Revising Water-Surface Elevation Data for Gages in Rainy Lake, Namakan Reservoir, and Selected Rivers in Minnesota, United States and Ontario, Canada

By Jeffrey R. Ziegeweid, R. Jason Silliker, and Brenda K. Densmore

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Executive Summary

Continuously-recording water-level gages in Rainy Lake and Namakan Reservoir are used to regulate water levels according to the 2000 Rule Curves established by the International Joint Commission. However, gage water levels were established using a variety of vertical datums, confounding efforts to model the flow of water through the system, regulate water levels during periods of high inflow, and evaluate the effectiveness of the 2000 Rule Curves. In October 2014, the U.S. Geological Survey, Natural Resources Canada, and Environment Canada began a joint field study with the goal of obtaining precise elevations referenced to a uniform vertical datum for all reference marks used to set water-level gages throughout Rainy Lake and Namakan Reservoir.

Three field crews deployed global navigation satellite system (GNSS) receivers statically over 17 reference marks co-located with active and discontinued water-level gages throughout Rainy Lake, Namakan Reservoir, and selected rivers. A GNSS receiver also was deployed statically over a National Geodetic Survey cooperative base network control station that was used as a quality-control reference mark, resulting in a total of 18 surveyed reference marks in this study. Satellite data were collected simultaneously over a five-day period and processed to obtain accurate positioning and elevations for surveyed reference marks. Processed satellite data were used to convert published water levels to elevations referenced to the Canadian Vertical Datum of 2013 (CGVD2013) in order to compare water-surface elevations referencing a uniform vertical datum throughout the study area. In this report, an “offset” will refer to the correction that needs to be applied to published data from a particular gage to produce elevation data referenced to CGVD2013.

Offsets were applied to water-level data from surveyed gages to further evaluate the accuracy and utility of updated reference mark elevations presented in this study. Mean water levels during the survey period for active gages surveyed in this study were converted to water-surface elevations

referenced to CGVD2013, and graphical comparisons of water-surface elevations for gages in Namakan Reservoir, Rainy Lake, and selected rivers are presented in this report. Four surveyed gages in Namakan Reservoir were discontinued in October 2012, so published mean daily water-levels (May-September 2012) were used to calculate mean monthly water levels in order to compare all gages in Namakan Reservoir. Mean monthly water levels were converted to water-surface elevations in CGVD2013, and a graphical comparison of water-surface elevations among gages is presented in this report.

Key findings:

1. Precise elevations referenced to CGVD2013 were obtained for 16 reference marks used to establish water levels at active and discontinued gages in the study area
2. A precise elevation referenced to CGVD2013 was not obtained for one discontinued gage (map number 12; station number 462626092302001) because the data card was damaged during retrieval
3. Elevation data obtained for an NGS cooperative base network control station of known elevation closely matched elevation data published in 1996
4. Elevation data were used to develop offsets that correct previously-published gage data to reference a uniform vertical datum (CGVD2013)
5. Comparison of previous and corrected elevations among active gages in Namakan Reservoir indicate improvements in the accuracy of water-elevation data as a result of this study
6. Corrected water-elevation data collected from active and discontinued gages in Namakan Reservoir during 2012 identified hydrologic discrepancies at two discontinued gages (map numbers 11 and 13, station numbers 482611092483801 and 482147092291701)
7. Caution should be used when applying presented gage offsets to discontinued gages
8. Additional surveys may help to (a) resolve hydrologic discrepancies at two discontinued gages and (b) develop an offset for a discontinued gage for which data could not be obtained in this study

Potential Applications of Key Findings:

The precision and accuracy of the elevation data presented in this study are suitable for several management applications in the Rainy River Basin. Water-level offset corrections can be used in the evaluation of the 2000 Rule Curves for Rainy Lake and Namakan Reservoir and in flood damage curves that fully assess the benefits of one regulation approach over another. Presented water-level offsets also may provide the information needed to calibrate HEC-RAS models developed by Environment Canada for four narrows that connect the lakes of Namakan Reservoir. Furthermore, improved accuracy of water-surface elevations can enhance a digital elevation model being developed by Environment Canada. Finally, corrected water-surface elevations can benefit other modeling studies designed to assess the effects of the 2000 Rule Curves on aquatic vegetation, benthic invertebrates, northern pike, and walleye.

Results of this study also indicate potential locations for additional data collection. Collected water-surface elevations data indicate that repeating the GNSS survey at USGS temporary gages 482611092483801 and 482147092291701 (map numbers 11 and 13, respectively) may be useful in resolving observed hydrologic discrepancies between these gages and the other gages surveyed for this study. In addition, because the data card was damaged during retrieval of deployed field equipment, no GNSS data was obtained for USGS temporary gage 482626092302001 (map number 12). Therefore, repeating the GNSS survey at this gage would provide the data required to develop an offset that corrects collected water-level data to elevations referenced to CGVD2013.

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Gail Faveri (Environment Canada) helped coordinate the joint field efforts between the United States and Canada as well as the joint funding through the U.S. and Canadian offices of the International Joint Commission. Ryan Maki and Chuck Remus (Voyageurs National Park) coordinated the support of the National Park Service and logistical support to complete the field data collection. Michael Craymer (Natural Resources Canada), Marc Veronneau (Natural Resources Canada), Jean Morin (Environment Canada), and Aaron Thompson (Environment Canada) provided input to improve the design of the survey and the presentation of the study results. Dr. Mark Colosimo (International Joint Commission) approved the study and participated in regular progress reviews. Bill Odell (U.S. Army Corps of Engineers) provided reference mark and elevation data for the gage on Crane Lake. James Wilcox (Environment Canada), Justin Krahulik (U.S. Geological Survey), Chris Sanocki (U.S. Geological Survey), and Catherine Christenson (U.S. Geological Survey) participated in field data collection efforts. Scott Bennett (U.S. Geological Survey contract employee) created the study area map.

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
	Flow rate	
miles per hour (mph)	1.60934	kilometers per hour (kph)

Abbreviations

BSW	Bernese GNSS Software v5.2
CACS	Canadian Active Control System
CGG2013	Canadian Gravimetric Geoid model of 2013
CGVD2013	Canadian Geodetic Vertical Datum of 2013
CORS	Continuously-Operating Reference Station
CSRS	Canadian Spatial Reference System
EC	Environment Canada
GLONASS	Global Orbiting Navigation Satellite System (Russian)
GNSS	Global Navigation Satellite System
IJC	International Joint Commission
NAD83	North American Datum of 1983 (horizontal datum)
NAVD88	North American Vertical Datum of 1988
NGS	National Geodetic Survey
NRCan	Natural Resources Canada
OPUS	Online Positioning Users Service
PPP	Precision Point Processing
RINEX	Receiver Independent Exchange
WSC	Water Survey Canada
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

Introduction

The Rainy River Basin of northern Minnesota and southwestern Ontario is a complex system of lakes and rivers (Kallemeyn and others, 2003), including Namakan Reservoir, Rainy Lake, and several rivers that feed these lake systems (fig. 1). Namakan Reservoir includes Crane, Little Vermilion, Sand Point, Kabetogama, and Namakan Lakes. Namakan Reservoir is fed by six major tributary rivers and flows north into Rainy Lake. Crane and Little Vermilion Lakes flow into Sand Point Lake, Sand Point Lake flows into Namakan Lake, and water moves bi-directionally between Namakan and Kabetogama Lakes depending on lake levels, wind direction, inflows from tributaries, and dam regulation. Water flows from Namakan and Kabetogama Lakes into Rainy Lake from outflows at Kettle and Squirrel falls and Gold Portage outlet, respectively. Rainy Lake is fed by Namakan Reservoir and several tributary rivers, including the Seine and Turtle Rivers. Rainy Lake drains into the Rainy River near the towns of Fort Frances, Ontario and International Falls, Minnesota. The Rainy River forms the border between the United States and Canada and flows west into Lake of the Woods.

Water levels in Rainy Lake and Namakan Reservoir are managed according to rule curves established by the International Joint Commission (IJC) with the assistance of the International Rainy Lake Board of Control (International Rainy Lake Board of Control, 1999). Rule curves established in 2000 (hereafter referred to as the 2000 Rule Curves; fig. 2) account for natural seasonal fluctuations in water level while balancing the requirements for several legally-recognized water uses within the basin (Kallemeyn and others, 2003). Water-level gages throughout Rainy Lake and Namakan Reservoir (fig. 1) are used to monitor water levels for compliance with the 2000 Rule Curves (fig. 2). However, monitoring has been complicated by the use of several different vertical datums to set water levels at these gages (table 1). Without comparable elevation data, water-resource managers cannot develop

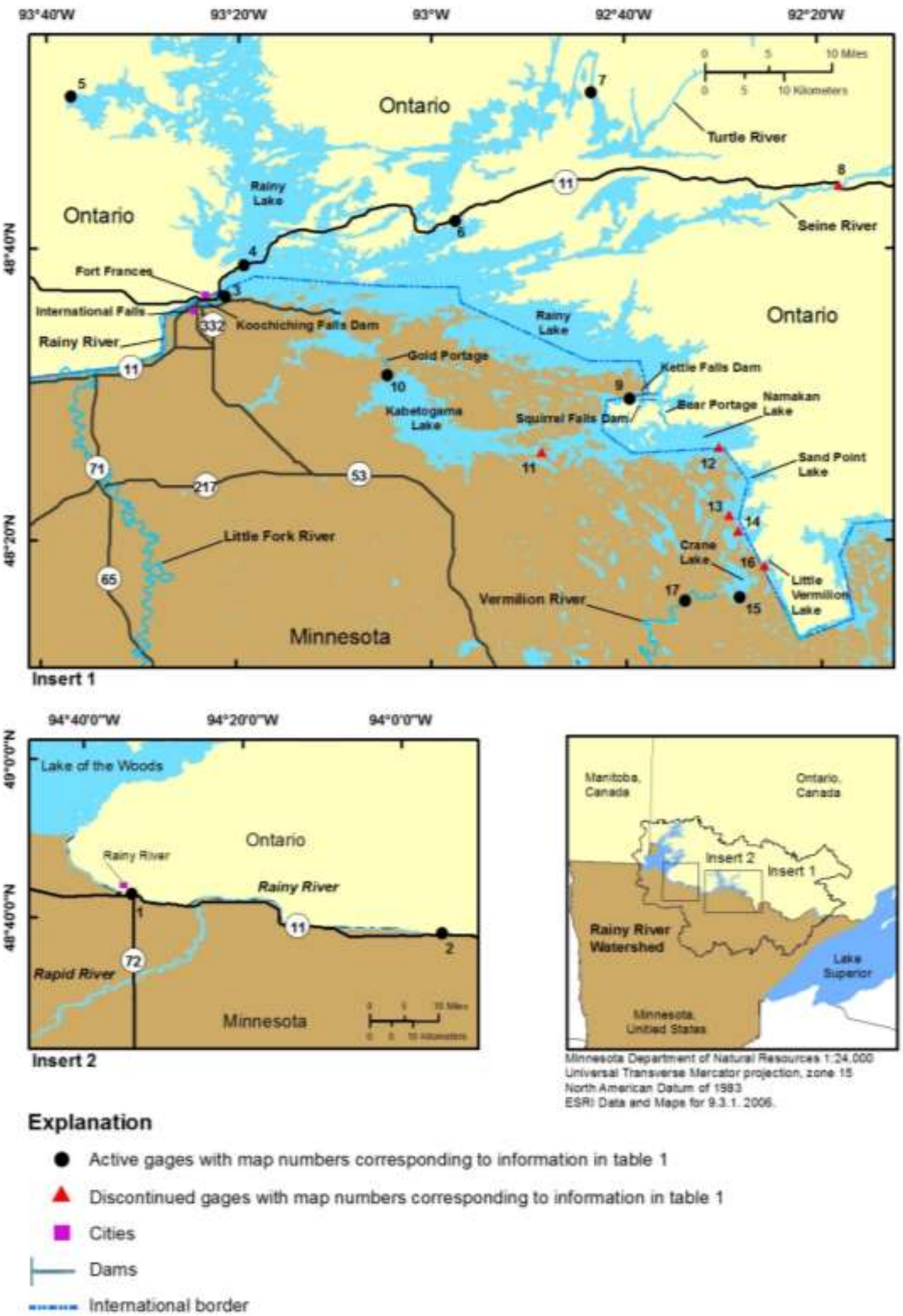


Figure 1. Map showing water-level gage locations for Rainy Lake, Namakan Reservoir, and selected rivers.

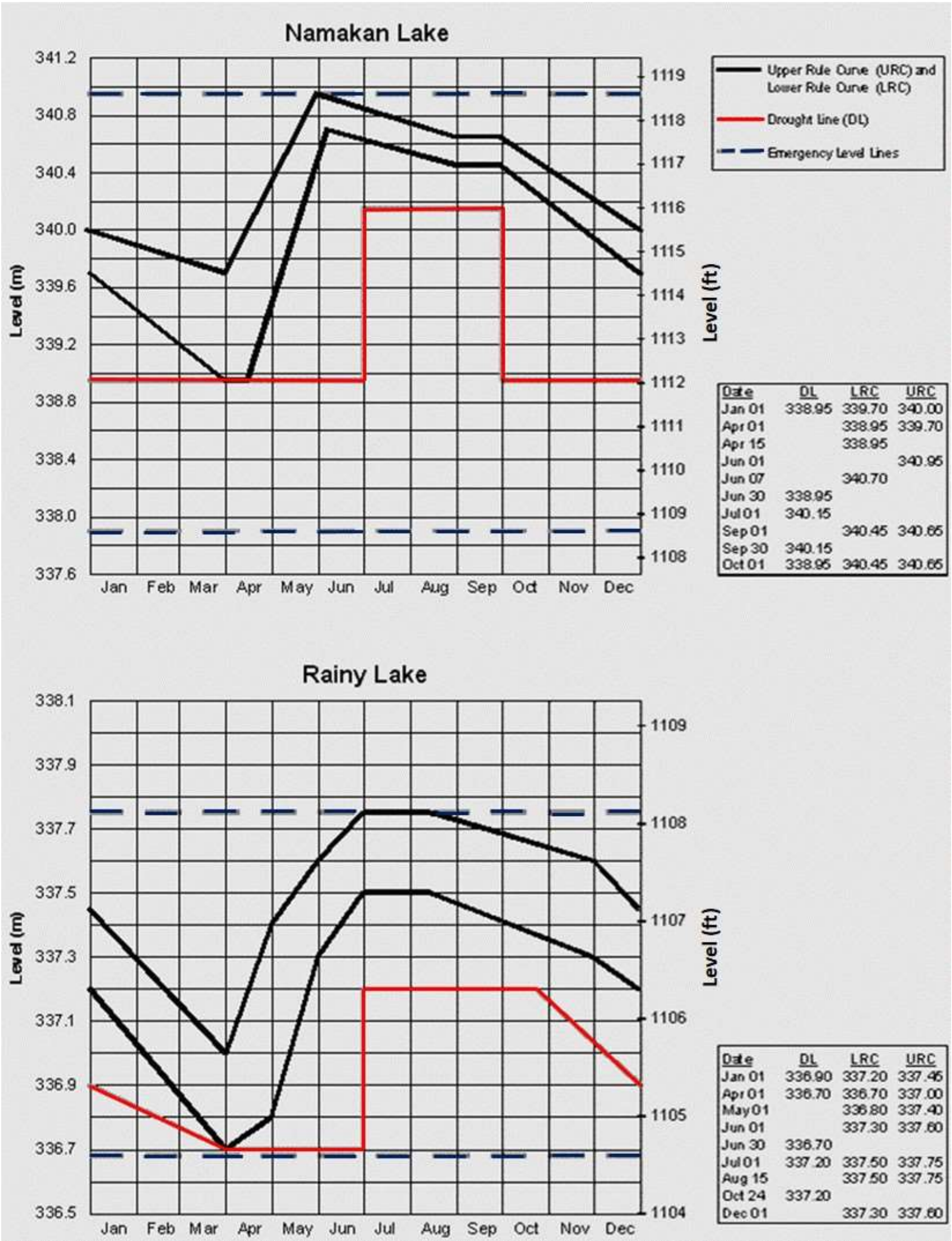


Figure 2. Graphs demonstrating the 2000 Rule Curves established by the International Joint Commission and used to regulate water levels in Rainy Lake and Namakan Reservoir (www.ijc.org).

Table 1. Information about water-level gages in Rainy Lake, Namakan Reservoir, and selected rivers in Minnesota, Unites States and Ontario, Canada.

[Map number, number assigned to represent the corresponding station number in map figures; Station number, identifier for a particular gage; Station name, description associated with a station number; Agency, the agency responsible for operating and maintaining the associated gage; Vertical datum, datum used to establish water levels at gages; Start date, the date that recording of water-level data began for each station; End date, the date that recording of water-level data stopped for each station; EC, Environment Canada; USGS, U.S. Geological Survey; SRFN, Seine River First Nation; USACE, U.S. Army Corps of Engineers; LOW, Lake of the Woods Vertical Datum; NGVD 1929, National Geodetic Vertical Datum of 1929; USC & GS 1912, United States Coast and Geodetic Survey Datum of 1912; Assumed Datum, arbitrary elevation used to set water levels at gages; NAVD 1988, North American Vertical Datum of 1988; MSL 1912, Mean Sea Level datum of 1912;]

Map number	Station number	Station name	Agency	Vertical datum	Start date	End date
1	05PC021	Rainy River at Rainy River	EC	LOW	1-Nov-1991	[1]---
2	05133500	Rainy River at Manitou Rapids, Minnesota	USGS	NGVD 1929	10-Nov-1934	[1]---
3	05PC024	Rainy River at Pithers Point Site No. 1	EC	USC & GS 1912	13-Oct-2011	[1]---
4	05PB007	Rainy Lake Near Fort Frances	EC	USC & GS 1912	20-Aug-1911	[1]---
5	05PB023	Rainy Lake at Northwest Bay	EC	Assumed Datum	13-Oct-2011	[1]---
6	05PB024	Rainy Lake Near Bear Pass	EC	USC & GS 1912	31-May-1988	[1]---
7	05PB014	Turtle River Near Mine Centre	EC	Assumed Datum	1-Aug-1914	[1]---
8	SRFN1	Seine River biological site	SRFN	[2]NA	[2]NA	[2]NA
9	05PA013	Namakan Lake at Squirrel Island	EC	USC & GS 1912	23-May-2007	[1]---
10	05129290	Gold Portage Outlet from Kabetogama Lake Near Ray, Minnesota	USGS	USC & GS 1912	14-Oct-1982	[1]---
11	482611092483801	Kabetogama Lake, East End, Near Old Dutch Bay	USGS	Assumed Datum	3-Nov-2010	3-Oct-2012
12	482626092302001	Namakan Lake below Namakan Narrows near Crane Lake, Minnesota	USGS	NAVD 1988	1-May-2012	22-Oct-2012
13	482147092291701	Sand Point Lake Below Harrison Narrows Near Crane Lake, Minnesota	USGS	NAVD 1988	29-Aug-2011	22-Oct-2012
14	482042092282501	Sand Point Lake Above Harrison Narrows Near Crane Lake, Minnesota	USGS	NAVD 1988	29-Aug-2011	22-Oct-2012
15	CNLM5	Crane Lake at Crane Lake, Minnesota	USACE	MSL 1912	15-Jan-2000	[1]---
16	481818092254201	Little Vermilion Lake Above Little Vermilion Narrows	USGS	NAVD 1988	29-Aug-2011	22-Oct-2012
17	05129115	Vermilion River Near Crane Lake, Minnesota	USGS	Assumed Datum	15-Aug-1979	[1]---

[1] Active gages

[2] Information not available - seasonal biological site; data not publicly accessible

accurate digital elevation models or hydraulic models that describe the movement of water through the basin (Densmore and others, 2013; Stevenson and Thompson, 2013). Furthermore, during periods of high inflow, water levels in lower Namakan Reservoir may differ from water levels in upper Namakan Reservoir by as much as 0.3 meters, creating situations in which lower portions of the reservoir are within the rule curve band while the upper portion of the reservoir is well above the rule curve band. Therefore, obtaining accurate elevation data in a uniform vertical datum is critical to understanding and managing water levels in Rainy Lake and Namakan Reservoir.

In this study, the U.S. Geological Survey (USGS), Natural Resources Canada (NRCan), and Environment Canada (EC) used geodetic-quality global navigation satellite system (GNSS) receivers to conduct simultaneous static surveys on 18 reference marks in Rainy Lake, Namakan Reservoir, Rainy River, and tributaries of Rainy and Crane Lakes using established methodologies (Canadian Geodetic Survey, 2003; Rydlund and Densmore, 2012; Canadian Geodetic Survey, 2013). The objective of this study was to obtain precise elevations referenced to a common vertical datum for these 18 reference marks, 17 of which are used to establish water-level gages throughout the Rainy River Basin. Eleven reference marks were used to establish water levels for active gages that provide real-time, continuous water-level data, and six reference marks surveyed were used to establish water levels for temporary gages operated during previous studies. Active gages are operated by the USGS, the U.S. Army Corps of Engineers (USACE), and Environment Canada (EC). The final reference mark surveyed was a National Geodetic Survey (NGS) Cooperative Base Network Control Station of known elevation that was used as a quality-control reference mark (fig. 3).

Figure 3. Map showing the locations of a National Geodetic Survey cooperative base network control station, four Canadian active control system stations, and ten continuously-operating reference stations that were used to process collected satellite data.

Methods

Methods are divided into four sections. The first section details how GNSS receivers were deployed and how field data were collected. The second section details the processing methods used by NRCan and USGS to obtain elevations for the surveyed reference marks. All reported elevations were measured to the nearest millimeter. The third section details how elevations of reference marks were used to develop offsets, which are values that can be added to or subtracted from published water levels in order to convert water-level data to elevations referenced to the Canadian Geodetic Vertical Datum of 2013 (CGVD2013). The fourth section details how offsets were applied to published water levels and how corrected elevations were used to compare and evaluate collected water-level data from gages throughout the study area.

Field Data Collection

Three field crews deployed 18 static geodetic-quality global positioning system GNSS receivers paired with choke ring antennas for satellite data collection. Deployment of GNSS units for data collection occurred from October 5, 2014, through October 9, 2014, at 17 specified gage locations and one NGS cooperative base network control station (figs. 1 and 3). The exact start and end dates and times for each GNSS unit are available in table 2; GNSS units were deployed to provide as much simultaneous data collection time as possible among all surveyed stations. The log files from the GNSS surveys are available electronically in Appendix 1.

Table 2. Summary of collected satellite data for all reference marks surveyed in this study.

[Map number, number assigned to represent the corresponding station number in map figures; Station number, unique identifier representing a streamgage; Reference mark, a stable point used to set water levels at gages with a known elevation; Levels used, distinguishes whether elevations were determined using surveyor level loops or measured directly; Yes, surveyor level loops were used to determine elevation from a directly measured point; No, elevations of reference marks were measured directly; Latitude, the latitude of the point where satellite data were collected; Longitude, the longitude of the point where satellite data were collected; deg min sec, the units of latitude and longitude data presented in the table; Start date, the date that recording of satellite data began for each station; Start time, the 24-hour clock time when recording of satellite data began; End date, the date that recording of satellite data ended; End time, the 24-hour clock time when recording of satellite data ended on the end date; Total time, the amount of time satellite data were collected at each station]

Map number	Station number	Reference mark	Levels used	Latitude	Longitude	Start date	Start time	End date	End time	Total time
			(Yes/No)	(deg min sec)	(deg min sec)	(2014)	(h:mm:ss)	(2014)	(h:mm:ss)	(h:mm:ss)
1	05PC021	NO12005	No	N 48 43 02.520104	W 94 33 54.556827	6-Oct	18:42:00	8-Oct	8:17:30	37:35:30
2	05133500	BM3	Yes	N 48 38 02.534415	W 93 54 47.940021	6-Oct	17:08:30	8-Oct	17:54:00	48:45:30
4	05PB007	NO93003	No	N 48 38 58.942833	W 93 19 20.921147	6-Oct	13:42:00	8-Oct	16:17:30	50:35:30
5	05PB023	NO12003	No	N 48 50 28.286011	W 93 37 22.901368	6-Oct	20:56:30	8-Oct	17:29:30	44:33:00
6	05PB024	NO88001	No	N 48 42 01.427456	W 92 57 30.802871	5-Oct	19:43:00	7-Oct	4:07:00	32:24:00
6	05PC024	NO11025	No	N 48 36 49.876695	W 93 21 17.603111	6-Oct	14:21:00	9-Oct	14:09:30	67:48:30
7	05PB014	NO57002	No	N 48 50 51.618241	W 92 43 22.000848	5-Oct	18:23:00	8-Oct	14:38:00	68:15:00
9	05PA013	NO07018	Yes	N 48 29 48.742609	W 92 39 32.483232	6-Oct	19:29:00	8-Oct	15:44:30	44:15:30
10	05129290	RP2	Yes	N 48 31 27.112602	W 93 04 31.294569	7-Oct	14:56:30	9-Oct	17:50:00	50:53:30
11	482611092483801	RP1	Yes	N 48 26 09.541587	W 92 48 36.504720	6-Oct	22:14:00	8-Oct	4:19:30	54:05:30
13	482147092291701	RP2	Yes	N 48 21 46.914481	W 92 29 16.915979	6-Oct	16:48:00	8-Oct	14:48:00	46:00:00
14	482042092282501	RM1	Yes	N 48 20 42.130103	W 92 28 25.414322	6-Oct	16:24:30	8-Oct	13:20:30	44:56:00
15	CNLM5	CLA	Yes	N 48 16 10.199537	W 92 28 18.875512	6-Oct	21:13:30	8-Oct	17:47:30	44:34:00
16	481818092254201	RM2	Yes	N 48 18 19.235258	W 92 25 43.755946	6-Oct	19:34:30	8-Oct	15:17:00	43:42:30
17	05129115	RM1	Yes	N 48 15 54.690527	W 92 33 54.523384	7-Oct	15:13:00	8-Oct	20:10:00	28:57:00
18	AC4984	GREG	No	N 48 15 09.726161	W 92 29 14.965549	7-Oct	14:13:30	8-Oct	19:48:00	29:34:30

Field data-collection procedures used during the survey followed current guidelines established for static network surveys as described by compatible methods from NRCan (Canadian Geodetic Survey, 2003; Canadian Geodetic Survey, 2013) and USGS (Rydlund and Densmore, 2012). When a clear view of the sky was possible, GNSS units were deployed directly above existing reference marks used to establish water levels at gage locations. However, at locations where a clear view of the sky was obstructed by tree cover or topographical relief, GNSS units were deployed nearby to improve the quality of satellite signal reception and reduce satellite signal multipath. Multipath is a condition in which the accuracy of collected satellite data diminishes because the satellite signal arrives at the receiver antenna by way of several different paths (Georgiadou and Kleusberg, 1988). Bodies of water can create reflective surfaces that cause multipath issues. For view-obstructed locations where reference marks could not be surveyed directly, surveyor level loops (also referred to as spirit level circuits) were used to accurately measure elevation differences between points surveyed with GNSS and gage reference marks (Kenney, 2010; Canadian Geodetic Survey, 2013). Instantaneous water levels were obtained at each station using either readings from operating gages (http://waterdata.usgs.gov/mn/nwis/rt; http://www.mvp-wc.usace.army.mil/dcp/; http://wateroffice.ec.gc.ca/) or direct measurement from a reference mark using surveyor level loops.

Data Processing

Elevations as defined by ellipsoid, geoid, and orthometric heights are all attempts to model the shape of the earth using real world coordinates. An ellipsoid is a spherical shape with a polar radius that is shorter in length than the equatorial radius, and the overall shape of the Earth is best predicted using an ellipsoid (Li and Gotze, 2001; GISTutor, 2015). Ellipsoid heights are offsets above or below a reference ellipsoid. A geoid is a model that represents the Earth's mean global sea level under the influence of gravitation and rotation alone (Milbert and Smith, 1996; GISTutor, 2015), and each vertical datum is associated with a particular geoid. Geoid heights are applied to ellipsoid heights to obtain orthometric heights, which refer to elevations above sea level referenced to the vertical datum associated with the geoid model.

Both NRCan and USGS post-processed GNSS data collected in receiver independent exchange (RINEX) format independently using different methods in order to provide a quality comparison. The reference frames used by Canada [NAD83; Canadian Spatial Reference System (CSRS)] and the United States (NAD83, 2011) are compatible and equivalent for the purposes of this study. Satellite data were processed by NRCan staff using Bernese GNSS Software (BSW) v5.2 (Piraszewski, 2006; Dach and others, 2007; Dach and Walser, 2015), a relative positioning method whereby coordinated differences between pairs of points (baselines) are computed (hereafter referred to as the NRCan method). Although BSW is capable of processing data from the Russian Global Orbiting Navigation Satellite System (GLONASS), GLONASS data were not processed in this study. Using BSW, three-dimensional coordinates (latitude, longitude, and ellipsoid heights) were determined for the reference marks in the geometric reference frame of NAD83 (CSRS) Velocity Grid v6 for epoch 2010.0.

Data from four Canadian active control system (CACS) stations were included to provide a connection to the NAD83 reference frame and the International Terrestrial Reference Frame (ITRF) in order to obtain specific coordinates; CACS stations included ALGO (Algonquin Park, Ontario), DUBO (Lac Du Bonnet, Manitoba), FLIN (Flin Flon, Manitoba), and PICL (Pickle Lake, Ontario). The CACS stations are shown in figure 3, and the location information associated with CACS stations is shown in table 3. Seven other CACS stations and NGS continuously-operating reference stations (CORS) were included as local quality-control points; however, a significant portion of available data from these stations could not be used because signal obstructions prohibited common satellites from being in view at both ends of the baseline. Session baselines from BSW were corrected for relative crustal motion between the observation epoch and the 2010.0 reference epoch using the adopted NAD83 (CSRS) Velocity Grid v6 (Craymer and others, 2011). Such crustal motions between local stations and CACS stations that are much farther away can affect reference frame realization significantly. Estimated session baselines were combined into a network adjustment using NRCan's GHOST software (Beattie, 1987), and CACS stations were weighted to known NAD83 (Canadian Spatial Reference System) Velocity Grid v6 coordinates at epoch 2010.0 using known accuracies. The Canadian Gravimetric Geoid model of 2013 (CGG2013) was applied to post-processed ellipsoid heights to obtain orthometric heights referenced to CGVD2013 (Huang and Veronneau, 2013; Veronneau and others, 2014a and 2014b).

Table 3. Location information for one National Geodetic Survey cooperative base network control station, four Canadian Active Control Stations, and ten Continuously-Operating Reference Stations.

[Map number, numerical identifier that corresponds with a number on the map in figure 2; Station ID, alpha-numeric descriptor assigned to each station; Station location, nearest city and state/province associated with each station; Minn., Minnesota; Latitude, the latitude associated with each station, in degrees/minutes/seconds; Longitude, the longitude associated with each station, in degrees/minutes/seconds]

Map number	Station ID	Station location	Latitude	Longitude
18	AC4984	Crane Lake, Minn.	N 48 15 09.72616	W 92 29 14.96555
19	ALGO	Algonquin Park, Ontario	N 45 57 20.84731	W 78 04 16.90648
20	DUBO	Lac Du Bonnet, Manitoba	N 50 15 31.68253	W 95 51 58.20777
21	FLIN	Flin Flon, Manitoba	N 54 43 32.07415	W 101 58 40.86832
22	PICL	Pickle Lake, Ontario	N 51 28 47.27895	W 90 09 43.06934
23	GDMA	Grand Marais, Minn.	N 47 44 54.75711	W 90 20 28.47144
24	MNAS	Ash Lake, Minn.	N 48 17 38.54626	W 92 58 13.42650
25	MNBD	Birchdale, Minn.	N 48 37 39.67691	W 94 04 02.15729
26	MNMG	Margie, Minn.	N 48 08 04.54490	W 93 52 42.50778
27	MNRV	Roosevelt, Minn.	N 48 47 21.79724	W 95 03 04.45950
28	MNSQ	Squaw Lake, Minn.	N 47 36 13.44132	W 94 07 36.20907
29	MNVI	Virginia, Minn.	N 47 31 23.77164	W 92 33 41.43356
30	MNWH	Waskish, Minn.	N 48 09 00.63600	W 94 30 42.99689
31	ROSS	Rossport, Ontario	N 48 50 01.39381	W 87 31 10.52238
32	YWG1	Winnipeg, Manitoba	N 49 54 02.06942	W 97 15 33.82364

The USGS post-processed GNSS data through the NGS Online Positioning Users Service (OPUS; National Geodetic Survey, 2014a), a service that uses the NGS PAGES processing software (National Geodetic Survey, 2015a), with baseline processing methodology similar to BSW (hereafter referred to as the USGS method). Using OPUS-Projects (National Geodetic Survey, 2014b), a network adjustment was applied to all reference marks by using 10 continuously-operating reference stations (CORS; National Geodetic Survey, 2014c) to define the NAD83 (2011) reference frame in epoch 2010.0; CORS used in the network adjustment included GDMA (Grand Marais, Minn.), MNAS (Ash Lake, Minn.), MNBD (Birchdale, Minn.), MNMG (Margie, Minn.), MNRV (Roosevelt, Minn.), MNSQ (Squaw Lake, Minn.), MNVI (Virginia, Minn.), MNWH (Waskish, Minn.), ROSS (Rossport, Ontario), and YWG1 (Winnipeg, Manitoba; National Geodetic Survey, 2014c). The CORS used in the network adjustment are shown in figure 3, and information associated with CACS stations is shown in table 3.

Using the USGS method, known geodetic-quality coordinates were established for each reference mark (Rydlund and Densmore, 2012); coordinate information for each reference mark includes NAD83 [2011 epoch 2010.00], latitude, longitude, and ellipsoid heights (National Geodetic Survey, 2012a). Geoid model 12A (National Geodetic Survey, 2015b) was applied to post-processed ellipsoid heights to obtain orthometric heights referenced to the North American Vertical Datum of 1988 (NAVD88; Zilkoski and others, 1992). However, after processing session baselines, more than half of the available data were omitted by OPUS based on an automated data quality criteria established by the NGS. As a result, as little as 13 hours of data were used to process session baselines for some reference marks. In addition, MNAS, MNBD, MNMG, MNRV, MNSQ, and MNWH have modeled velocities that do not include vertical velocities. Therefore, corrections for vertical crustal motion cannot be applied uniformly across the area covered by the CORS for data processed in OPUS-Projects by the

USGS. In contrast, processing completed by NRCan using BSW included corrections for vertical crustal motion applied to all processed baselines and estimated coordinates.

As an additional measure of quality control, NRCan processed data using Precise Point Positioning (PPP; Kouba and Héroux, 2001) and the NGS Online Positioning Users Service (OPUS; National Geodetic Survey, 2014a). Processing completed using OPUS was similar to the USGS method, but NRCan purposely prevented OPUS from omitting data based on satellite signal quality thresholds. However, unlike the USGS method, PPP directly computes absolute coordinates using undifferenced carrier phase observations. The PPP technique uses high-accuracy satellite orbits and clocks from the International GNSS Service to avoid forming baselines. Using PPP, adjustments and processing of baselines to other known stations are unnecessary, resulting in more efficient data processing. In addition, PPP uses all available data. In contrast, the baseline processing method used by BSW and OPUS only can use common satellites in view at both ends of the baselines, which results in fewer observations being used, especially when there are obstructions to a clear view of the sky. Results of PPP processing were obtained in ITRF (2008), transformed to NAD83 (CSRS) using the adopted model of Craymer (2006), and corrected for vertical crustal motion using the NAD83 (CSRS) Velocity Grid v6 (Craymer and others, 2011).

Development of Gage Datum Offsets

Orthometric heights obtained from processing collected GNSS data were used to develop offsets that convert published water levels to elevations referenced to CGVD2013, either through direct gage reference mark surveys or surveyor level loops between surveyed points and gage reference marks. Offsets are based on published water levels, so the magnitude of each offset depends on whether water levels are published as actual elevations or as local datums that allow smaller numbers to be used for publication. For example, USGS station 05129290 (map number 10; Gold Portage Outlet from

Kabetogama Lake near Ray, Minnesota) was established referencing the United States Coast and Geodetic Survey Datum of 1912; however, water levels are published as elevations minus 1,100 feet (U.S. Geological Survey, 2015). Therefore, the offset for USGS station 05129290 will be much larger compared to the offset for USACE station CNLM5 (map number 15; Crane Lake at Crane Lake, Minnesota), which are published as elevations referenced to 1912 Mean Sea Level (MSL) datum (http://www.mvp-wc.usace.army.mil/dcp/). Offsets are presented in metric and English units. The vertical datums used to establish water levels for gages examined in this study are presented in table 1.

Application of Gage Datum Offsets

Gage datum offsets were applied to surveyed gages, and water-surface elevations referenced to CGVD2013 were compared among active gages in Namakan Reservoir, Rainy Lake, and the Vermilion, Turtle, and Rainy Rivers. In addition, because there were four temporary gage stations surveyed in Namakan Reservoir that were discontinued (fig.1, table 1), the time period from May 1, 2012 through September 30, 2012 was used to compare water-surface elevations among gages. This period represents the last period when all active and discontinued gages in Namakan Reservoir operated simultaneously. Monthly mean water-surface elevations (referenced to CGVD2013) were compared among all gages in Namakan Reservoir in order to average variability in the data associated with the temporary installations at discontinued gages.

Results

Results are divided into two main sections. First, general results of GNSS surveys are presented. In the second section (Survey Comparisons), offsets developed from surveys presented in this report are applied to collected water-level data in order to compare water-surface elevations referenced to CGVD2013 among gages.

Global Navigation Satellite System Surveys

Deployment times for GNSS units ranged from 29 to 68 hours, with an average deployment time of 46 hours. Satellite data quality was generally good during the GNSS surveys. Despite the best efforts of the field crews to find locations with a clear view of the sky, steep terrain and dense tree cover surrounding some of the gage locations interfered with satellite coverage during certain times of the day. In addition, proximity of the GNSS units to the water surface created multipath issues that had to be accounted for during data processing. Surveyor level loops between GNSS survey points and reference marks of known elevation likely introduced a small amount of error (less than or equal to 0.005 meters) into the elevation data. During the time of the surveys, wind gusts ranged from 25-40 miles per hour (www.windfinder.com), so wind and wave action likely affected instantaneous water level measurements at the temporary gages. However, variability associated with wind was not quantified.

Four methods of processing collected satellite data were evaluated prior to selecting a method to use for developing gage datum offset corrections. Data processing files can be found in Appendix 2. All four methods produced comparable results, and a comparison of ellipsoid heights using all four processing methods can be found in table 4. The measured ellipsoid and orthometric heights of 17 survey locations processed using NRCan and USGS methods are presented in table 5 using standard geoids and vertical datums of Canada (geoid CGG2013, CGVD2013 datum) and the United States (geoid 12A, NAVD88 datum), respectively. Table 5 does not include survey results for USGS station 482626092302001 (map number 12; Namakan Lake below Namakan Narrows near Crane Lake, Minnesota) because the data card was damaged during the retrieval of the GNSS unit, and satellite data could not be recovered. Station 482626092302001 was a temporary gage used to collect one open-water season of data on Namakan Lake. However, water-surface elevations for Namakan Lake still can be obtained from the active water-level gage on Squirrel Island (map number 9; station 05PA013).

The NAD83 ellipsoid heights obtained using NRCan and USGS processing methods closely approximated each other (table 5) even though the USGS method did not include application of corrections for vertical crustal motion to processed baselines or estimated coordinates; corrections for vertical crustal motion may be ± 0.003 meters per year depending on the location within the study area (Henton and others, 2006; Craymer, 2006; Snay and Pearson, 2010). Ellipsoid heights obtained using USGS methods generally were higher than ellipsoid heights obtained using NRCan methods. Differences between methods ranged from -0.003 to +0.045 meters, with a mean difference of 0.011 meters. Furthermore, determined ellipsoid heights for NGS cooperative base network control station AC4984 (map number 18) closely approximate published values (National Geodetic Survey, 2015c). An ellipsoid height of 344.633 meters was determined for AC4984 during the last static GNSS survey done by the NGS in 1996 (National Geodetic Survey, 2015). Ellipsoid heights of AC4984 determined using NRCan and USGS processing methods were 344.628 meters and 344.632 meters, respectively. Offsets were developed using GNSS survey elevations and surveyor leveling information (Appendix 3).

A summary of calculated gage offset corrections is presented in table 6. Because Canada recently adopted a national reference standard for elevations (Veronneau and others, 2014a; Veronneau and others, 2014b) that is based on a geoid model and compatible with GNSS positioning, the NRCan method was selected over the USGS method for developing offsets between published gage water levels and elevations referenced to CGVD2013. Furthermore, elevations referenced to CGVD2013 will be useful to other ongoing studies being conducted by NRCan. Instantaneous water-level measurements in published gage format and instantaneous water-surface elevations in CGVD2013 are available in Appendix 3. Subsequent comparisons of water-surface elevations among gages will be referenced to CGVD2013 and presented in metric units (meters).

Table 4. Summary of ellipsoid heights obtained for 17 surveyed reference marks using four different processing methods; all values are presented in meters.

[Map number, number assigned to represent the corresponding station number in the map figures; Station number, unique identifier representing a streamgage; BSW, Bernese Software v5.2; OPUS_USGS, processing done by the U.S. Geological Survey using the Online Positioning Users Service; PPP, Precise Point Positioning; OPUS_NRCan, processing done by Natural Resources Canada using the Online Positioning Users Service; Mean, average difference between results using compared methods; StDev, standard deviation of the average difference between results using compared methods]

Map number	Station number	BSW	OPUS_USGS	PPP	OPUS_NRCan	OPUS_USGS - BSW	PPP - BSW	OPUS_NRCan - BSW	OPUS_NRCan - OPUS_USGS
1	05PC021	296.952	296.959	296.963	296.963	0.007	0.011	0.011	0.004
2	05133500	311.001	310.998	311.011	311.006	-0.003	0.010	0.005	0.008
3	05PC024	307.964	307.972	307.974	307.975	0.008	0.010	0.011	0.003
4	05PB007	309.039	309.041	309.045	309.057	0.002	0.006	0.018	0.016
5	05PB023	307.412	307.424	307.433	307.428	0.012	0.021	0.016	0.004
6	05PB024	306.839	306.848	306.853	306.859	0.009	0.014	0.020	0.011
7	05PB014	315.727	315.714	315.708	315.725	-0.013	-0.019	-0.002	0.011
8	SRFN1	307.101	307.110	307.111	307.118	0.009	0.010	0.017	0.008
9	05PA013	319.136	319.163	319.156	319.164	0.027	0.020	0.028	0.001
10	05129290	309.624	309.646	309.656	309.646	0.022	0.032	0.022	0.000
11	482611092483801	311.975	311.989	311.976	311.981	0.014	0.000	0.006	-0.008
13	482147092291701	309.554	309.599	309.614	309.602	0.045	0.060	0.048	0.003
14	482042092282501	315.242	315.259	315.267	315.263	0.017	0.025	0.021	0.004
15	CNLM5	311.226	311.234	311.230	311.241	0.008	0.004	0.015	0.007
16	481818092254201	309.788	309.785	309.805	309.796	-0.003	0.017	0.008	0.011
17	05129115	326.747	326.773	326.775	326.775	0.026	0.028	0.028	0.002
18	AC4984	344.628	344.632	344.637	344.643	0.004	0.009	0.015	0.011
					Mean	0.011	0.015	0.017	0.006
					StDev	0.014	0.016	0.011	0.006

Table 5. Global Navigation Satellite System reference mark survey results processed using Natural Resources Canada and U.S. Geological Survey methods.

[Map number, number assigned to represent the corresponding station number in map figures; Station number, identifier for a particular gage; Station name, description associated with a station number; NRCan, results processed using Natural Resources Canada method; USGS, results processed using the U.S. Geological Survey method; Ellipsoid height, surveyed height determined when an ellipsoid model is fit to satellite data to account for the shape of the Earth; m, meters; CGG2013, correction for the Canadian gravimetric geoid model of 2013; Orthometric Height, height above sea level and elevation referenced to the vertical datum corresponding to the applied geoid; 12A, correction for geoid model 12A]

Map number	Station number	Station name	NRCan			USGS		
			Ellipsoid height (m)	CGG2013 (m)	Orthometric height (m)	Ellipsoid height (m)	12A (m)	Orthometric height (m)
1	05PC021	Rainy River at Rainy River	296.952	28.295	325.247	296.959	29.077	326.036
2	05133500	Rainy River at Manitou Rapids, Minnesota	311.001	29.028	340.029	310.998	29.792	340.790
3	05PC024	Rainy River at Pithers Point Site No. 1	307.964	30.013	337.977	307.972	30.817	338.789
4	05PB007	Rainy Lake Near Fort Frances	309.039	30.130	339.169	309.041	30.920	339.961
5	05PB023	Rainy Lake at Northwest Bay	307.412	29.962	337.374	307.424	30.743	338.167
6	05PB024	Rainy Lake Near Bear Pass	306.839	30.796	337.635	306.848	31.561	338.409
7	05PB014	Turtle River Near Mine Centre	315.727	31.302	347.029	315.714	32.062	347.776
8	SRFN1	Seine River First Nation biological site	307.101	31.636	338.737	307.110	32.374	339.484
9	05PA013	Namakan Lake at Squirrel Island	319.136	30.915	350.051	319.163	31.684	350.847
10	05129290	Gold Portage Outlet from Kabetogama Lake Near Ray, Minnesota	309.624	30.361	339.985	309.646	31.151	340.797
11	482611092483801	Kabetogama Lake, East End, Near Old Dutch Bay	311.975	30.584	342.559	311.989	31.366	343.355
13	482147092291701	Sand Point Lake Below Harrison Narrows Near Crane Lake, Minnesota	309.554	30.855	340.409	309.599	31.634	341.233
14	482042092282501	Sand Point Lake Above Harrison Narrows Near Crane Lake, Minnesota	315.242	30.837	346.079	315.259	31.617	346.876
15	CNLM5	Crane Lake at Crane Lake, Minnesota	311.226	30.705	341.931	311.234	31.482	342.716
16	481818092254201	Little Vermilion Lake Above Little Vermilion Narrows	309.788	30.811	340.599	309.785	31.589	341.374
17	05129115	Vermilion River Near Crane Lake, Minnesota	326.747	30.585	357.332	326.773	31.371	358.144
18	AC4984	Cooperative Base Network Control Station	344.628	30.657	375.285	344.632	31.434	376.066

Table 6. Offsets to convert published water levels to water-surface elevations referenced to the Canadian Geodetic Vertical Datum of 2013 for gages in Rainy Lake, Namakan Reservoir, and selected rivers.

[Map number, numerical identifier that corresponds with a number on the map in figure 1; Station number, identifier for a particular streamgage; Station name, description associated with a station number; Agency, the agency responsible for operating the corresponding streamgage; EC, Environment Canada; USGS, U.S. Geological Survey; USACE, U.S. Army Corps of Engineers; Published data type, descriptor of type of water-level data published at a streamgage; Elevation, water levels are published as elevations referenced to a previously-specified vertical datum; Local datum, an arbitrary datum used to simplify data display when publishing water-level data for streamgages; Published units, the units used in publishing water-level data online for each streamgage; Offset, the value to be added or subtracted to water-level data to convert published streamgage data to elevations in Canadian Geodetic Vertical Datum of 2013]

Map number	Station number	Station name	Agency	Published data type	Published units	Offset	
						meters	feet
1	05PC021	Rainy River at Rainy River	EC	Elevation	meters	-0.361	-1.18
2	05133500	Rainy River at Manitou Rapids, Minnesota	USGS	Local Datum	feet	+323.499	+1,061.35
3	05PC024	Rainy River at Pithers Point Site No. 1	EC	Elevation	meters	-0.637	-2.09
4	05PB007	Rainy Lake Near Fort Frances	EC	Elevation	meters	-0.608	-1.99
5	05PB023	Rainy Lake at Northwest Bay	EC	Local Datum	meters	+328.315	+1,077.15
6	05PB024	Rainy Lake Near Bear Pass	EC	Elevation	meters	-0.599	-1.97
7	05PB014	Turtle River Near Mine Centre	EC	Local Datum	meters	+344.176	+1,129.19
9	05PA013	Namakan Lake at Squirrel Island	EC	Elevation	meters	-0.613	-2.01
10	05129290	Gold Portage Outlet from Kabetogama Lake Near Ray, Minnesota	USGS	Local Datum	feet	+334.701	+1,098.10
11	482611092483801	Kabetogama Lake, East End, Near Old Dutch Bay	USGS	Local Datum	feet	+334.384	+1,097.06
13	482147092291701	Sand Point Lake Below Harrison Narrows Near Crane Lake, Minnesota	USGS	Elevation	feet	-0.820	-2.69
14	482042092282501	Sand Point Lake Above Harrison Narrows Near Crane Lake, Minnesota	USGS	Elevation	feet	-0.802	-2.63
15	CNLM5	Crane Lake at Crane Lake, Minnesota	USACE	Elevation	feet	-0.597	-1.96
16	481818092254201	Little Vermilion Lake Above Little Vermilion Narrows	USGS	Elevation	feet	-0.808	-2.65
17	05129115	Vermilion River Near Crane Lake, Minnesota	USGS	Local Datum	feet	+352.769	+1,157.38

Survey Comparisons

Namakan Reservoir

Active gages for Namakan Reservoir are located at Crane Lake (map number 15; station CNLM5), the Gold Portage outlet of Kabetogama Lake (map number 10; station 05129290), and Squirrel Island near the outlet of Namakan Lake (map number 9; station 05PA013). Boxplots of water-surface elevations (referenced to CGVD2013) for the data collection period (October 5-9, 2014) at the active gages in Namakan Reservoir are presented in figure 4. Using gage datums (fig. 4a), water-surface elevations at Crane Lake and Squirrel Island (Namakan Lake) are similar and higher than water-surface elevations at the Gold Portage outlet of Kabetogama Lake. In contrast, using elevations in CGVD2013 (fig. 4b), water-surface elevations are similar and lower at Squirrel Island and Gold Portage compared to water-surface elevations at Crane Lake. The gages at Squirrel Island and Gold Portage represent the two major outlets that flow from Namakan Reservoir into Rainy Lake, and the gage at Crane Lake represents the most upstream end of Namakan Reservoir. Increased differences between the upper and lower ends of Namakan Reservoir and increased similarity between the major outlets from Namakan Reservoir make more hydrologic sense than the water-surface elevation differences observed using gage datums.

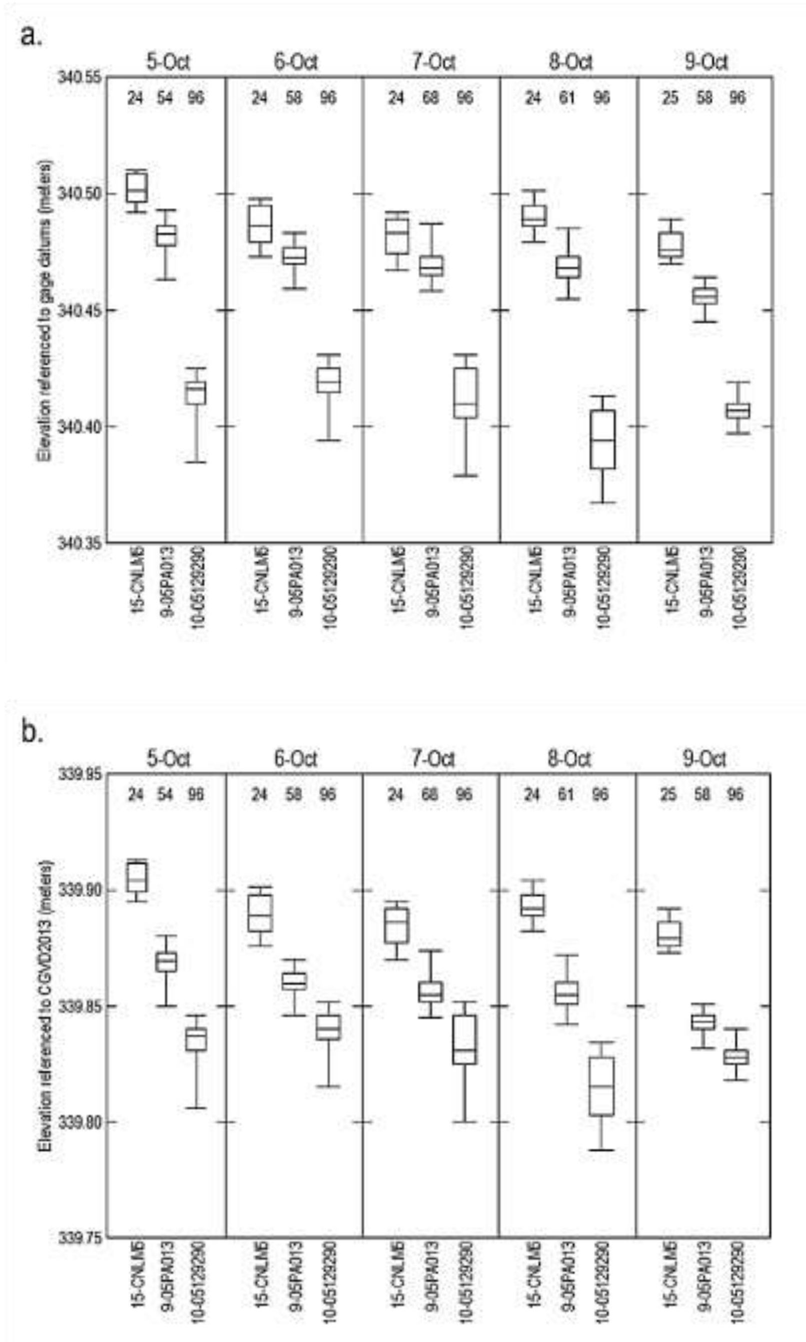
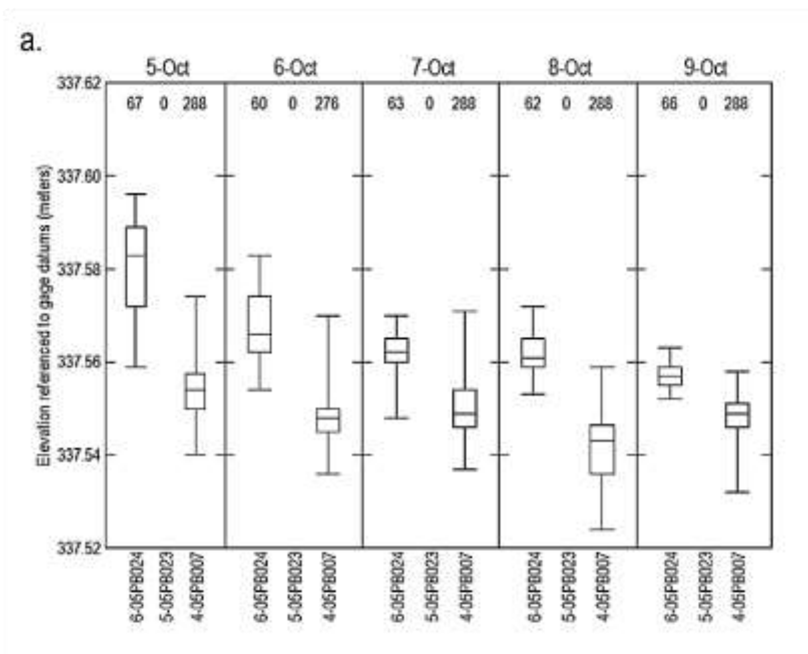


Figure 4. Boxplots of water-surface elevation data referenced to (a) gage datums and (b) the Canadian Geodetic Vertical Datum of 2013 for the data collection period (October 5-9, 2014) at active gages in Namakan Reservoir, which are identified using map and station numbers associated with data in table 1; numbers inside boxes represent the number of measured data points available for each gage.

Rainy Lake

Active gages in Rainy Lake are located at Bear Pass (map number 6; station 05PB024), Northwest Bay (map number 5; EC station 05PB023), and Fort Frances (map number 4; station 05PB007). Boxplots of water-surface elevations (in gage datum and CGVD2013) for the data collection period (October 5-9, 2014) at the active gages in Rainy Lake are presented in figure 5. Because the gage at Northwest Bay (map number 5; station 05PB023) uses an assumed datum without a correction to a known elevation datum, gage datum elevations could not be visually compared in an effective manner. Therefore, the gage at Northwest Bay (map number 5; station 05PB023) was excluded from figure 5a but included in figure 5b. Mean water elevations during the data collection period were similar among all three gages.



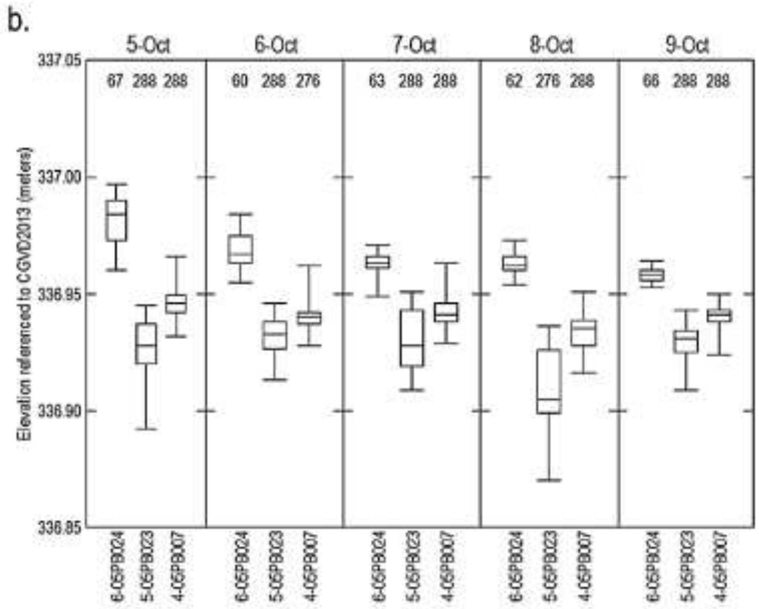


Figure 5. Boxplots of water-surface elevation data referenced to (a) gage datums and (b) the Canadian Geodetic Vertical Datum of 2013 for the data collection period (October 5-9, 2014) at active gages in Rainy Lake, which are identified using map and station numbers associated with data in table 1; 5-05PB023 was excluded from (a) because the arbitrary local datum was much lower than the vertical elevation datums used at other gages; numbers inside boxes represent the number of measured data points available for each gage.

Rivers

Rivers with active gages that were surveyed in this study include the Vermilion, Turtle, and Rainy Rivers. Mean daily water-surface elevations (in CGVD2013) for active river gages surveyed in this study are presented in figure 6. The Vermilion River near Crane Lake, Minnesota (map number 17; station 05129115) and the Turtle River near Mine Centre (map number 7; station 05PB014) represent inflow gages to Namakan Reservoir and Rainy Lake, respectively. Water-surface elevations at the inflow gages are substantially higher than the water-surface elevations of Namakan Reservoir (fig. 4) and Rainy Lake (fig. 5). Starting at the outlet of Rainy Lake and moving downstream towards Lake of the Woods, Rainy River gages were surveyed at Pithers Point (map number 3; station 05PC024), Manitou Rapids (map number 2; station 05133500), and the town of Rainy River, Ontario (map number 1; station 05PC021). Water-surface elevation at the outlet of Rainy Lake (map number 3; station 05PC024) was slightly lower in elevation than Rainy Lake (fig. 6), and there was a substantial drop in elevation from Pithers Point (map number 3; station 05PC024) to Manitou Rapids (map number 2; station 05133500). A smaller drop in elevation was observed between Manitou Rapids (map number 2; 05133500) and the town of Rainy River, Ontario (map number 1; station 05PC021).

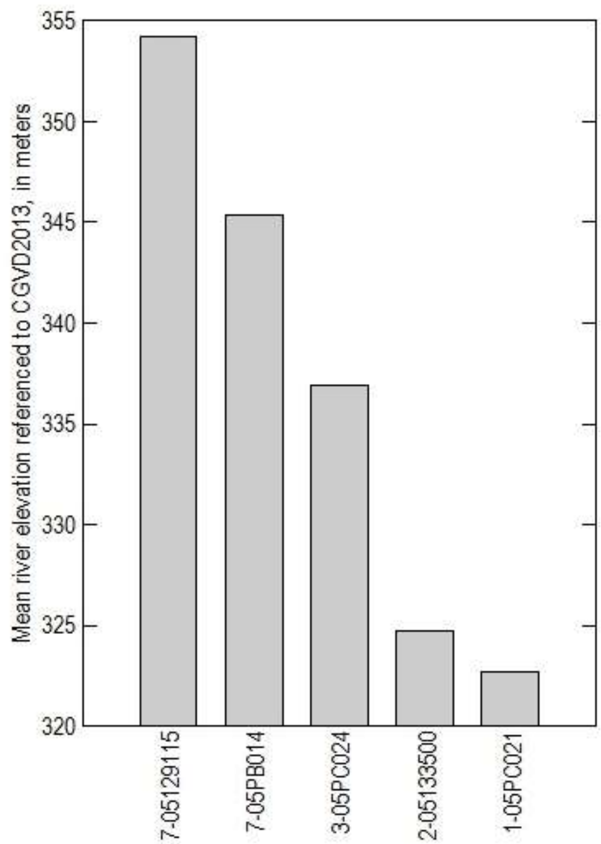


Figure 6. Mean daily water-surface elevations using the Canadian Geodetic Vertical Datum of 2013 for the data collection period (days of year 278-282) at the continuous streamgages on the Vermilion (map number 17; station 05129115), Turtle (map number 7; station 05PB014), and Rainy (map numbers 2 and 3; stations 05133500 and 05PC021) rivers; gages are identified using map and station numbers associated with data in table 1.

2012 Namakan Reservoir Data

Because some surveyed gages were discontinued, mean monthly water-level data collected in 2012 were compared for all active and discontinued gages in Namakan Reservoir (fig. 1, table 1). Monthly mean water-surface elevations in CGVD2013 for May through September of 2012 are presented in figure 7. Elevations generally decrease from upstream to downstream, with the most notable exception being the discontinued index-velocity gage used to measure flow between Namakan and Kabetogama Lakes (map number 11; station 482611092483801). In addition, water-surface elevations for the temporary gage at Sand Point Lake below Harrison Narrows (map number 13; station 482147092291701) appear to be lower than elevations at the outlet gages at Squirrel Island (map number 9; station 05PA013) and Gold Portage (map number 10; station 05129290).

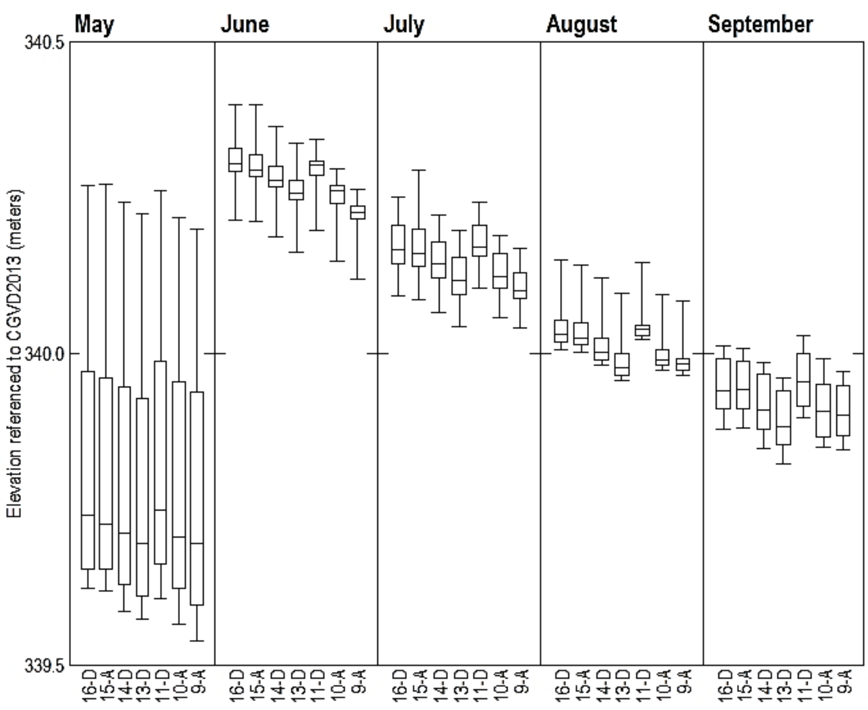


Figure 7. Mean monthly elevations of all active (-A) and discontinued (-D) gages in Namakan Reservoir during the open water period of 2012 converted from gage datums to the Canadian Geodetic Vertical Datum of 2013 using the offsets presented in table 6; gages are identified using map numbers associated with data in table 1.

The observed water levels at discontinued gages 482611092483801 (map number 11) and 482147092291701 (map number 13) do not make sense hydrologically given the direction of flowing water. A time mismatch could have occurred when programming the water levels into the transducers based on a measurement from a reference point of known elevation. During windy and wavy conditions, water levels can vary by as much as ± 0.060 m (U.S. Geological Survey, 2015), and there is a delay associated with programming water levels into the transducers. If the measurement from a reference point occurs during the trough of the waves and is applied to the transducer during the peak of the waves, then the transducer readings will read consistently low. Similarly, if the measurement from a reference point occurs during the peak of the waves and is applied to the transducer during the trough of the waves, then the transducer will read consistently high.

Published daily mean water-surface elevations (referenced to NAVD 88) from 2012 were compared for the two discontinued gages on Sand Point Lake (map numbers 13 and 14; station numbers 482147092291701 and 482042092282501, respectively) to further address the hydrologic discrepancy observed at station 482147092291701 (map number 13; fig. 8). Changes in water levels associated with precipitation and changes in dam regulation track perfectly between the two gages (fig. 8), and water-surface elevations measured manually during site visits that occurred on the same day were identical or demonstrated substantial overlap in observed ranges (U.S. Geological Survey, 2015). These data suggest that a time mismatch did not cause the differences between the two gages observed in figure 7. The observed differences likely are attributable to variability associated with collected satellite data and/or variability in the instantaneous water level measured during the GNSS survey, which was used to develop the offset that corrects collected water-level data to elevations referenced to CGVD2013.

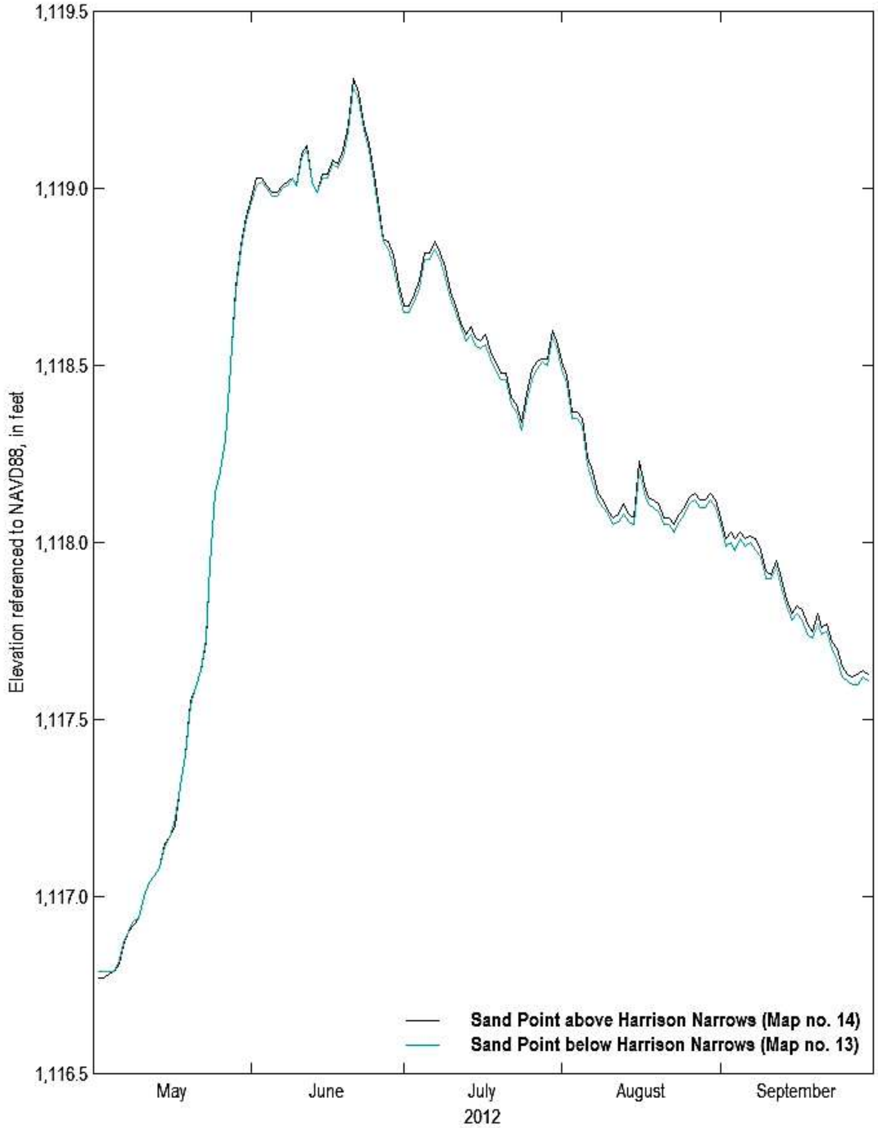


Figure 8. Published mean daily water-surface elevations (referenced to the North American Vertical Datum of 1988) for discontinued U.S. Geological Survey water-level gages on Sand Point Lake above (map number 14; station 482042092282501) and below (map number 13; station 482147092291701) Harrison Narrows (U.S. Geological Survey, 2015).

There is insufficient data to similarly address whether a time mismatch occurred at station 482611092483801 (map number 11). Possible causes for the observed hydrologic discrepancy could include a time mismatch, variability in the collected satellite data, and variability in the instantaneous water level measured during the GNSS survey, which was used to develop the offset that corrects collected water-level data to elevations referenced to CGVD2013. For active gages in Namakan Reservoir, data collected in 2012 (fig. 7) showed a similar pattern to data collected during 2014 surveys when both datasets were corrected to reference CGVD2013 (fig. 4), suggesting that active gages have remained stable over time. Finally, five of the seven surveyed gages (active and discontinued) in Namakan Reservoir demonstrated water-surface elevations that consistently decreased from upstream to downstream when offsets were applied to water-level data collected in 2012.

Conclusions

Precise elevations referenced to a uniform vertical datum (CGVD2013) were obtained for reference marks used in establishing water levels at 16 of the 17 originally-targeted gages. In addition, a precise elevation in CGVD2013 was obtained for an NGS cooperative base network control station of known elevation. Collected elevation data were used to determine offsets that convert published gage water levels to elevations referenced to CGVD2013. Comparisons between previous gage datum water elevations and newly-calculated CGVD2013 water elevations among continuous gages in Namakan Reservoir demonstrate improved accuracy of water elevation data as a result of this study (fig. 3).

Although water-surface elevations corrected to CGVD2013 demonstrated good hydrologic agreement among active gages, some discrepancies were observed among water-surface elevations at discontinued gages. Because discontinued gages were not operating during the time of GNSS surveys, water-surface elevations during the survey only could be measured during site visits by the survey crew; therefore, the effects of wind and wave action on the measured water-surface elevations could not be examined over the duration of GNSS surveys. Caution should be used when applying presented gage offsets to discontinued gages. If discrepancies between water-surface elevations at discontinued gages and active gages demonstrate consistency over time, then data corrections could be applied to water-level data collected at discontinued gages in order to incorporate the data into modeling applications and rule curve evaluations. However, the described analyses are beyond the scope of this report.

Key Findings

1. Precise elevations referenced to CGVD2013 were obtained for 16 reference marks used to establish water levels at active and discontinued gages in the study area
2. A precise elevation referenced to CGVD2013 was not obtained for one discontinued gage (map number 12; station number 462626092302001) because the data card was damaged during retrieval
3. Elevation data obtained for an NGS cooperative base network control station of known elevation closely matched elevation data published in 1996
4. Elevation data were used to develop offsets that correct previously-published gage data to reference a uniform vertical datum (CGVD2013)
5. Comparison of previous and corrected elevations among active gages in Namakan Reservoir indicate improvements in the accuracy of water-elevation data as a result of this study
6. Corrected water-elevation data collected from active and discontinued gages in Namakan Reservoir during 2012 identified hydrologic discrepancies at two discontinued gages (map numbers 11 and 13, station numbers 482611092483801 and 482147092291701)
7. Caution should be used when applying presented gage offsets to discontinued gages
8. Additional surveys may help to (a) resolve hydrologic discrepancies at two discontinued gages and (b) develop an offset for a discontinued gage for which data could not be obtained in this study

Potential Applications of Key Findings

The precision and accuracy of the elevation data presented in this study are suitable for several management applications in the Rainy River Basin. Water-level offset corrections can be used in the evaluation of the 2000 Rule Curves for Rainy Lake and Namakan Reservoir and in flood damage curves that fully assess the benefits of one regulation approach over another. Presented water-level offsets also may provide the information needed to calibrate HEC-RAS models developed by Environment Canada for four narrows that connect the lakes of Namakan Reservoir (Stevenson and Thompson, 2013). Furthermore, improved accuracy of water-surface elevations can enhance a digital elevation model being developed by Environment Canada. Finally, corrected water-surface elevations can benefit other modeling studies designed to assess the effects of the 2000 Rule Curves on aquatic vegetation, benthic invertebrates, northern pike, and walleye.

Results of this study also indicate potential locations for additional data collection. Collected water-surface elevations data indicate that repeating the GNSS survey at USGS temporary gages 482611092483801 and 482147092291701 (map numbers 11 and 13, respectively) may be useful in resolving observed hydrologic discrepancies between these gages and the other gages surveyed for this study. In addition, because the data card was damaged during retrieval of deployed field equipment, no GNSS data was obtained for USGS temporary gage 482626092302001 (map number 12). Therefore, repeating the GNSS survey at this gage would provide the data required to develop an offset that corrects collected water-level data to elevations referenced to CGVD2013.

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Appendices

Appendix 1. Global Navigation Satellite System data collection information for all reference marks surveyed in this study; the appendix is available electronically and is not included in the body of this report.

Appendix 2. Files from processing of raw data collected using global navigation satellite systems; data were processed by Natural Resources Canada and the U.S. Geological Survey, and there is a separate folder for the processing file outputs from each agency; the appendix is available electronically and is not included in the body of this report.

Appendix 3. Surveyor level loop information for stations with reference marks that could not be surveyed directly using global navigation satellite systems; the appendix is available electronically and is not included in the body of this report.