ENVIRONMENT CANADA

Namakan Chain of Lakes

Supplementary Information and Analysis of Bathymetry and Water Level Data

David Stevenson

Boundary Water Issues
MSC Operations, Ontario
7/8/2013

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LIST OF ABBREVIATIONS

1D	One-dimensional
2D	Two-dimensional
CGVD 28	Canadian Geodetic Vertical Datum of 1928
CORS	Continuously Operating Reference Station
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
OPUS	Online Positioning User Service
NAVD 88	North American Vertical Datum of 1988
NGS	National Geodetic Survey
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 BACKGROUND

This document provides supplemental information and analysis of bathymetry and water level data beyond the scope of what is included in the report "Namakan Chain of Lakes: Pinch Point Modelling" by Stevenson and Thompson (2013). It addresses issues encountered with data used in the development of the HEC-RAS model, provides a more in-depth analysis of raw data, and discusses sources of uncertainty related to the data sets.

This document contains analysis of bathymetry data provided by LakeMaster™ which is subject to a data use agreement with the IJC.

2 STUDY AREA AND REGULATION

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 (IJC, 2001, p.17).

Figure 3 shows historical daily Lake Namakan water levels at the Kettle Falls Dam. The data shows how fluctuations in water levels have changed over time. Prior to the first IJC Orders in June 1949, there were significant fluctuations in water levels on Namakan Lake at Kettle Falls ranging over 5 metres. The effects of regulation on water levels between 1949 and 2000 are obvious in Figure 3, showing a consistent band of observed water levels (IJC, 2001). The current rule curve specified in 2000 can also be distinctly observed in Figure 3, where water levels over the past 13 years show a tighter annual range shown by the red data points.

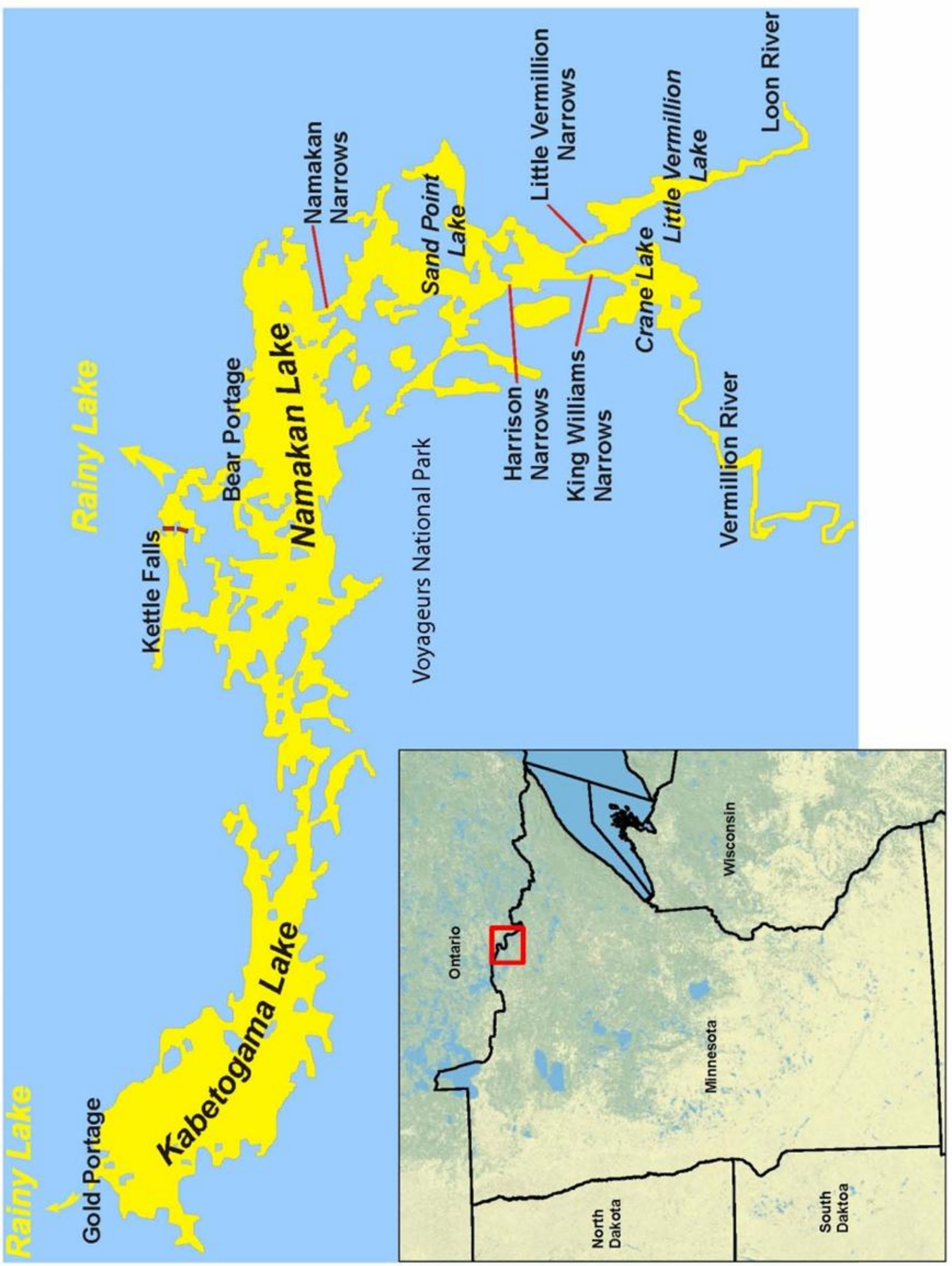
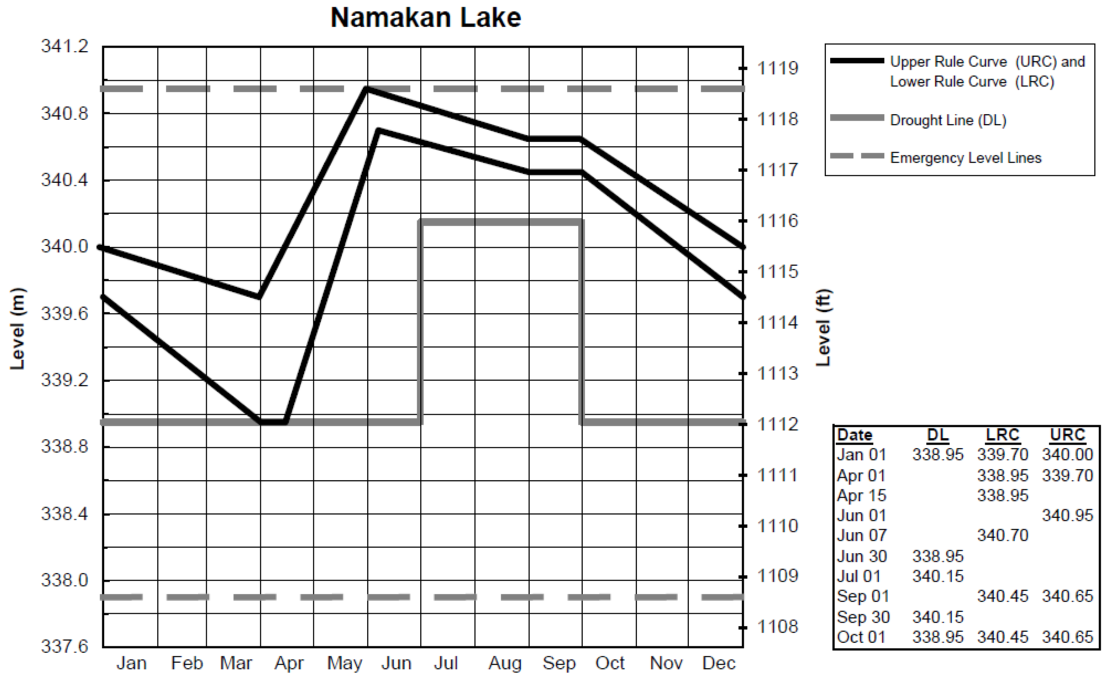


Figure 1: Namakan reservoir system



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

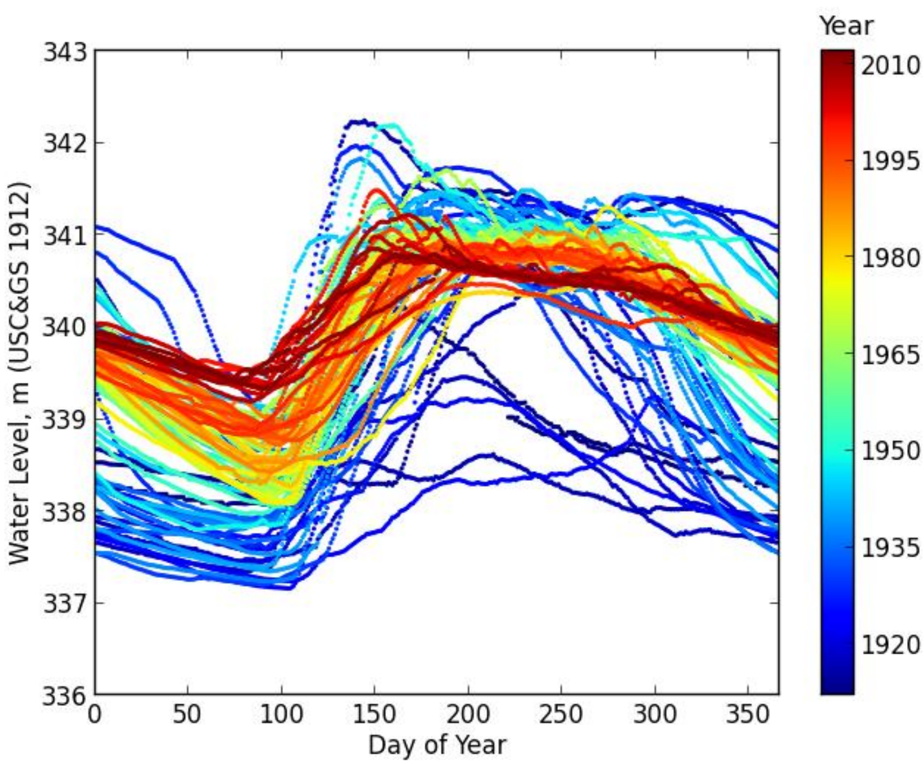


Figure 3: Historical daily Lake Namakan water levels at Kettle Falls

3 VERTICAL DATUM CONVERSIONS

Water levels in the Namakan chain study area are regulated according to the United States Coast and Geodetic Survey datum of 1912 (USC&GS 1912). This datum was used historically in the original Orders specifying regulation at Kettle Falls and International Falls in 1949. To this day, the Orders of Approval (updated in Supplementary Orders in 1957, 1970, and 2000) and subsequent operational activities use the USC&GS 1912 datum to regulate water levels on the Namakan Reservoir system (IJC, 2001, p.1).

The use of the USC&GS 1912 vertical datum has proven to be sufficient for carrying out operations throughout the Namakan Reservoir system. However, it poses difficulties when new surveys and data collection methods are completed in the area with the purpose of providing scientific and modelling analyses. New GPS surveying and ADCP technology do not typically collect data to the USC&GS 1912 vertical datum. Instead, common practice is to collect data to a more widely used vertical reference standard and then convert collected data to USC&GS 1912.

Data for this project was obtained from several sources and agencies. All data was either provided or converted to a consistent vertical reference USC&GS 1912. Bathymetry and temporary water level data was collected in NAVD 1988 vertical datum. Table 1 gives a summary of datum conversion factors used that are specific to the study area.

The study area has a known constant conversion between CGVD 1928 and USC&GS 1912 of 0.254 m (LWS, 2012) which has been applied in previous modelling projects in the region (CHC, 2010). It was therefore necessary to convert between CGVD 1928 and NAVD 1988 to allow conversion of the collected water level and bathymetry data to the local datum. There is no model which directly converts between NAVD 1988 and CGVD 1928; hence, it is necessary to find a benchmark with both vertical elevations listed.

Benchmarks close to the study area were obtained from the Canadian Spatial Reference System (CSRS) database where benchmark elevations were listed in CGVD

1928. Corresponding NAVD 1988 elevations at these benchmarks were obtained through a data request submitted to: ISU.Request@NRCan-RNCan.gc.ca. Figure 4 shows the difference in elevation between the two datums for the benchmarks surrounding the study area. Furthermore, elevations at benchmarks along the Rainy River, West of the study area at the mouth of the Rainy River, were also obtained (Figure 5). These elevations showed the difference between the two datums to be 42 cm, which is consistent with what the benchmarks closest to the study area in Figure 4 show. Figure 4 indicates the difference between the two datums increases as you move further North. Based on the differences between the two datums at the available benchmarks, it was determined that the NAVD 1988 datum was 42 cm higher than the CGVD 1928 datum as shown in Table 1. Combining this conversion with the known local conversion between USC&GS 1912 and CGVD28 produces a conversion where NAVD 1988 is 0.166 m higher than USC&GS 1912. This conversion was applied to the bathymetry and water temporary water level datasets described in this report.

Figures 4 and 5 show benchmarks with elevations in CGVD 1928 and NAVD 1988 are not available directly in the study area and a conversion of 42 cm is a best-estimate based on available information. As shown in Figure 4, the difference between CGVD 1928 and NAVD 1988 appears to increase as you move North, where the benchmarks at the top of the map show a change of 5 cm over a North-South distance of approximately 7 km. The increasing difference between the two datums also appears in Figure 5. This indicates a constant conversion between CGVD 1928 and NAVD 1988 for the entire Namakan Chain study area, which spans a North-South distance of over 20 km, may not be correct. Based on the benchmarks shown in Figures 4 and 5, it is likely the difference between NAVD 1988 and USC&GS 1912 could increase as you move North through the study area (NAVD 1988 would always be higher than USC&GS 1912, although there would be a greater difference between the two datums at the North end of the study area in comparison to the South end). However, because benchmarks with both CGVD 1928 and NAVD 1988 elevations could not be found directly in the study area, and no model was found to convert between the two datums, analysis in this report and the main report by Stevenson and Thompson (2013) used a constant conversion of 42 cm.

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]: (NRCAN, 2012)
[b]: Known local conversion (CHC, 2010; LWS, 2013)
[c]: a+b

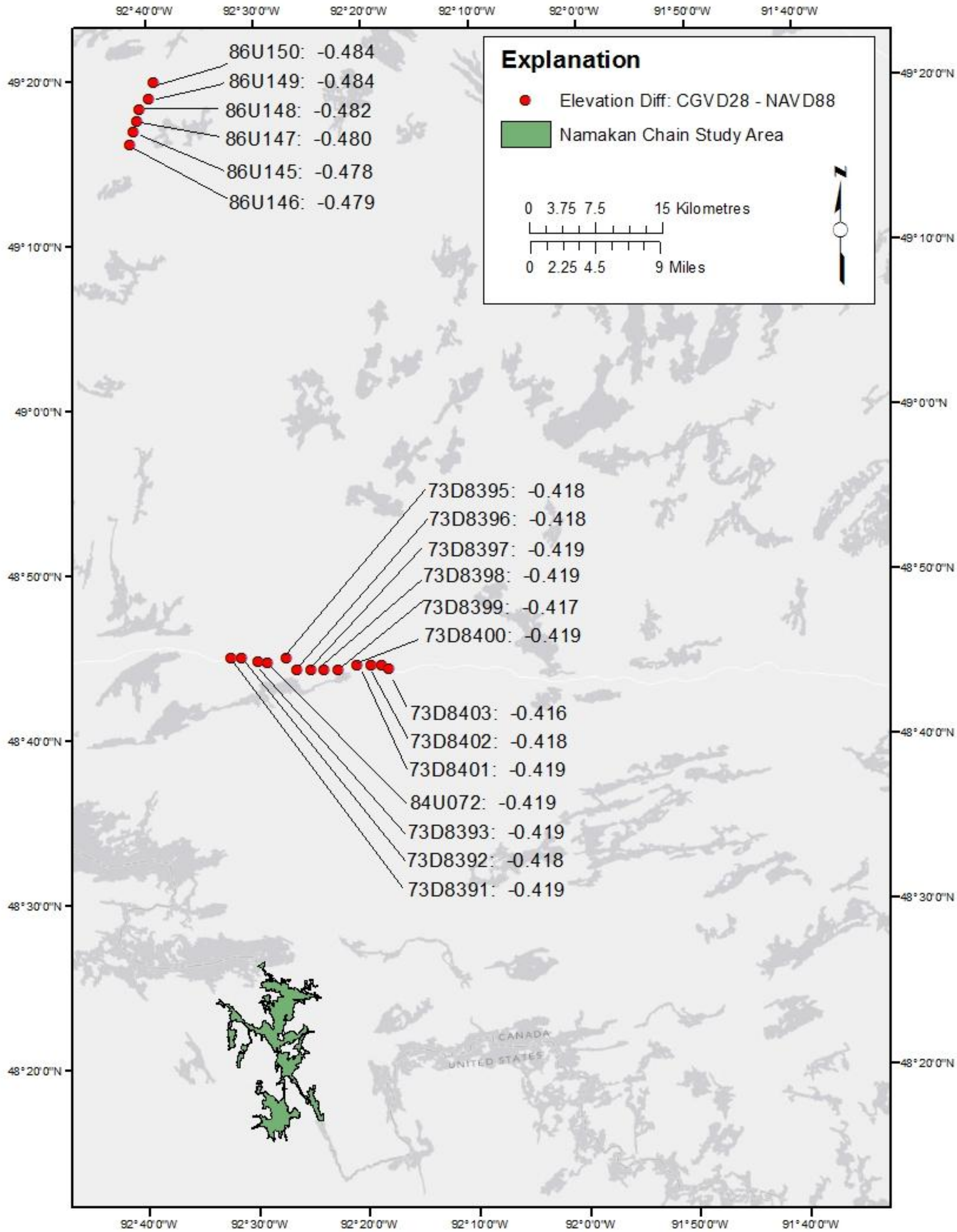


Figure 4: Difference between CGVD 1928 and NAVD 1988 in metres at benchmarks North of the study area, shown in UTM Zone 15 projection.

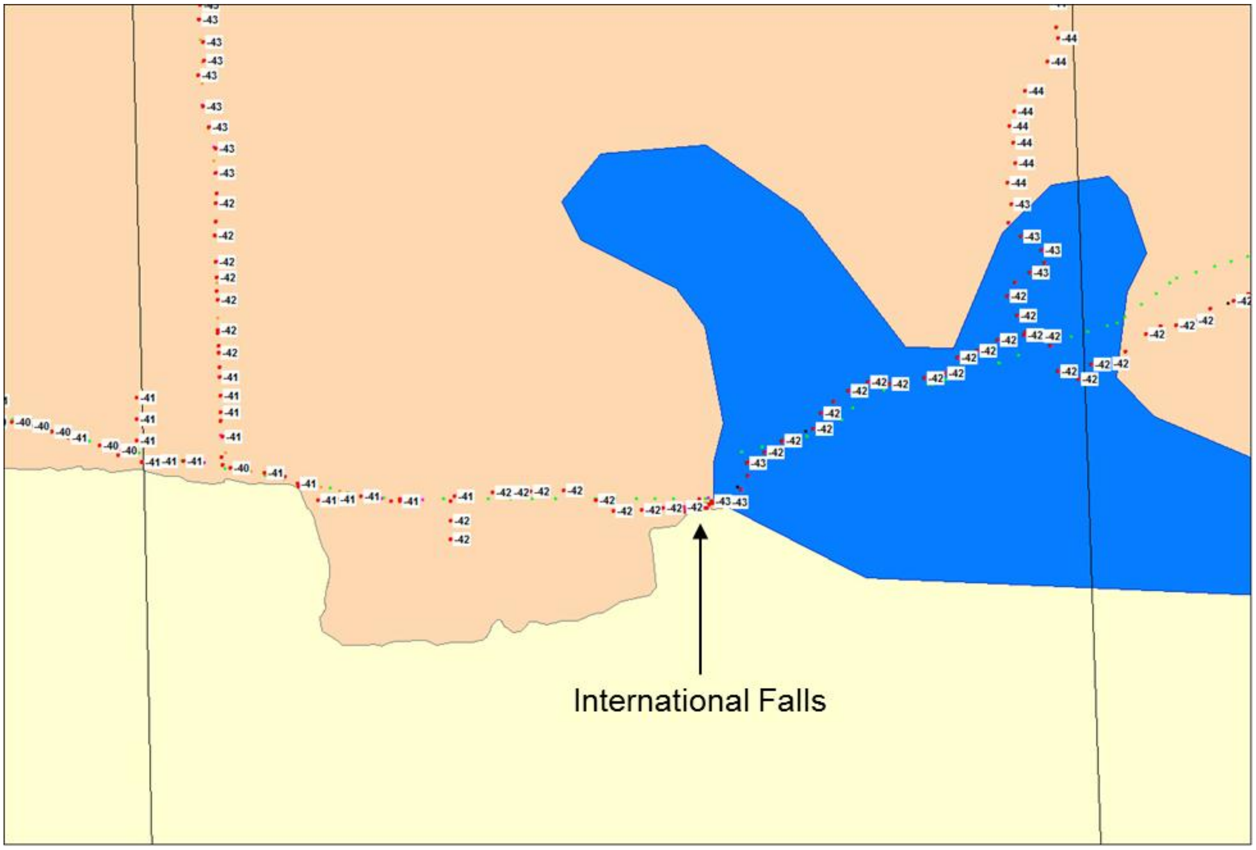


Figure 5. Benchmarks West of study area. Points show difference between CGVD 1928 and NAVD 1988 vertical datums in cm. (Véronneau, 2012).

4 BATHYMETRY

Bathymetry data throughout the study are was obtained from three sources; the Minnesota Department of Natural Resources (MinDNR), the United States Geological Survey (USGS), and LakeMaster^{TM}.

4.1 Minnesota Department of Natural Resources Depth Contours

Digitized contour data was obtained from the MinDNR data deli website (MinDNR, 2012). This dataset contained digitized depth contours available throughout the study area at either 1.5 m (5 ft) or 3.0 m (10 ft) interval. The digitized data was assumed to be a compilation of several historical surveys. This dataset was used during the construction of a HEC-RAS model for the study area (Stevenson and Thompson, 2013), but is not discussed in more detail in this report.

4.2 2011 Multi-Beam Survey

A bathymetric survey of the four pinch point channels was conducted in August 2011 by the USGS NE Water Science Center (NE WSC). The data was collected on a 50 cm grid and was referenced to the NAVD 1988 vertical datum. A multi-beam echosounder system along with a real-time kinematic global positioning system (RTK GPS) was used for data collection. The multi-beam echosounding system included a RESON SeaBat™ 7125 multi-beam echo sounder (MBES), an Applanix POS MV™ navigation unit with an Inertial Measurement Unit (IMU) for motion sensing, and two computers with HYPACK®/HYSWEEP® Data Acquisition Software. Locations of the connecting pinch points are shown in Figure 1. Table 2 provides summary statistics of the data collected for each pinch point channel.

Table 2: Statistics of point data from USGS 2011 bathymetry survey. All data reported as NAVD88 vertical datum

Narrow	Number of Points	Minimum (m)	Maximum (m)	Average (m)	Standard Deviation
King Williams	1564332	329.294	340.242	336.976	1.496
Little Vermillion	2702068	326.429	340.506	335.059	2.656
Harrison	1115442	318.609	339.73	329.716	4.624
Namakan	1059579	316.355	340.052	332.890	5.142

4.3 LakeMaster™ Depth Contours

The last source of bathymetry data was obtained from LakeMaster™, a division of Johnson Outdoors. The LakeMaster™ data was obtained as 0.3 m (1 ft) contours with a depth from surface field to indicate bathymetry elevation. Correspondence with Jeff Hedlund from LakeMaster (Jeff.Hedlund@johnsonoutdoors.com) indicated all surveys were collected in US survey feet and were referenced to the water levels in Table 3 for each location. These values were assumed to be reported in USC&GS 1912 vertical datum, which is a logical assumption because the primary gauging location in the system at Kettle Falls reports water levels to this datum. Although Namakan Lake is downstream of the study location for the HEC-RAS model, the water level conversion provided for “Namakan” was assumed to be applicable to the study area.

Table 3: Water levels used to convert depth contours to elevation

Location	Water Surface During Survey (ft)
Kabetogama	1118.6
Namakan	1117.22
Rainy	1108

4.4 Comparison of USGS Bathymetry to LakeMaster™ Contours

A comparison of the USGS multi-beam bathymetry and the LakeMaster contour data was completed to determine whether the LakeMaster™ data set was in agreement with the 2011 survey. The purpose of completing this analysis was to provide greater certainty whether vertical levelling used during the 2011 USGS multi-beam survey was expected to be accurate. Motivation for this analysis was to investigate potential causes of the divergence between water levels simulated with a HEC-RAS model and observed water levels at both permanent and temporary gauges (Stevenson and Thompson, 2013). Digital Elevation Models (DEMs) were produced for both data sets and a cut-fill analysis was used to analyze the difference between DEMs for both data sets in each of the four pinch points.

4.4.1 Conversion of LakeMaster™ Data to Bathymetric Elevations

The first stage of the comparison was to convert the LakeMaster depth contours to elevation point data. Data was compared using the NAVD88 vertical datum to minimize errors introduced during conversions. The USGS bathymetry represented the most detailed and recent dataset so it was logical to use this bathymetry as the comparison standard. Hence, the LakeMaster™ data was converted to NAVD88 vertical datum for the comparison.

The depth contours were clipped to the study area in the Namakan chain and converted to point data using the regular points vector tool in Quantum GIS (1.7.1). A new field for bathymetric elevation in metres referenced to USCGS 1912 vertical datum was calculated using Eq. (1):

$$Elev\_m = (DEPTH + 1117.22) * 0.3048 \quad (1)$$

where the depth field was the contours provided in 0.3 m (1 ft) intervals. The original depth contours did not contain any significant digits after the decimal, while the new “Elev_m” field was calculated to several significant digits.

A second elevation field (m_1988) was added to convert the LakeMaster elevation points to NAVD 1988 as shown in Eq.(2). This conversion is based on the known conversion between CGVD 1928 and USCGS 1912 and a conversion between CGVD 1928 and NAVD 1988 that is specific to the area of study which is described in Table 1.

$$m\_1988 = Elev\_m + 0.166 \tag{2}$$

4.4.2 Interpolation

The two bathymetry surveys were interpolated to create DEM surfaces that could be compared. The procedure described by Bennion (2009) which compared different bathymetry datasets for the St. Clair River was followed for the cut-fill analysis. The kriging option in the Geostatistical Analyst tool for ArcGIS 10 (ESRI, 2011) was used to interpolate surfaces. Prior to interpolation, the LakeMaster point data was clipped around the general area of each pinch point channel to prevent bias during interpolation from locations surrounding the pinch points Interpolations were completed using the NAVD 1988 elevation fields for all datasets. Kriged models were completed for each pinch point for both the USGS bathymetry and the LakeMaster point data, resulting in eight interpolations. Raster datasets for each interpolation model were produced by using the “GA Layer to Grid” tool in the Geostatistical analyst. Cell size for the raster DEMs were set to 1 m.

4.4.3 Cut-Fill Analysis

The cut-fill analysis tool in 3D Analyst Toolbox of ArcGIS 10 (ESRI, 2011) was used to compare the interpolated raster surfaces. The interpolated surfaces were only compared for the minimum extent of the data points in each pinch point channel. If areas outside the extent of data were included, the cut-fill analysis would be subject to more error because comparisons would not be based on real data. For all pinch points, the USGS bathymetry survey had a smaller areal extent than the point data produced from the LakeMaster contours. The outline of the USGS bathymetry datasets were digitized manually and then used to clip the raster DEMs for each respective pinch point. The USGS DEMs were input as the "before" raster and the LakeMaster DEMs were used at the "after" raster when the cut-fill analysis tool was used.

4.4.4 Results

The results of the cut-fill analysis in Figures 6-9 show a relatively even balance of locations where the LakeMaster DEMs are above and below the elevation of the DEMs from the 2011 USGS survey. The distribution of LakeMaster points above the USGS data (blue) compared to LakeMaster points below the USGS data (red) does not shift significantly for each pinch point channel. This indicates a constant elevation bias is not present in either of the surveys. It also indicates the conversions applied to the LakeMaster contours to convert the data to NAVD88 bathymetric elevations appear to be acceptable.

Some differences between DEM surface elevations observed for the cut-fill analysis were expected due to differences in point density for the two datasets. As indicated in Table 4, the multi-beam bathymetry had significantly higher point density than the point data produced from the LakeMaster contours. In addition, the LakeMaster data points followed the 0.3 m (1 ft) contour lines with high density, but did not have any data points between the contours. Therefore, when a DEM was developed for the LakeMaster data, large areas needed to be filled by interpolated values in comparison to the USGS survey which had raw point data with high density collected on a 50 cm grid.

The spatial distribution of the two sets of point data are evident in the cut-fill analysis. Figure 10 shows a close-up of the Little Vermillion pinch point with the LakeMaster contour point data overlaid on the cut-fill analysis. The bottom selection box shows zones where the contour data is very sparse (ie: little elevation change so large spacing between contours). The area inside this selection shows the cut-fill analysis indicates locations where the LakeMaster DEM is both above and below the USGS 2011 survey DEM. This would suggest bathymetric elevations of the two DEMs are rather close.

Small differences between the two datasets were also expected due to inaccuracies in the USGS bathymetry due to incorrect pitch and roll settings during data collection.

These errors were most pronounced for the King Williams narrows data set. Figures 11 and 12 show examples of pitch and roll errors, which could account for up to 20 cm of error in the most extreme cases. It should be noted that obvious pitch and roll errors in the bathymetry was removed from the HEC-RAS model by smoothing cross-sections to have a more natural shape (Stevenson, 2013).

The cut-fill analysis confirmed the 2011 USGS multi-beam survey and the LakeMaster contour data were in relative agreement where no distinct bias in vertical elevations of the pinch point bathymetry was evident. Based on this analysis, the 2011 USGS multi-beam survey appeared to be reliable for use in a HEC-RAS model suggesting any divergence between observed and simulated water levels did not appear to be directly caused by the multi-beam bathymetry.

Table 4: Calculation of point density for point datasets

	Number of Points		**Point Density (pts/m^2)**	
Narrow	**USGS 2011 Survey**	**LakeMaster™ contours converted to points***	**USGS 2011 Survey**	**LakeMasterTM contours converted to points***
King Williams	1564332	40625	3.64	0.09
Little Vermillion	2702068	46334	3.78	0.07**
Harrison	1115442	46136	4.00	0.17
Namakan	1059579	58975	3.97	0.22

*Number of points within DEM comparison area
**LakeMaster™ contours did not extend over entire pinch point, point density calculated only for area with contour coverage

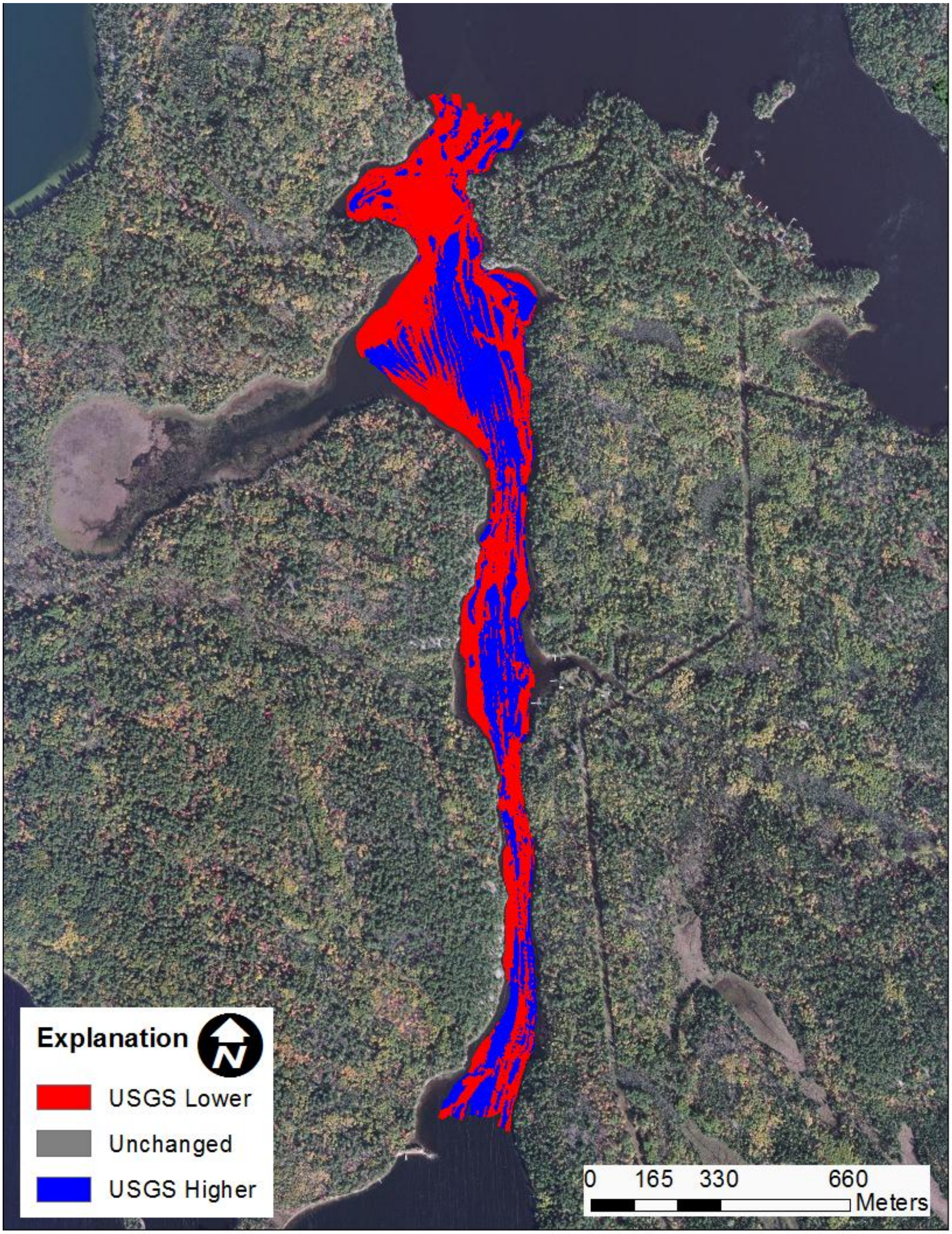


Figure 6: Comparison of USGS 2011 multi-beam bathymetry survey to LakeMaster contour data for King Williams narrows

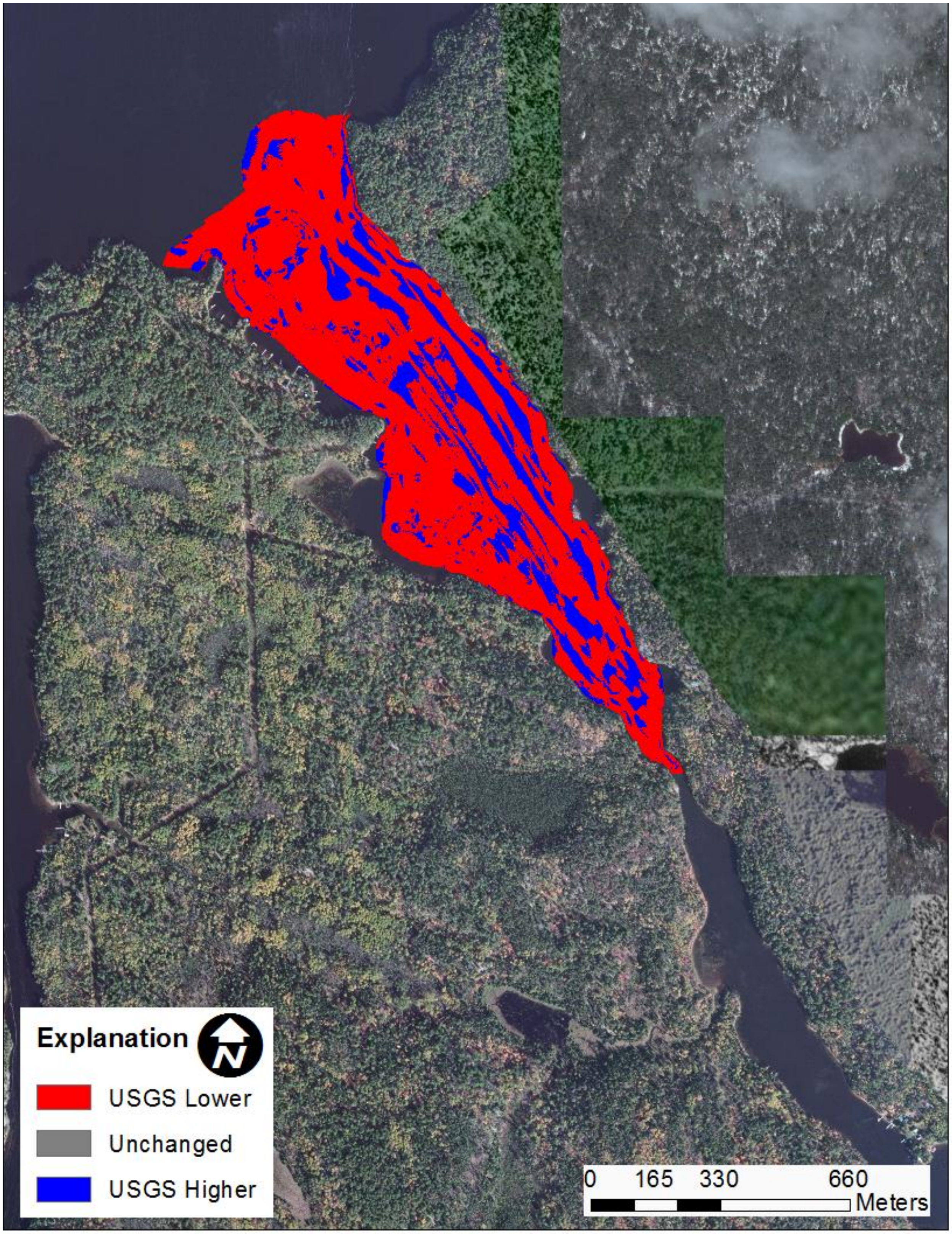


Figure 7: Comparison of USGS 2011 multi-beam bathymetry survey to LakeMaster contour data for Little Vermillion narrows

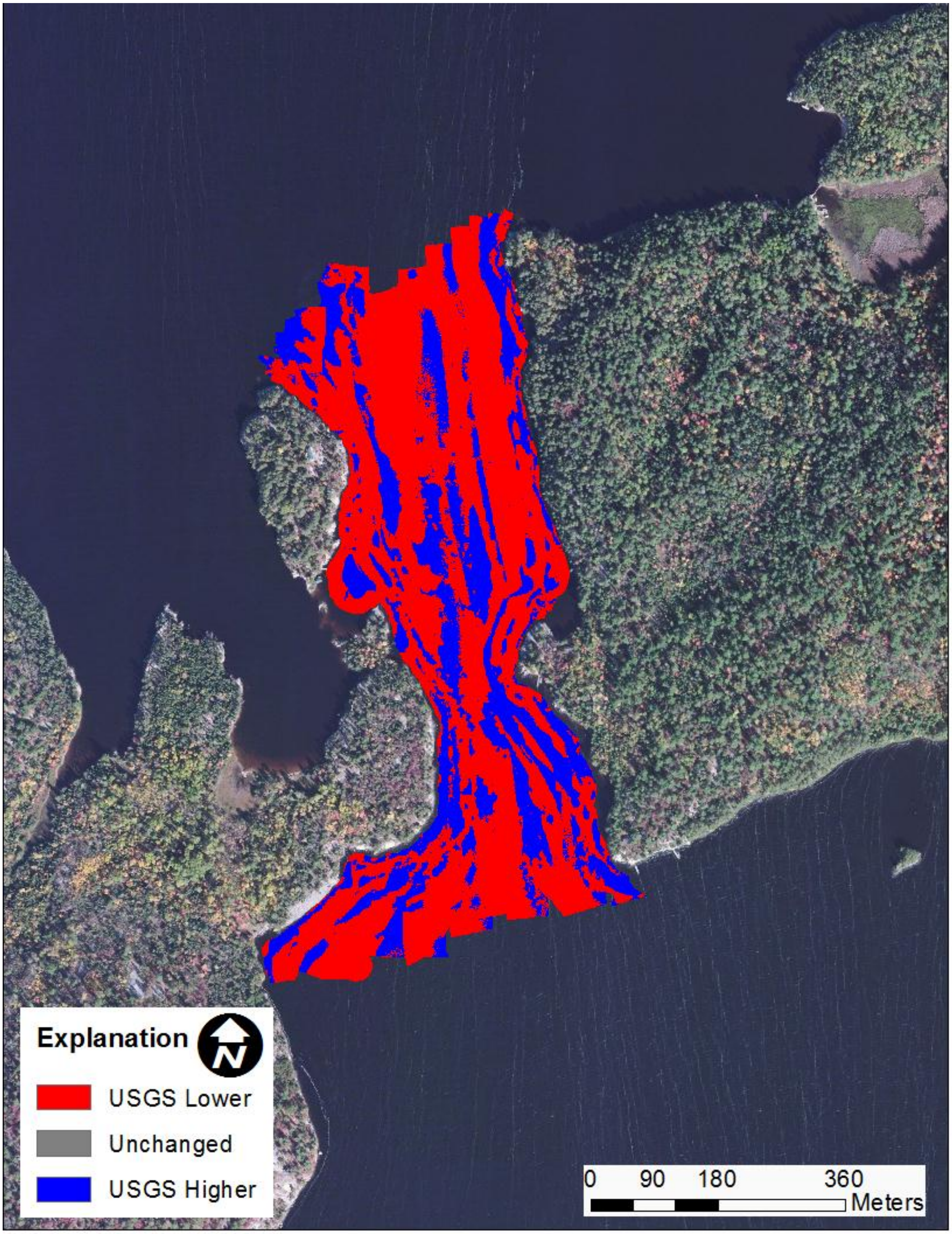


Figure 8: Comparison of USGS 2011 multi-beam bathymetry survey to LakeMaster contour data for Harrison narrows

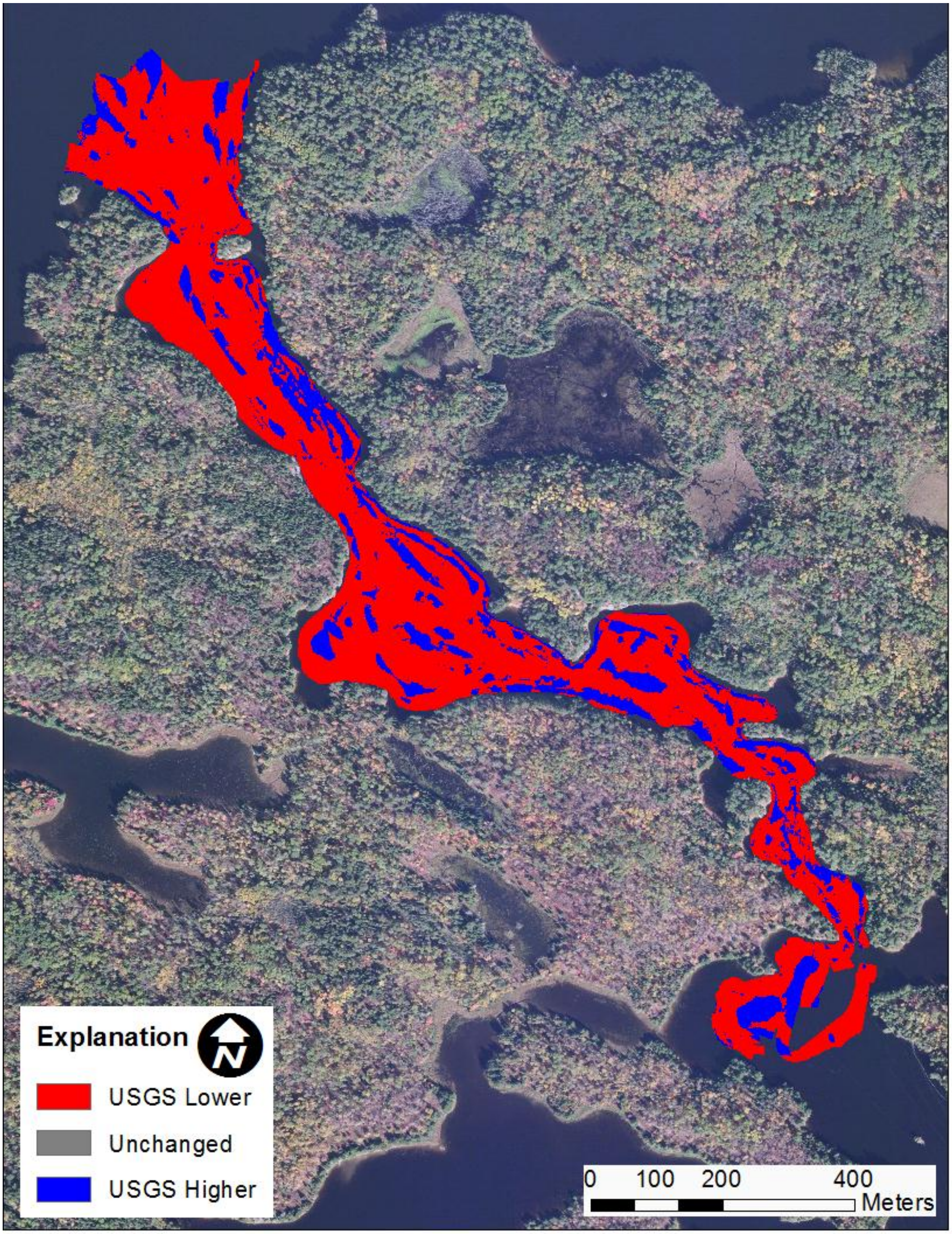


Figure 9: Comparison of USGS 2011 multi-beam bathymetry survey to LakeMaster contour data for Namakan narrows

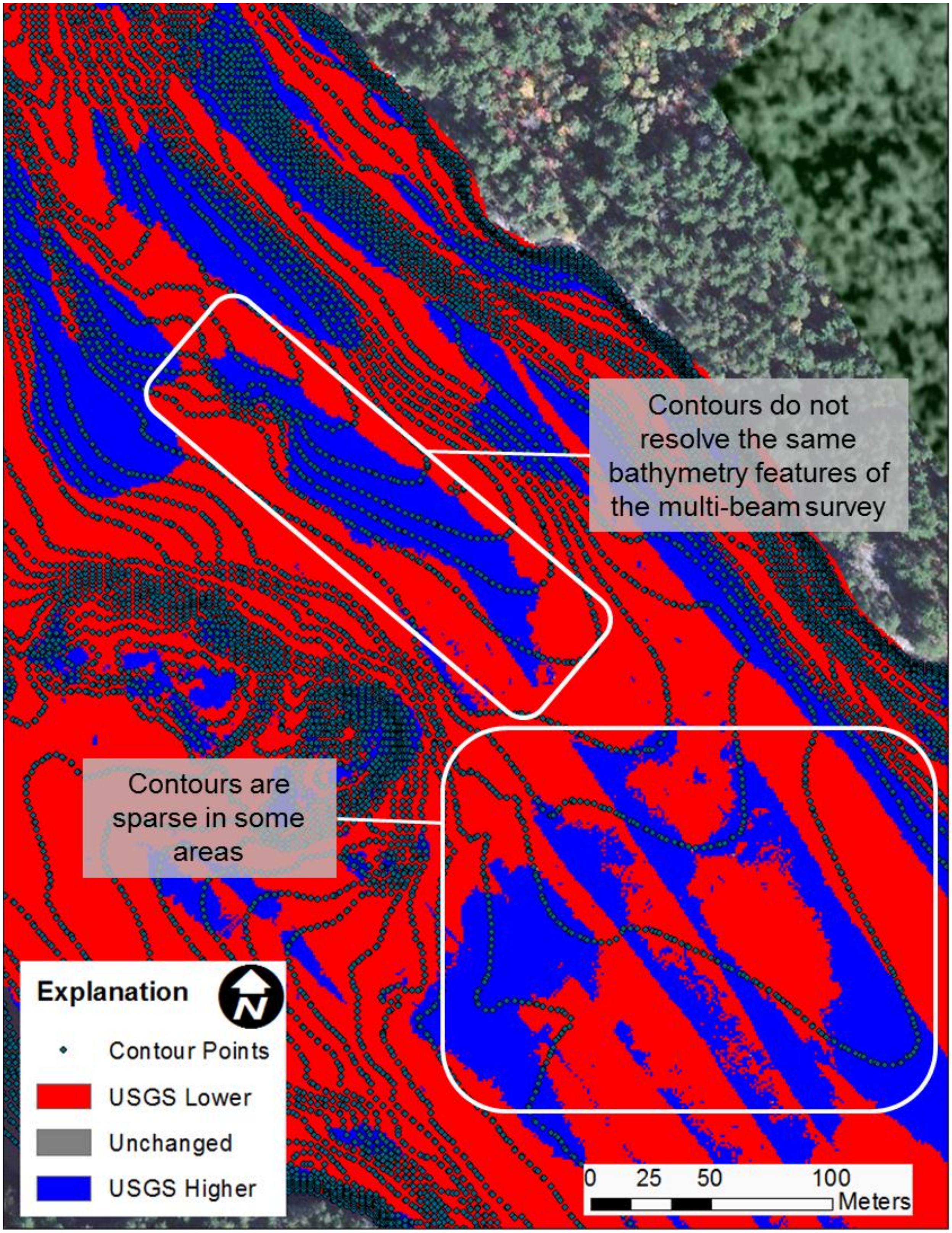


Figure 10: Close-up of contour density and analysis of features resolved by multi-beam survey for Little Vermillion

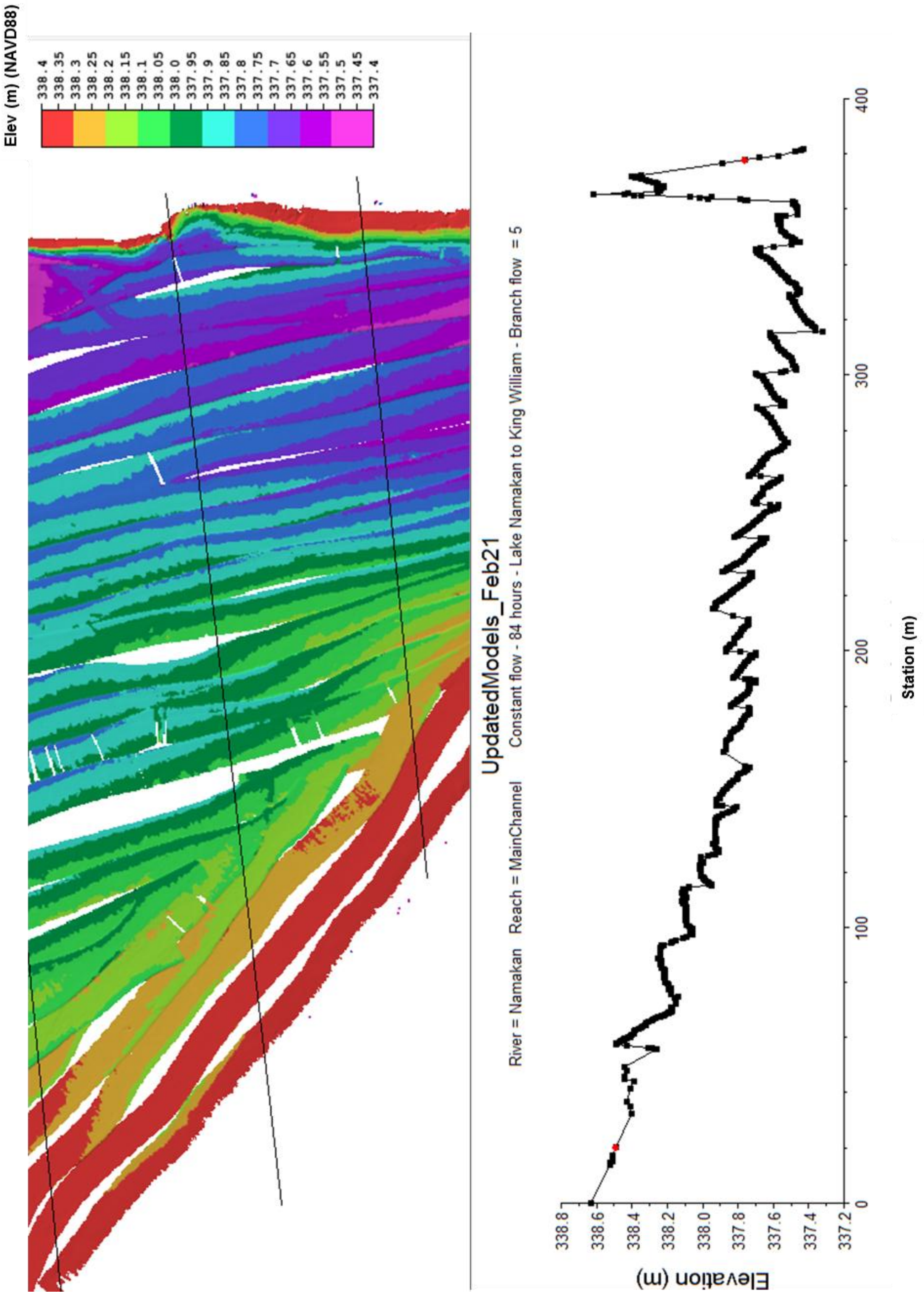


Figure 11: Pitch and roll errors in bathymetry for HEC-RAS cross-section 127 in King Williams narrows

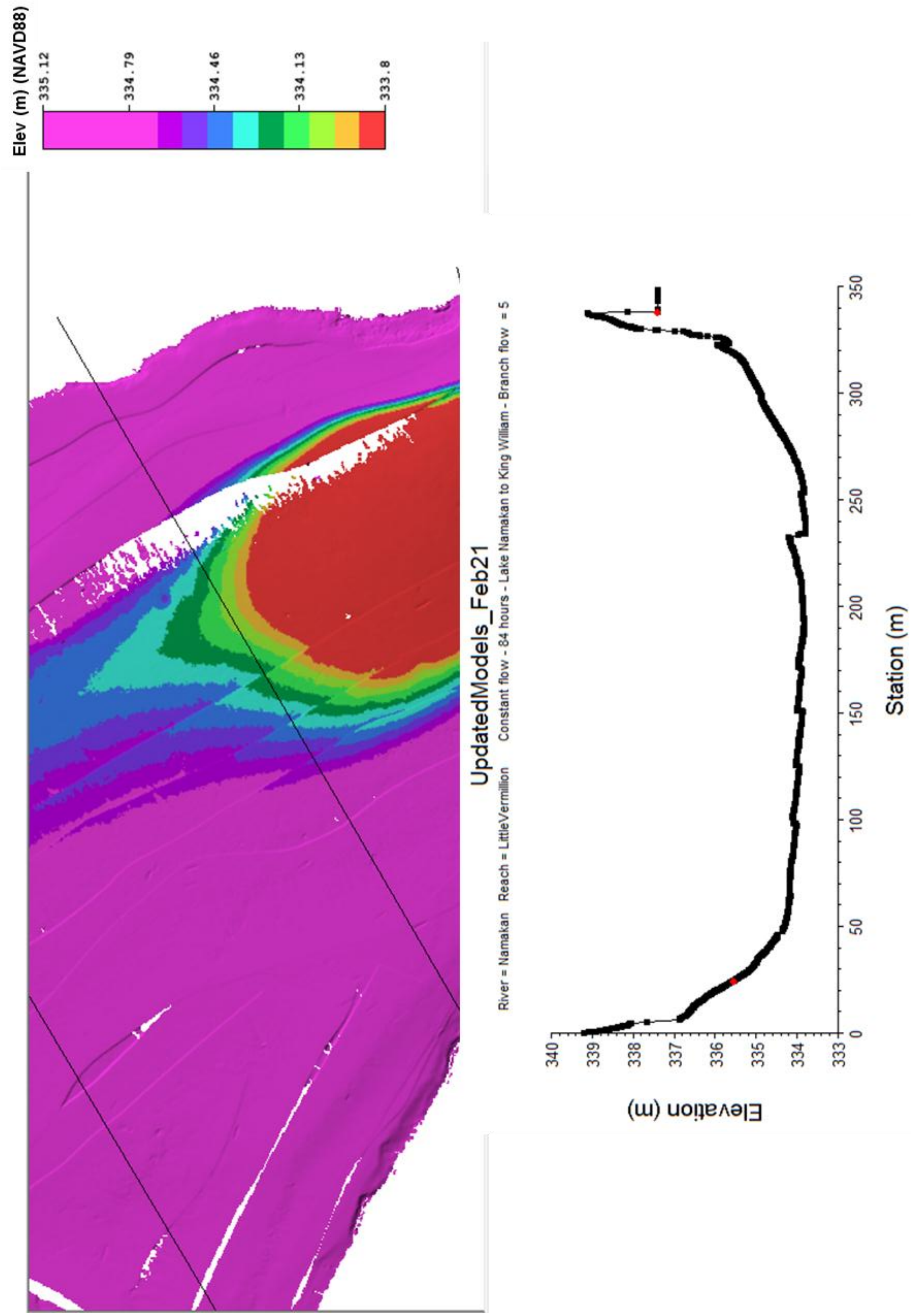


Figure 12: Pitch and roll errors in bathymetry for HEC-RAS cross-section 178 in Little Vermillion narrows

5 ANALYSIS OF WATER LEVELS

5.1 Purpose of Analysis

Water level gauges throughout the Namakan reservoir are an integral component of developing a hydraulic model of the system. Water level data are needed for model boundary conditions to run simulations and are also the main source of information needed for model calibration and validation. The study area includes three permanent water level gauges operating year-round and four temporary water level transducers that were installed during the summers of 2011 and 2012. Due to the need to incorporate and harmonize water level data collected and maintained by multiple government agencies and reported in different vertical datums, the analysis of collected water level records included here was expanded beyond the scope of the original hydraulic modelling project described by Stevenson and Thompson (2013). A detailed understanding of the accuracies and uncertainties for water level time series was necessary to provide direction for interpretation of model simulations.

The following sections describe water level data collected in the system for 2011-2012 and analyze how each data series should be incorporated into a hydraulic model. In addition, the analysis and discussion of uncertainties in stage data provides insight for water managers regulating water levels throughout the study area.

5.2 Permanent Gauge Data

The study area includes three permanent gauges that report water levels year-round. Gauges are operated on Kabetogama Lake and Crane Lake by the United States Army Corps of Engineers (USACE), and Squirrel Island on Namakan Lake by Water Survey of Canada (WSC) as indicated in Table 5. All gauges report data to the USC&GS 1912 vertical datum.

Hourly data for the Squirrel Island gauge was downloaded from WSC'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 made for Squirrel Island with all values recorded one minute after each hour. Hourly Crane Lake and Kabetogama Lake time series were downloaded from the USACE website (http://www.mvp-wc.usace.army.mil/dcp/). In addition to hourly data, daily water levels for the three gauges were obtained from the Lake of the Woods Control Board. Gauge stations throughout the system are shown in Figure 13.

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, data analysis in this report and the primary pinch point modelling report provided by Stevenson and Thompson (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.

Figure 14 shows hourly water levels at the permanent gauges between January 2011 and December 2012. Figure 15 shows daily water level records for the same locations. Water levels recorded in USC&GS 1912 vertical datum are shown in the top panel of each figure, while comparisons between gauge pairs are shown in the bottom panels. Water levels in the Namakan chain have a seasonal cycle from low levels in March that rise sharply during the spring and then peak and begin declining during June. Seasonal water level changes larger than one metre typically occur during the year. As mentioned above, the Namakan chain drains northward, from Crane Lake at the upstream end towards Namakan Lake at the downstream end.

The bottom panels of Figures 14 and 15 indicate water levels on Crane Lake are generally similar to the downstream end of the system, although precipitation and runoff lead to times when Crane Lake is elevated above Namakan Lake and Kabetogama Lake. However, the data shows several instances where Crane Lake records are slightly below Squirrel Island. The Squirrel Island gauge is consistently lower than the Kabetogama Lake gauge (3.2 cm average for hourly values between June 19, 2011 and December 19, 2012). One difference observed between the hourly and daily records is a spike in Crane Lake water levels at the beginning of May 2011 that is observed in the daily records in Figure 15 but is not observed in the hourly records of Figure 14. This spike is attributed to an adjustment in the provisional data provided on the USACE website. The daily data in Figure 15 was obtained from the Lake of the Woods

Secretariat and had not been processed through year-end quality assurance/quality control (QA/QC) checks at the time it was obtained. It is expected that this particular difference would be removed during standard data QA/QC (LWS, 2013).

Table 6 shows that daily records between 2011-2012 indicate Squirrel Island water levels were higher than Crane Lake levels 36% of those two years, and were more than 1 cm below Crane Lake 14% of the time. In contrast, analysis of daily levels at Kabetogama Lake show it was above Crane Lake for fifteen days representing 2% of all values. There were only two days when Crane Lake water levels were more than 2 cm below Kabetogama Lake.

Table 7 shows a summary when Crane Lake water levels are above the Squirrel Island and Kabetogama Lake gauges. These statistics show Crane Lake is almost always above the Kabetogama Lake water level and that for 68 percent of the days in 2011-2012, Crane Lake was more than 3 cm above Kabetogama Lake. The summary statistics in Table 8 show Crane Lake water levels are generally closer to Squirrel Island levels in comparison to Kabetogama Lake.

Comparing water levels recorded for Crane Lake and Kabetogama Lake show expected conditions where Crane Lake is always above or at the same level as the downstream end of the system. From looking at the statistics in Tables 6 and 7, it appears the Squirrel Island data does not agree well with the data reported by the USACE gauges. Factors such as wind and ice have the potential to distort gauge readings which can account for some anomalies between comparisons of upstream and downstream gauges. It is possible that the location of the Squirrel Island gauge makes is more or less susceptible to disturbances caused by ice in wind than the two USACE gauges; the Squirrel Island gauge is tucked within a series of islands at the northern end of the system while both USACE gauges are on larger open lakes, which could potentially increase the impact from ice or could change the influence of wind on that particular location. Other unknown factors to consider are whether the hydraulics of the connection between Kabetogama Lake and Namakan Lake could potentially allow each lake to be at a different elevation and whether the outflows at Gold Portage and Bear

Portage could potentially cause localized differences in water levels observed for either gauge.

Another factor which could account for the differences between the USACE and EC gauges are differences in surveying and leveling methods used by each agency. It is possible that regular gauge maintenance by the USACE for Crane Lake and Kabetogama Lake differs from methods applied by EC at the Squirrel Island gauge; use of different equipment, leveling methods, and incorporation of different local benchmarks could result in disagreement in vertical leveling by each agency.

Although it would appear the Kabetogama Lake water levels are in better agreement with Crane Lake levels, the summary statistics in Table 8 show there is minimal time when the water levels at the upstream and downstream ends of the system are equal and therefore no flow is travelling through the system. Historical knowledge of the system suggests most times of the year water levels through the system are relatively flat, which does not strongly agree with the summary data in Table 8.

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

Table 6: Statistics for daily water levels when Crane Lake is below downstream gauges

Cases	Records	% of Time
Total Days: Jan 1, 2011 – December 31, 2012	731	100
Crane Lake < Squirrel Island	263	36
Crane Lake more than 1 cm below Squirrel Island	103	14
Crane Lake more than 2 cm below Squirrel Island	36	5
Crane Lake more than 3 cm below Squirrel Island	19	3
Crane Lake < Kabetogama	15	2
Crane Lake more than 1 cm below Kabetogama	4	1
Crane Lake more than 2 cm below Kabetogama	1	0
Crane Lake more than 3 cm below Kabetogama	1	0

Table 7: Statistics for daily water levels when Crane Lake is above downstream gauges

Cases	Records	% of Time
Total Days: Jan 1, 2011 – December 31, 2012	731	100
Crane Lake > Squirrel Island	453	62
Crane Lake more than 1 cm above Squirrel Island	325	44
Crane Lake more than 2 cm above Squirrel Island	220	30
Crane Lake more than 3 cm above Squirrel Island	143	20
Crane Lake > Kabetogama	713	98
Crane Lake more than 1 cm above Kabetogama	687	94
Crane Lake more than 2 cm above Kabetogama	615	84
Crane Lake more than 3 cm above Kabetogama	494	68

Table 8: Summary statistics

Cases	Records	% of Time
Total Days: Jan 1, 2011 – December 31, 2012	731	100
Crane Lake +/- 1 cm of Squirrel Island	407	56
Crane Lake +/- 2 cm of Squirrel Island	511	70
Crane Lake +/- 3 cm of Squirrel Island	588	80
Crane Lake +/- 1 cm of Kabetogama Lake	44	6
Crane Lake +/- 2 cm of Kabetogama Lake	116	16
Crane Lake +/- 3 cm of Kabetogama Lake	237	32

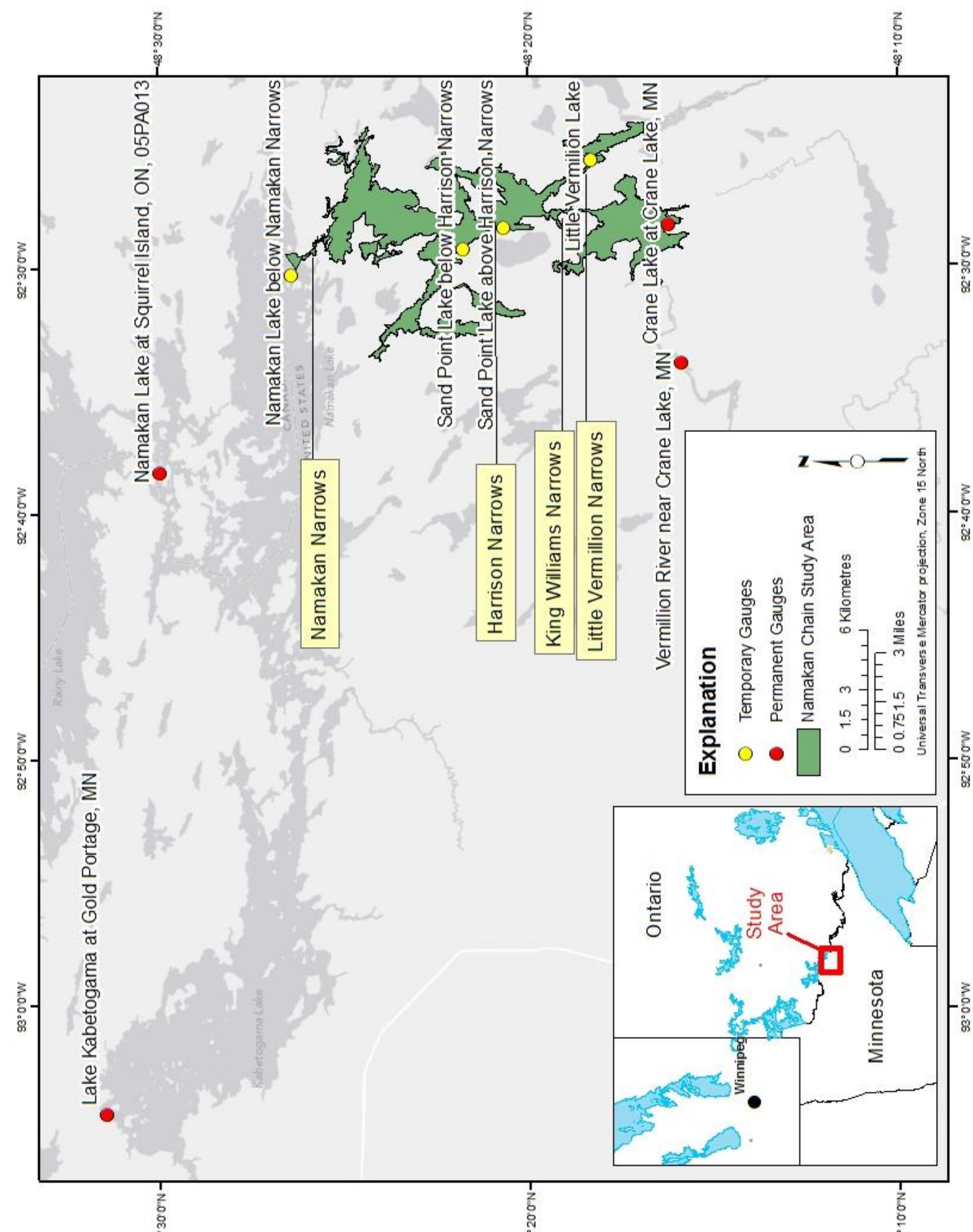


Figure 13: Namakan Chain model extent and pocation ofpPinch point channels. Permanent gauges in the system are shown with red points, temporary water level gauges installed during ice-free seasons of 2011-2012 shown with yellow points.

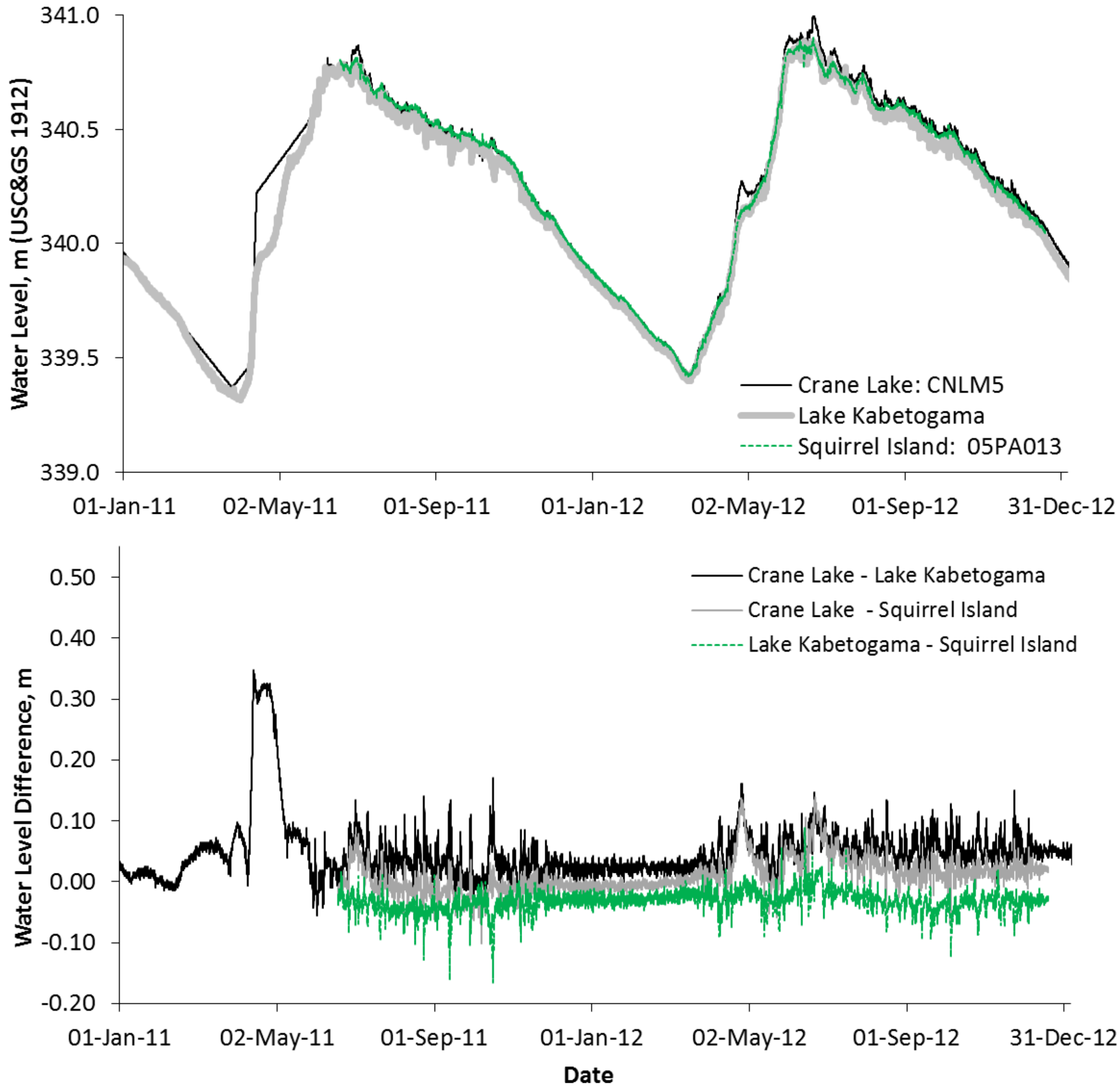


Figure 14: Hourly water level gauge data at permanent gauges. Top panel shows water levels while bottom panel shows water level differences between gauge pairs.

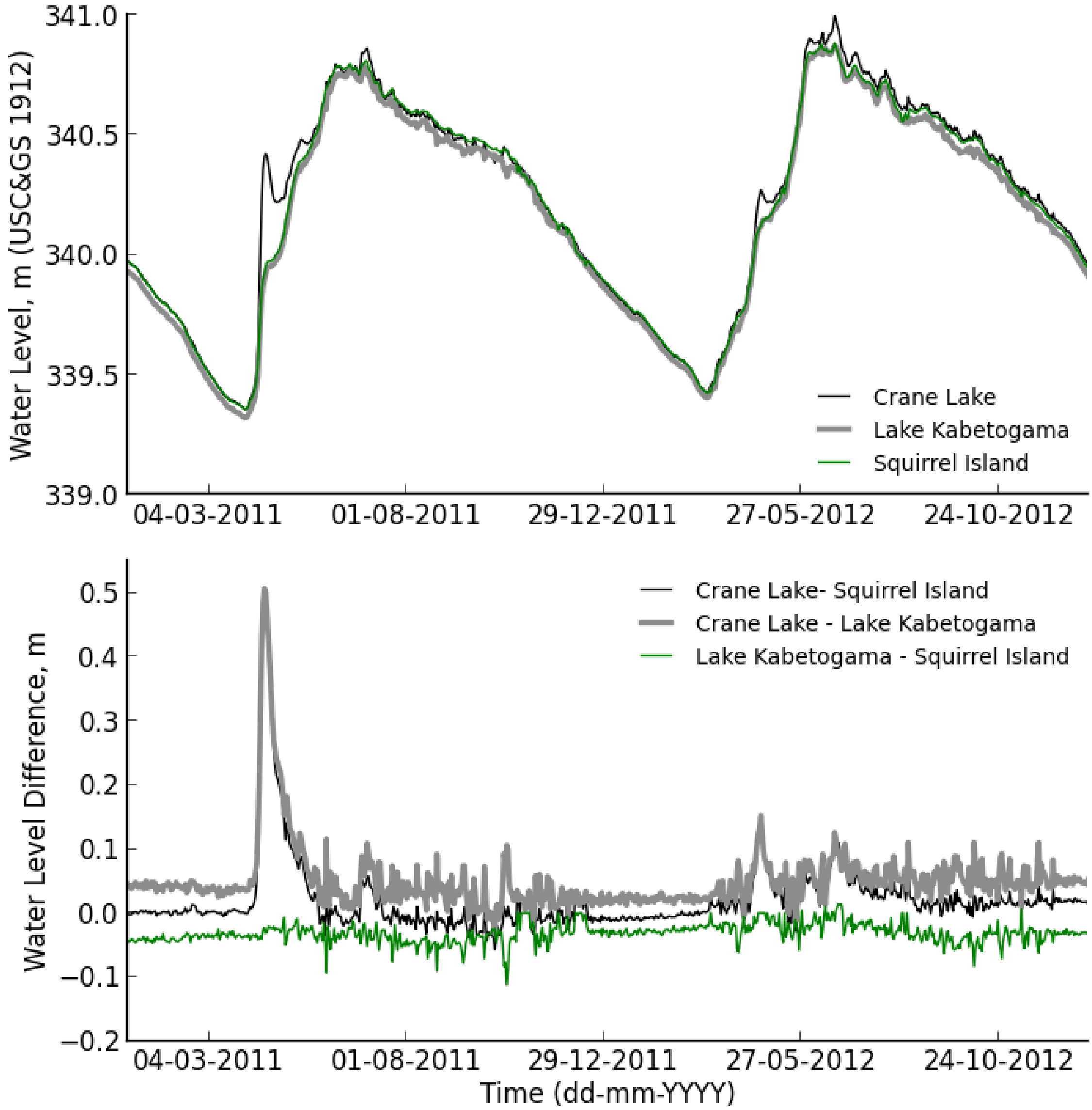


Figure 15: Daily water level gauge data at permanent gauges provided by the Lake of the Woods Control Board. Top panel shows water levels while bottom panel shows water level differences between gauge pairs.

5.3 Temporary gauge data

Four temporary water level gauges (Ott Hydromet) were installed throughout the system to provide boundary condition and calibration data for the model. Loggers were first installed in August 2011, and then removed in November for the winter until May 2012. Stage and temperature data were logged at a 15 minute interval. Water levels were collected in NAVD88 vertical datum and then converted to USC&GS 1912 vertical datum according to the procedure described in section 3 to allow for comparison with permanent gauge data. Installation locations and dates are shown in Figure 13 and Table 8. Hourly time series of the temporary transducer measurements were created by selecting the fifteen minute value for the beginning of each hour. Daily water levels were computed by averaging hours 0:00 to 23:00 CST for each day.

Hourly water levels collected at the temporary transducers are shown in Figure 16. Data at the temporary transducers show a natural slope through the system, where water levels in Little Vermillion narrows are always above water levels recorded downstream at Namakan Lake during 2012 and levels recorded for Sand Point Lake fall between the upstream and downstream gauges.

Water levels at both locations on Sand Point Lake were very similar to each other as shown in Figure 17. There was more variability between the two gauges on Sand Point Lake during 2011 compared to 2012. For the 2011 data shown in the top panel of Figure 17, Sand Point Lake above Harrison narrows is lower than Sand Point Lake below Harrison an average of 0.010 m for the daily values. The bottom panel of Figure 17 shows this difference is closer to zero for the 2012 values and is also more consistent with expected conditions where the upstream end of Sand Point Lake is higher than the downstream end of Sand Point Lake. The contrast in behavior of the two Sand Point Lake gauges between 2011 and 2012 indicates the 2011 field installation may be prone to more error, on the order of 1 cm, potentially caused by gauge placement and leveling.

Figure 18 shows the upstream temporary water level gauges compared to the downstream Namakan Lake transducer. During the annual spring rise from May to July (approximately 1.5 m for each lake as shown in Figure 14), there were three events where Sand Point Lake was around 10 cm above the downstream Namakan transducer. After these events, and later in the summer, the head drop between Sand Point Lake and the Namakan transducer decreased and stabilized around 5-6 cm. The head difference between the Little Vermillion transducer and the Sand Point Lake water levels was consistently between 2 and 5 cm for 2012.

Table 8: 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

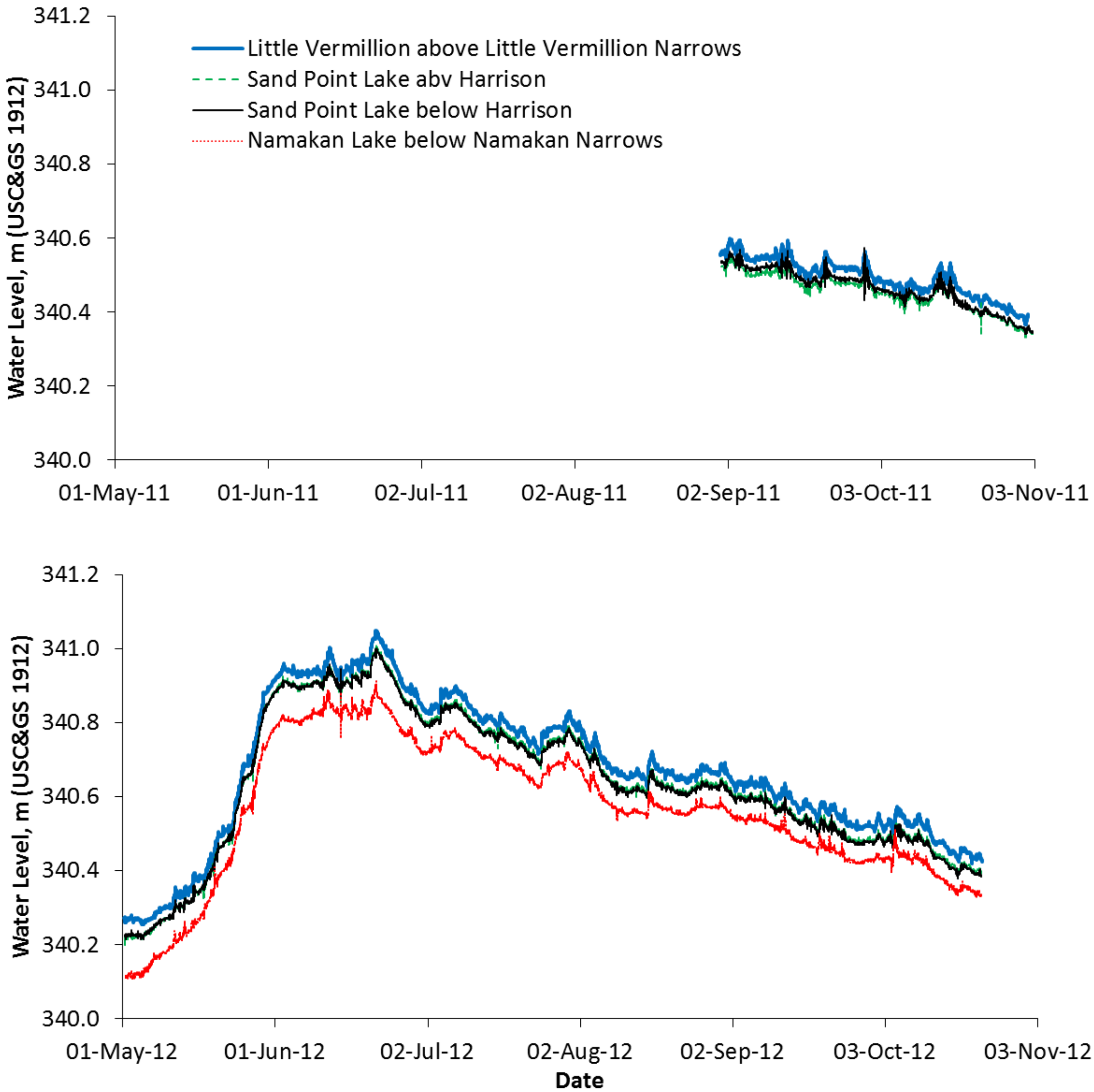


Figure 16: Hourly water level data collected at temporary gauges. Top panel shows 2011 field collection, bottom panel shows 2012 field collection.

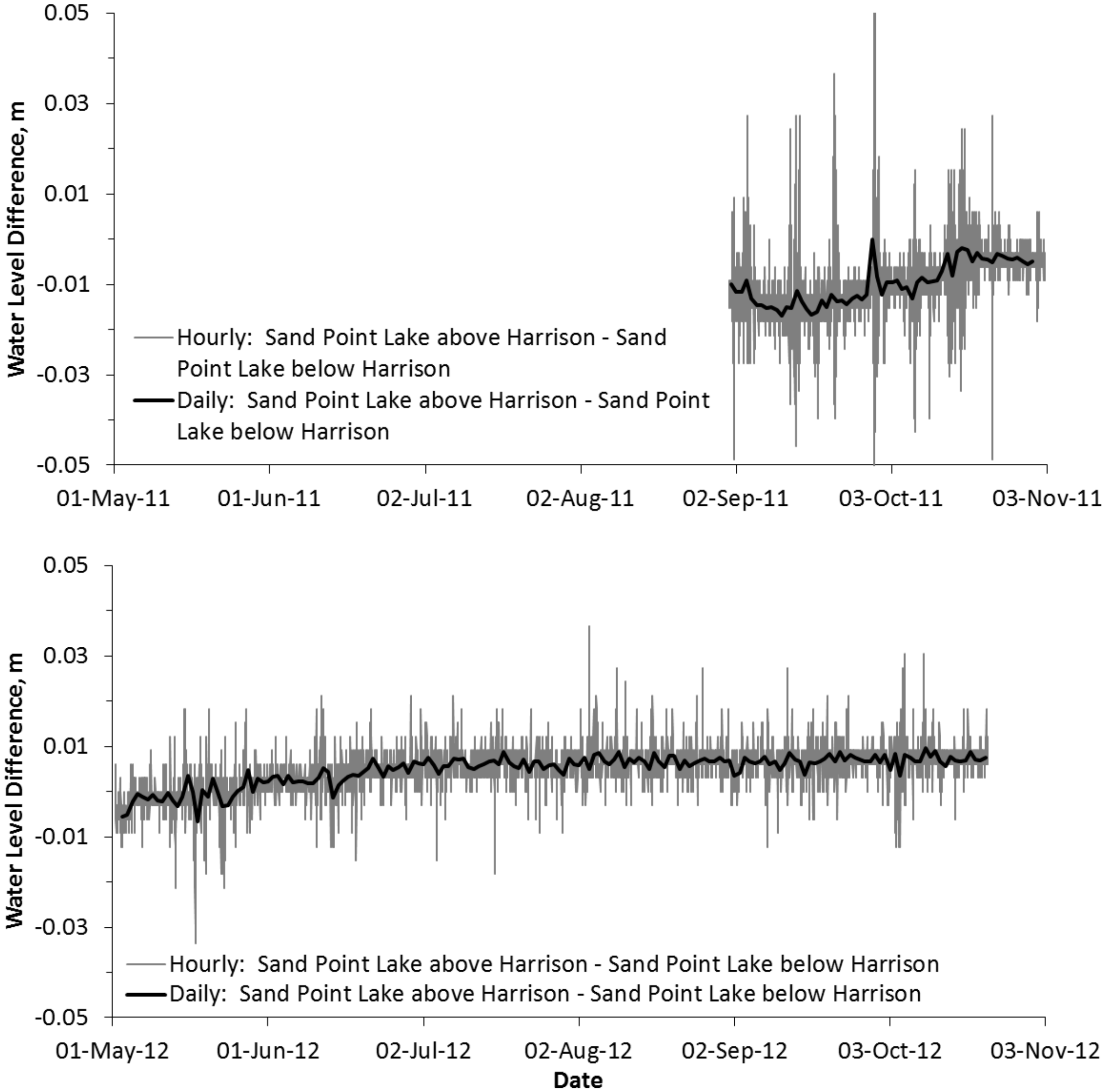


Figure 17: Comparison of temporary gauge data collected on Sand Point Lake, above and below Harrison narrows. Top panel shows 2011 field collection, bottom panel shows 2012.

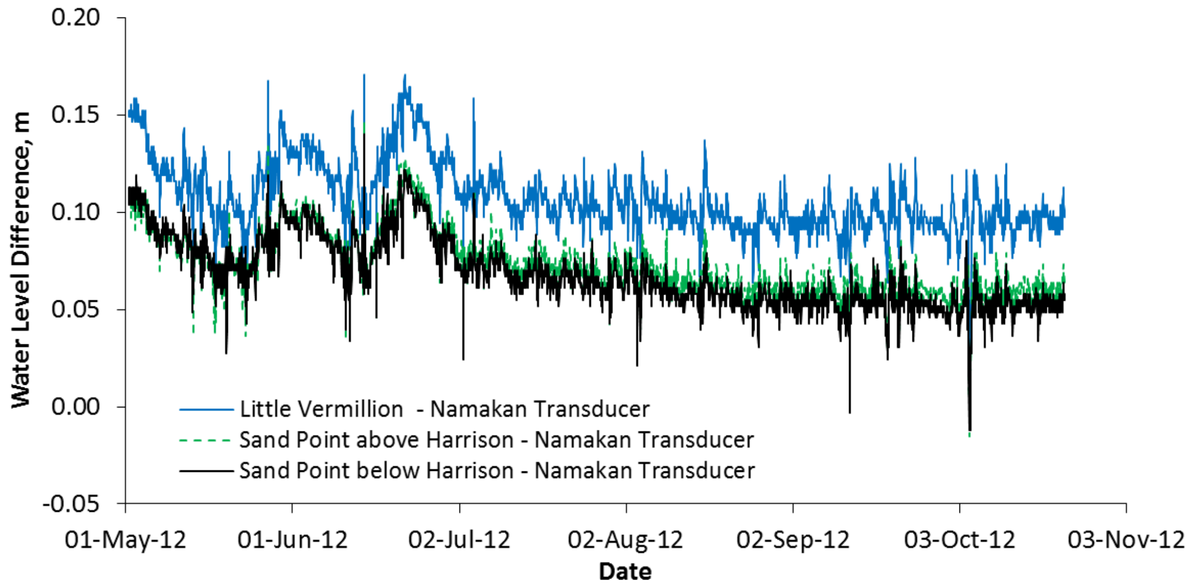


Figure 18: 2012 temporary water levels referenced to Namakan temporary gauge

5.4 Comparison of temporary and permanent gauge data

Comparison of the Squirrel Island and Namakan temporary transducer showed some disagreement between observed water levels. The Squirrel Island and Namakan transducer gauges are located at different ends of Namakan Lake; the permanent gauge at Squirrel Island is located at the northern end of the lake close to the Kettle Falls Dam, while the temporary transducer was installed at a small island close to Namakan narrows (see Figure 13). Figure 19 shows water levels collected at Namakan Lake and Kabetogama Lake during 2012 and compares the two permanent gauges to the temporary Namakan transducer. Water levels recorded at each gauge are shown in the top panel, the middle panel shows the two Namakan gauges compared, and the bottom panel compares the Kabetogama gauge to the Namakan transducer. Squirrel Island water levels are typically always above the Namakan transducer, with the exception of two brief periods in May and June 2012. The average daily difference between these gauges was 3.3 cm between May and October 2012 (see Table 9).

Comparison of the Namakan temporary transducer with the Kabetogama Lake gauge in the bottom panel of Figure 19 shows closer agreement. The hourly and daily differences between these two gauges fluctuate significantly, although the average difference between the two gauges is close to zero. It is possible that the East-West distance between the Kabetogama Lake and Namakan transducer allows for wind set-up on the two lakes accounting for the variations in water levels between the Kabetogama gauge and the Namakan gauge. Because the average hovers around zero, it appears the Kabetogama Lake gauge provides a better average representation of the water levels recorded by the Namakan transducer compared to the Squirrel Island gauge. The comparison between the Namakan transducer and the Squirrel Island gauge suggests factors other than wind effects are responsible for the differences and that a leveling issue may be present in one of the data series. However, the middle panel of Figure 19 shows that the difference between Squirrel Island and the Namakan transducer is not constant, and appears to drift or change during the year. Comparison of the Namakan transducer and Squirrel Island data also shows less variability in day-to-day fluctuations, which indicates wind may have less influence in the comparison of this gauge pair than what is observed for the Kabetogama gauge.

Figure 20 shows all daily gauge data referenced to Crane Lake, USACE gauge CNLM5, with 2011 in the top panel and 2012 in the bottom panel. The data collection period in 2011 shows reported Crane Lake water levels were below all the temporary gauge records between September and November 2011. In addition, the Squirrel Island readings for 2011 are below Crane Lake water levels for all of June to November, with the exception of two weeks in July. Kabetogama Lake water levels, however, were lower than Crane Lake records for all of May to November 2011, with the exception of two short periods in June and October.

For the 2012 field installation, water levels at Crane Lake are still below the Little Vermillion transducer measurements, which is possible if the head drop through Little Vermillion narrows is larger than the head drop through King Williams narrows at that time. At the beginning of 2012, Crane Lake water levels were below measurements at Sand Point Lake transducers, and by late June, around the time of the seasonal peak for the year, the Sand Point transducers show they are at the same level as Crane Lake. Water levels at Squirrel Island were typically less than Crane Lake, except for a brief period in May 2012. In addition, Kabetogama Lake water levels and the temporary Namakan transducer were below recorded Crane Lake levels.

The gauge data shows Crane Lake and Sand Point Lake appear to have the same level for most of 2012. The periods between May-June 2012 where Sand Point Lake is below Crane Lake indicate potential issues with harmonizing the temporary transducers with the permanent Crane Lake gauge. Furthermore, ADCP measurements and modelling results discussed by Stevenson and Thompson (2013) indicated a head drop through King Williams narrows was expected on May 2 and June 26, 2012, although reported water levels show a flat profile between Crane Lake and Sand Point Lake.

Table 9: Average daily difference between gauge pairs

Gauge Pair	Time	Total Days	Average Difference (m)
Sand Point above Harrison - Sand Point below Harrison	Sept 2011 to Nov 2011	62	-0.010
	May 2012 to Oct 2012	173	0.005
Little Vermillion - Namakan Temporary	May 2012 to Oct 2012	173	0.107
Sand Point above Harrison - Namakan Temporary	May 2012 to Oct 2012	173	0.073
Sand Point below Harrison - Namakan Temporary	May 2012 to Oct 2012	173	0.068
Squirrel Island - Namakan Temporary	May 2012 to Oct 2012	173	0.033
Kabetogama Lake - Namakan Temporary	May 2012 to Oct 2012	165	0.006

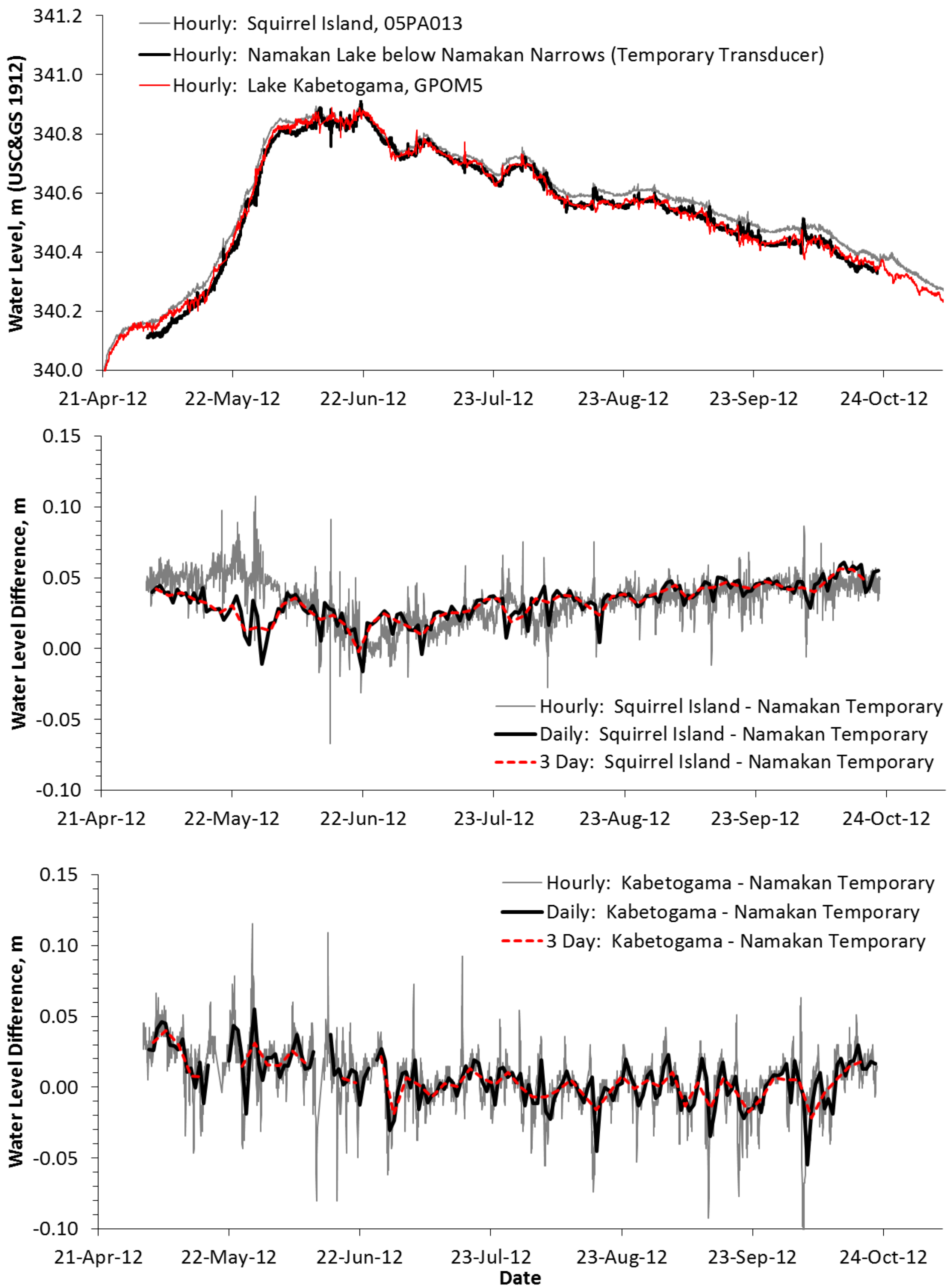


Figure 19: Hourly water levels on Namakan Lake and Kabetogama Lake. Top panel shows data collected at each gauge during May-Nov 2012. Middle panel compares Squirrel Island to Namakan transducer, bottom panel compares Kabetogama to Namakan transducer. Daily values calculated from hourly time series, 3 day average calculated from daily time series.

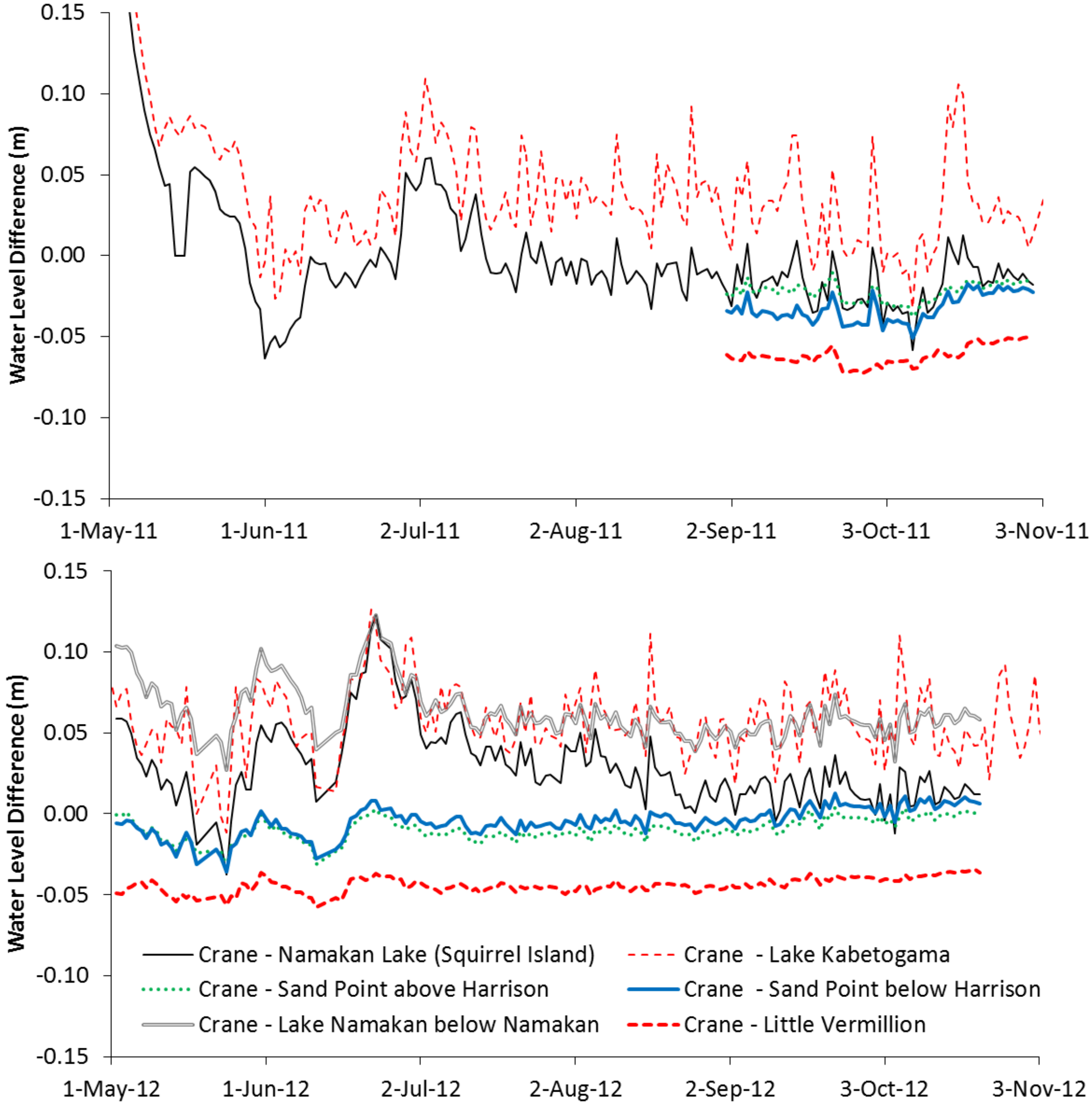


Figure 20: Comparison of daily water level gauge data to daily Crane Lake gauge readings. Daily values were calculated from hourly time series.

5.5 Surveys of water level gauges

Inconsistencies between permanent and temporary water level gauge data prompted two vertical leveling surveys in early 2013. The USACE completed a vertical leveling survey of the Crane Lake gauge on January 9, 2013. The survey was completed with an RTK GPS and also collected static GPS data set up for 2 hours over a National Geodetic Survey (NGS) benchmark. A loop was completed between the benchmark and Crane Lake gauge. The survey indicated Crane Lake gauge was reading 2.43 cm higher than in should have been. The change was incorporated into the online data provided by the USACE from January 10, 2013 onwards. These survey results did not provide a simple solution to harmonizing water levels for all gauges in the system. As discussed above and by Stevenson and Thompson (2013), the Crane Lake gauge readings did not appear to agree with the temporary water level measurements on Sand Point Lake because they showed no head drop through King Williams narrows for the May 2 and June 26 flow scenarios which contrasted with simulation results. If the temporary gauge readings on Sand Point Lake above and below Harrison narrows (which are shown in Figure 17 to provide close agreement) are assumed to be correct, it would indicate the Crane Lake readings were too low rather than too high.

A vertical leveling survey of the Kettle Falls benchmark was completed by the USGS on February 8, 2013. The survey employed an RTK GPS situated over the benchmark. Data collected during the survey was used to provide a network adjustment between the USGS benchmarks used for bathymetry collection and Kettle Falls. Further details of results are discussed in section 5.6.

An issue with the vertical leveling surveys that were conducted is they only included local benchmarks at a single gauge location. This allows discrepancies between local benchmarks and an individual gauge to be corrected, but it does not provide information about how that gauge is reading in relation to another gauge in the system. The gauges at Kettle Falls, Kabetogama Lake, and Crane Lake need to be tied together in a single survey to allow direct comparison of water levels and determine whether a specific gauge is reporting incorrect data with respect to the rest of the local gauge network. Furthermore, this data should also be tied to any temporary water level gauges such as those installed in 2011 and 2012. This is particularly important for the Namakan Chain system because data has been collected from permanent and temporary gauges operated and installed by multiple agencies (USACE, USGS, and EC). The two leveling surveys which were conducted in early 2013 were able to correct gauge data for accuracy with respect to local benchmarks, but it did not conclusively identify the accuracy of each surveyed gauge with respect to the other gauges in the Namakan Chain of lakes.

5.6 OPUS-Projects

During bathymetry collection in the pinch point channels, individual GPS stations were set up for each pinch point location which led to a concern each data set was not tied together vertically. GPS data collected at each pinch point used its own network of satellites and Continuously Operating Reference Station (CORS) benchmarks and there was a concern the GPS solutions for each survey location may not have vertical agreement. This could potentially introduce errors into the modelling analysis when all data sets were used in a single model. Furthermore, there were concerns the water level gauge were not tied together vertically. In an attempt to rectify these concerns, the Online Positioning User Service Projects (OPUS-Projects) system was used to provide a network adjustment for all surveyed data sets.

GPS data from field surveys during bathymetry collection, temporary gauge installation, and the vertical leveling surveys in January and February 2013 were processed in OPUS-Projects. OPUS combines GPS data with the CORS benchmark network operated by the NGS. OPUS-Projects is a web-based tool that allow multiple OPUS sessions to be included in a single network adjustment to minimize vertical error by finding an optimal combination of benchmarks. A network adjustment was completed with the GPS data collected during the bathymetry surveys and vertical leveling surveys at Crane Lake and Kettle Falls in an attempt to tie all survey data together. OPUS-Projects was able to create a solution for the entire network, which included corrections which could be applied at each temporary gauging station and each set of pinch point bathymetry.

The OPUS-Projects network adjustment is summarized in Table 10. The site names correspond to the GPS locations where each pinch point was surveyed. Table 11 lists the bathymetry and water level data sets where each vertical adjustment from Table 10 would be applied. The OPUS-Projects adjustment shows a large range in the corrections recommended at each location, ranging from 5 mm to 17.6 cm.

The network adjustment did not appear to agree with the water level analysis in this report and modelling results from Stevenson and Thompson (2013). Figure 20 shows Crane Lake appeared to be lower than other gauges at various times. Crane Lake was below Sand Point Lake for 2011 and was below or equal to Sand Point Lake in 2012, while 2011 and 2012 showed isolated times when Crane Lake was also reading below Squirrel Island. Based on modelling results and observed ADCP measurements, this data indicated Crane Lake should be reading higher with respect to the other water level gauges. However, Table 10 shows the network adjustment indicated little elevation change was needed for Crane Lake and King Williams narrows, while Sand Point Lake data should be raised by 8.8 cm and the Namakan transducer data should also be raised by 17.6 cm. Applying this adjustment to the collected water level data would significantly increase the amount of time Crane Lake was reading below other gauges in the system, which conflicts with field observations and modelling results. Therefore, the results from the network adjustment were not incorporated into the modelling analysis by Stevenson and Thompson (2013). Although it was desirable for all data sources used in the pinch point modelling analysis to be tied together vertically, the network adjustment provided using OPUS-Projects was unable to produce a solution which agreed with historical data and knowledge of the Namakan Chain system. Consequently, the network adjustment was not incorporated into any further analysis.

Table 10: Results from OPUS-Projects network adjustment

Site	Original Orthometric Height (m)*	OPUS-Projects Orthometric Height (m)**	Difference between original survey and network adjustment (m)
Harr	341.462	341.55	0.088
King	346.039	346.044	0.005
Verm	341.436	341.512	0.076
Nama	346.604	346.78	0.176
Kett		341.524	

*NAD83(CORS96), UTM Zone 15 N, Geoid09
**NAD83(CORS2011), UTM Zone 15 N, Geoid12A

Table 11: Data sets where network adjustment would be applied

Site	Applicable Pinch Point Bathymetry	Applicable Water Level Gauges
Harr	Harrison narrows	Sand Point Lake above Harrison, Sand Point Lake below Harrison
King	King Williams narrows	Crane Lake
Verm	Little Vermillion Narrows	Little Vermillion transducer
Nama	Namakan narrows	Namakan transducer
Kett	N/A	Squirrel Island

6 DISCUSSION AND CONCLUSIONS

6.1 Vertical datum conversions

Conversion between vertical datums in the Namakan Chain was found to be difficult due to a lack of benchmarks directly in the system which had both CGVD 28 and NAVD 88 elevations. In addition, no model exists which provides a conversion between these two datums. The modelling analysis provided by Stevenson and Thompson (2013) and the data analysis in this report use a constant conversion of 42 cm between NAVD 88 and CGVD 28. However, Figures 4 and 5 suggest a constant conversion for the entire study area may not be applicable. Furthermore, the value of 42 cm for the datum conversion is also subject to some uncertainty based on the locations of surrounding benchmarks. Even if the conversion were constant, 42 cm may not be the exact conversion value in the study area.

6.2 Bathymetry

The analysis provided in this report did not reveal significant concerns with respect to vertical leveling of the multi-beam bathymetry collected in the pinch point channels. A cut-fill analysis comparing the multi-beam USGS bathymetry to contour data obtained from the private company LakeMaster did not show any distinct vertical bias between the two data sets for each pinch point channel.

The LakeMaster contour data was much higher resolution than the MinDNR contour data, with a resolution of 0.3 m compared to a 1.5 or 3.0 m contour interval.

Furthermore, the method described by Stevenson and Thompson (2013) to convert the MinDNR contours to a bathymetric elevation was subject to significant uncertainty due to the lack of metadata provided on survey maps. The modelling analysis provided by Stevenson and Thompson (2013) used the MinDNR contour data because the LakeMaster data was not available at the time the model was developed.

6.3 Water levels

Comparison of the permanent and temporary water level gauges in the system indicated three major points of concern:

1. The Squirrel Island gauge and temporary transducer on Namakan Lake were not in agreement for 2012 as shown in Figure 19. Furthermore, the difference between these two gauges changed throughout the season. Figure 19 indicated that the observed differences between the Namakan temporary transducer and the Lake Kabetogama gauge were influenced by wind effects, although the average difference between these two gauges appeared to be more stable, with an offset close to zero. The modelling analysis described by Stevenson and Thompson (2013) used the Squirrel Island gauge as the downstream boundary condition for water level simulations. This is a source of uncertainty in modelling results. The water level analysis contained in this report indicate the Squirrel Island gauge may not have been providing accurate data for 2012, in comparison to what was collected at Lake Kabetogama and the Namakan Lake transducer. However, the analysis in this report was not able to conclusively show the Squirrel Island gauge was incorrect, but rather that there was disagreement with other gauge pairs.
2. Crane Lake water levels were not in agreement with the other water level gauges in the system for many periods during 2011 and 2012. Based on historical knowledge of the system, Crane Lake should never report lower water levels than the downstream end of the system. Such occurrences (see Figure 20) are expected to be errors caused by wind set-up and/or vertical levelling issues at gauges in the Namakan Chain. Furthermore, ADCP measurements on May 2 and June 26 2012, coupled with modelling results indicated a head drop through

King Williams narrows was present, although observations showed a flat profile between Crane Lake and Sand Point Lake.

3. The top and bottom panels of Figure 20 show a difference between where the temporary water level transducers read in relation to Crane Lake for the 2011 and 2012 field installations. The top panel shows the 2011 installation reported temporary water levels that were all above Crane Lake water levels. However, for 2012, the bottom panel shows Sand Point Lake water levels were typically above Crane Lake early in the year and the same as Crane Lake later in the year. This comparison indicates it is possible there were differences between vertical positioning of the temporary gauges during the 2011 and 2012 field installations. However, the limited amount of data available prevents further conclusions.
4. Vertical levelling surveys at the Crane Lake gauge on January 9, 2013 identified a 2.43 cm correction to be applied at the gauge, while a survey of the Kettle Falls benchmark on February 8, 2013 produced a network adjustment in OPUS-Projects which recommended several significant changes to water level and bathymetry elevations. However, the results from the Crane Lake survey and the network adjustment from OPUS-Projects did not produce corrections which were logical based on existing knowledge of the system and field observations from 2011 and 2012. In addition, the Crane Lake survey was not able to identify when the error between local benchmarks and the water level gauge was introduced. As a result, the suggested corrections from the vertical surveys and the OPUS-Projects network adjustment were no applied to the historical data described in this report and used by Stevenson and Thompson (2013).
5. Any errors caused by the selected method of converting between vertical datums would translate into errors in an analysis of water levels. The Crane Lake, Squirrel Island, and Kabetogama Lake gauges all report data in USC&GS 1912, while the temporary transducers collected data in NAVD 1988. Potential errors in vertical datum conversions would affect where the temporary water level gauges read with respect to the permanent gauge records.

7 RECOMMENDATIONS

1. It is recommended that further vertical leveling in the Namakan Chain system be undertaken, consistent with what is discussed in Recommendation #1 of Stevenson and Thompson (2013). High precision vertical leveling at local bench marks and water level gauges in the Namakan system is required to allow water level data from all gauge locations to be tied together accurately. If further hydraulic or hydrodynamic modelling work is undertaken in the Namakan Chain study area, it is recommended that vertical leveling surveys be completed first to reduce uncertainty in modelling results.
2. Further investigation into whether vertical datum conversions are accurate for the study area is recommended. If vertical leveling for the system is completed, survey data should be used to confirm whether a constant conversion for the study area is acceptable. GPS data collected during leveling surveys in 2013, as well as in the future should be used with geodetic leveling tools such as Precise Point Positioning (PPP) and GPS-H to determine if the conversions used in this report and the modelling report by Stevenson and Thompson (2013) are subject to error.
3. Analysis of the multi-beam pinch point bathymetry collected by the USGS in 2011 indicated no significant vertical errors were present in the data set other than those caused by pitch and roll effects. The LakeMaster contour data appeared to be an extensive and reliable dataset. It is recommended that further modeling in the Namakan Chain of lakes use the LakeMaster contour data set over the MinDNR contour data which was used in the modelling analysis described by Stevenson and Thompson (2013).

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