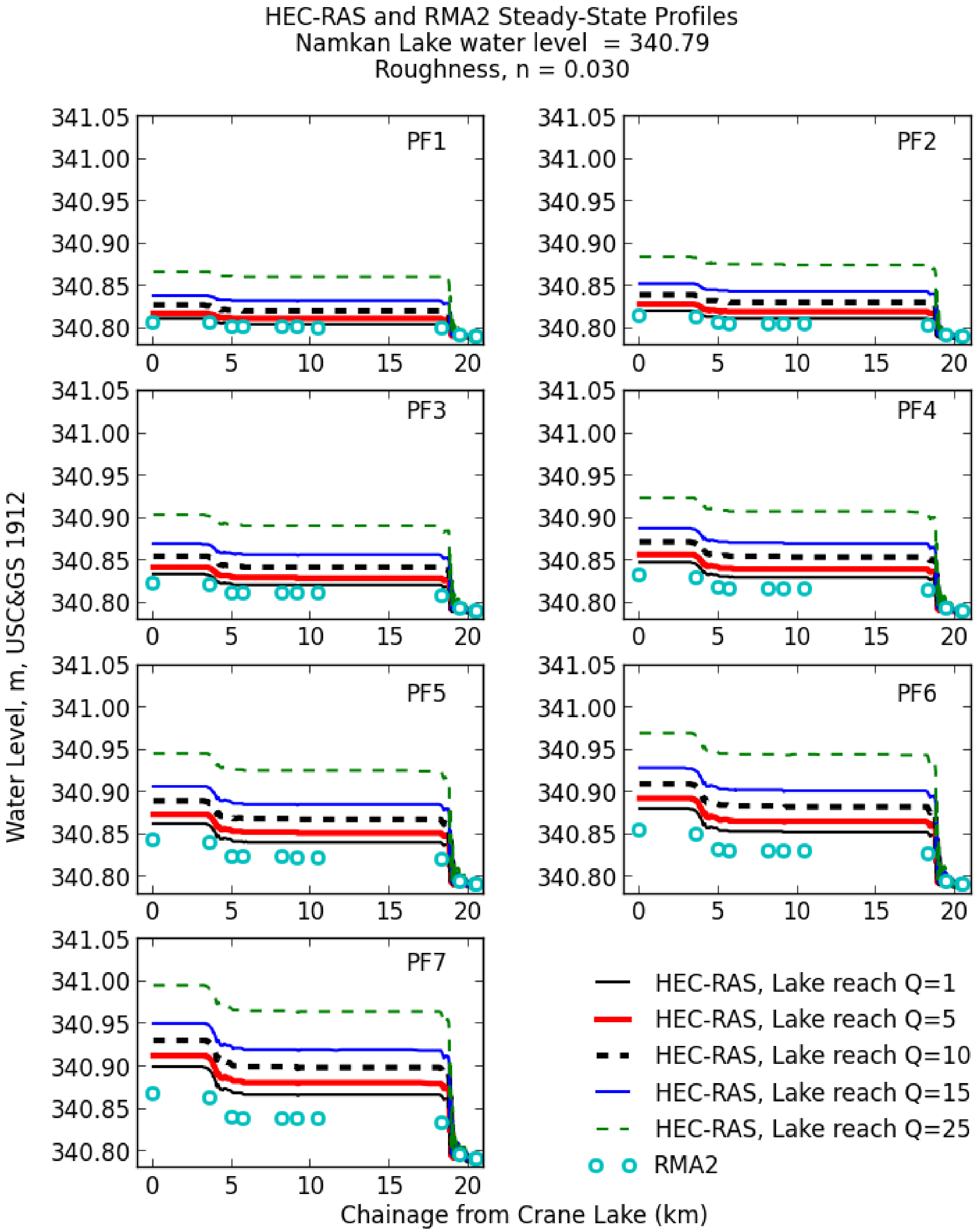

Figure A5: Water surface profiles from HEC-RAS and RMA2 steady-state simulations from Crane Lake to Namakan Lake, roughness = 0.030. HEC-RAS boundary conditions for lake reaches = 5, 10, 15, and 25 m^3/s.

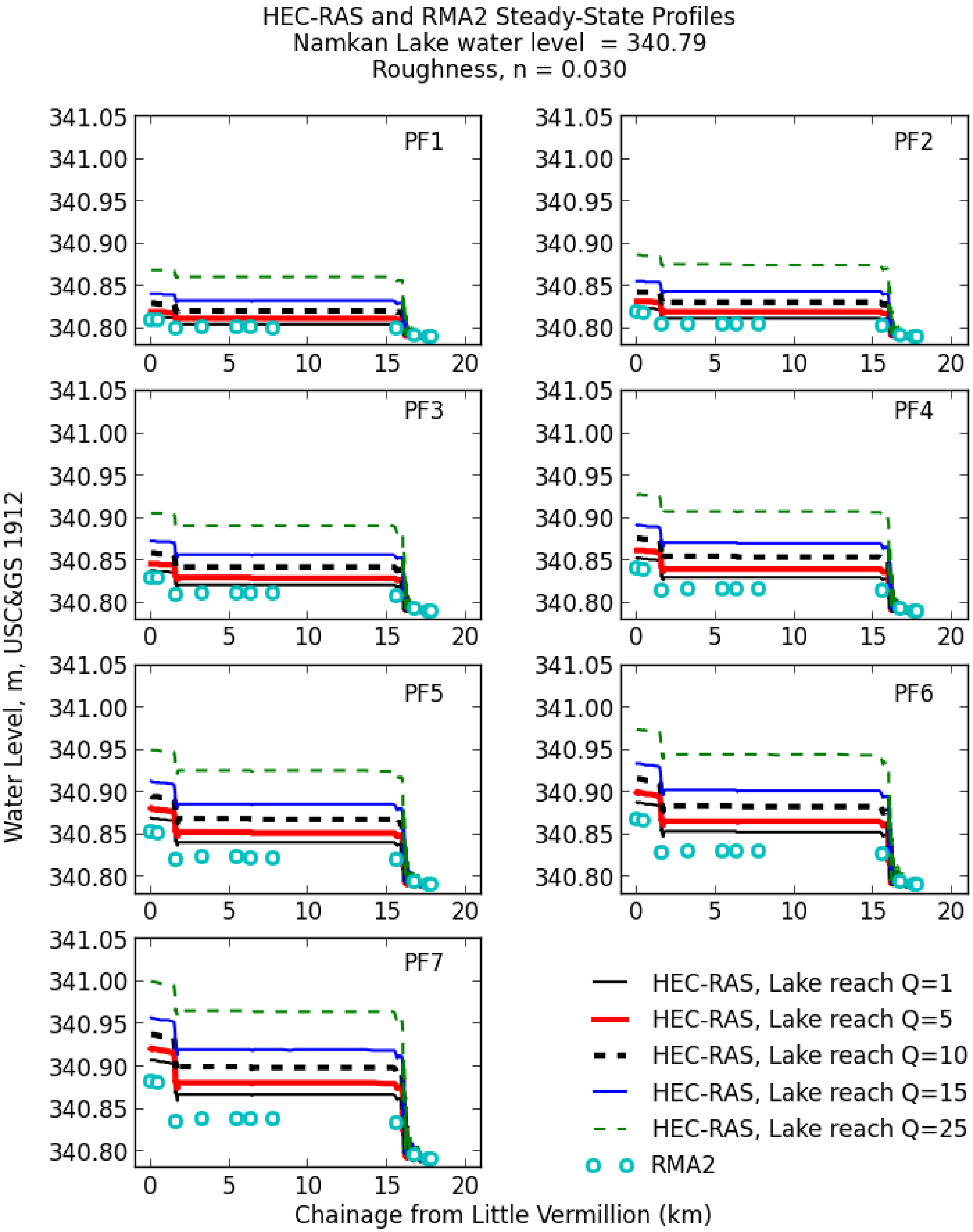

Figure A6: Water surface profiles from HEC-RAS and RMA2 steady-state simulations from Little Vermillion to Namakan Lake, roughness = 0.030. HEC-RAS boundary conditions for lake reaches = 5, 10, 15, and 25 m3/s.

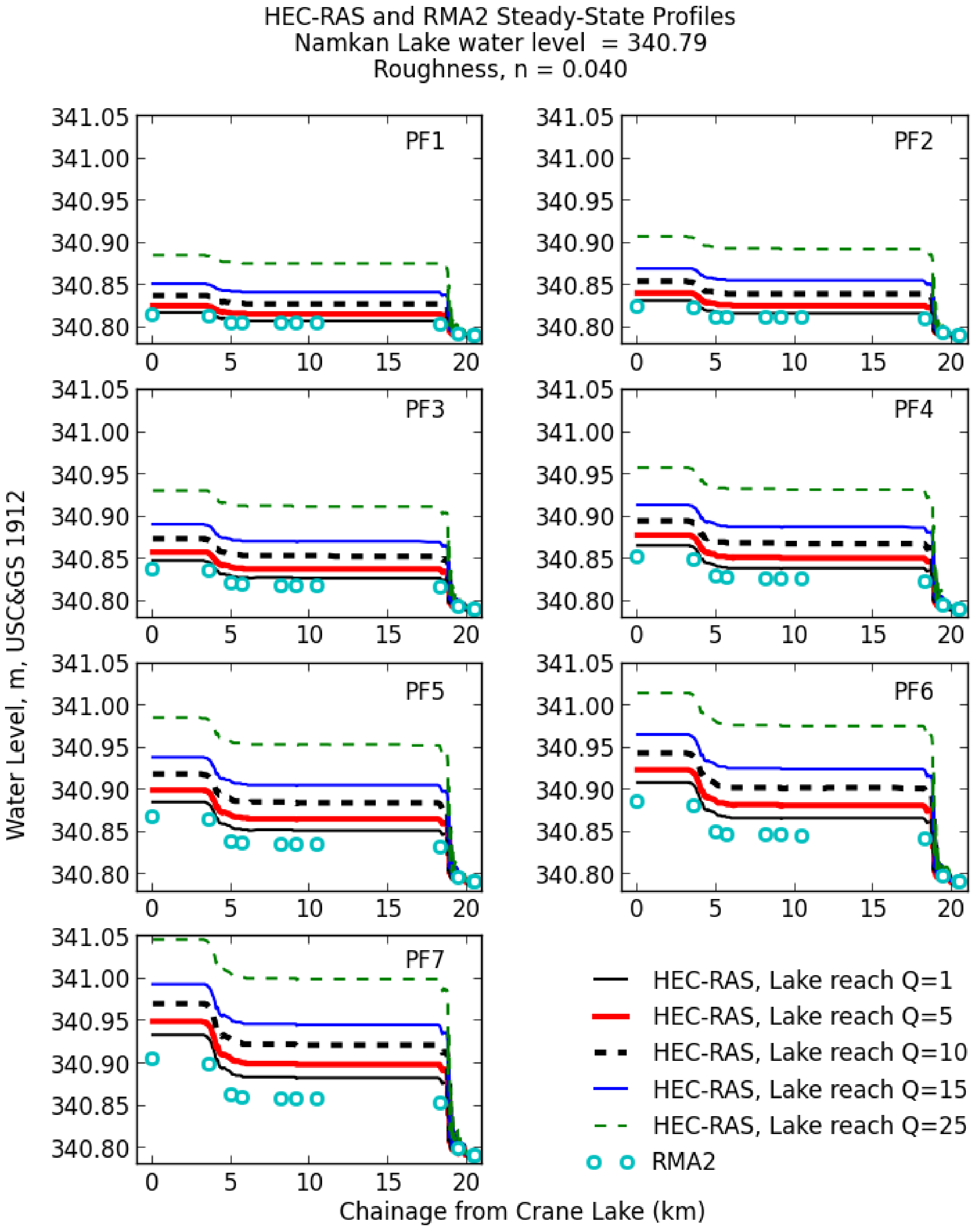

Figure A7: Water surface profiles from HEC-RAS and RMA2 steady-state simulations from Crane Lake to Namakan Lake, roughness = 0.040. HEC-RAS boundary conditions for lake reaches = 5, 10, 15, and 25 m^3/s.

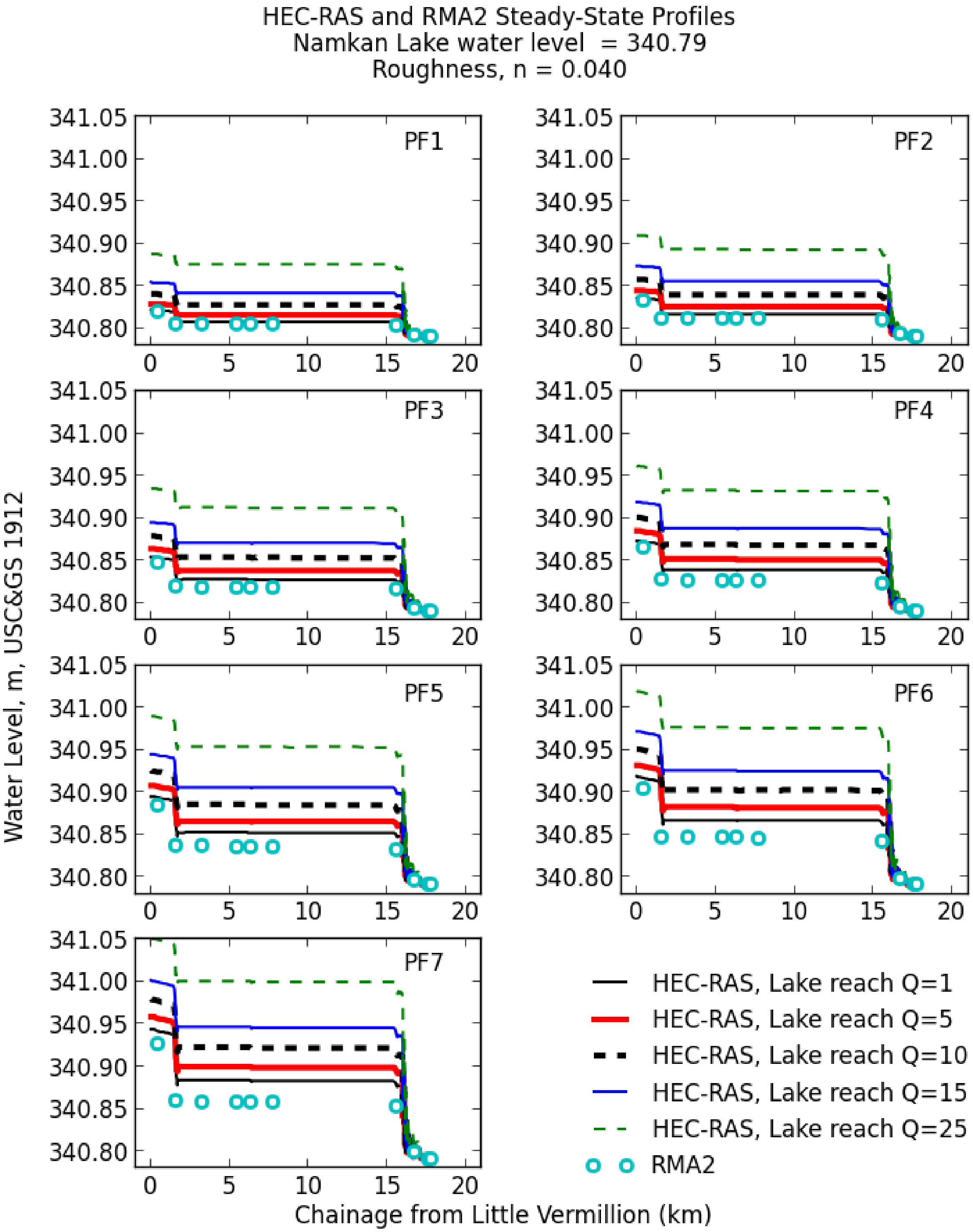

Figure A8: Water surface profiles from HEC-RAS and RMA2 steady-state simulations from Little Vermillion to Namakan Lake, roughness = 0.040. HEC-RAS boundary conditions for lake reaches = 5, 10, 15, and 25 m^3/s.