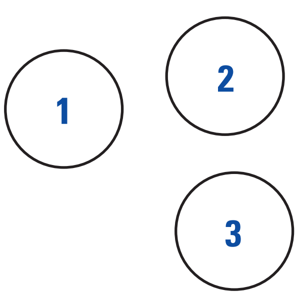
Prepared in cooperation with the New York City Department of Environmental Protection

Bathymetry of Ashokan, Cannonsville, Neversink, Pepacton, Rondout, and Schoharie Reservoirs, New York, 2013–15

Scientific Investigations Report 2017–5064

U.S. Department of the Interior
U.S. Geological Survey



Cover. Background photograph: Schoharie Reservoir, September 2014; (1) U.S. Geological Survey boat on the Schoharie Reservoir; (2) data collection computer at Cannonsville Reservoir; (3) base station and radio antenna.

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By Elizabeth A. Nystrom

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
billion gallons (Ggal)	3,785,000	cubic meter (m^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as °C = (°F – 32) / 1.8.

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

ADCP	acoustic Doppler current profiler
BWS	Bureau of Water Supply
CORS	continuous operating reference station
DEP	Department of Environmental Protection (New York City)
FGDC	Federal Geographic Data Committee
GIS	geographic information system
GNSS	global navigation satellite system
GPS	global positioning system
lidar	light detection and ranging
NAIP	National Agriculture Imagery Program
NOAA	National Oceanic and Atmospheric Administration
NSSDA	National Standard for Spatial Data Accuracy
NYSDOP	New York State Digital Orthoimagery Program
QA	quality assurance
RMSE	root mean square error
RTK–GPS	real-time kinematic global positioning system
TIN	triangulated irregular network
USGS	U.S. Geological Survey
WOH	West of Hudson

Bathymetry of Ashokan, Cannonsville, Neversink, Pepacton, Rondout, and Schoharie Reservoirs, New York, 2013–15

By Elizabeth A. Nystrom

Abstract

Drinking water for New York City is supplied from several large reservoirs, including a system of reservoirs west of the Hudson River. To provide updated reservoir capacity tables and bathymetry maps of the City's six West of Hudson reservoirs, bathymetric surveys were conducted by the U.S. Geological Survey from 2013 to 2015. Depths were surveyed with a single-beam echo sounder and real-time kinematic global positioning system along planned transects at predetermined intervals for each reservoir. A separate quality assurance dataset of echo sounder points was collected along transects at oblique angles to the main transects for accuracy assessment. Field-survey data were combined with water surface elevations in a geographic information system to create three-dimensional surfaces in the form of triangulated irregular networks (TINs) representing the elevations of the reservoir geomorphology. The TINs were linearly enforced to better represent geomorphic features within the reservoirs. The linearly enforced TINs were then used to create raster surfaces and 2-foot-interval contour maps of the reservoirs. Elevation-area-capacity tables were calculated at 0.01-foot intervals. The results of the surveys show that the total capacity of the West of Hudson reservoirs has decreased by 11.5 billion gallons (Ggal), or 2.3 percent, since construction, and the useable capacity (the volume above the minimum operating level required to deliver full flow for drinking water supply) has decreased by 7.9 Ggal (1.7 percent). The available capacity (the volume between the spillway elevation and the lowest intake or sill elevation used for drinking water supply) decreased by 10.0 Ggal (2.1 percent), and dead storage (the volume below the lowest intake or sill elevation) decreased by 1.5 Ggal (9.0 percent).

Introduction

The New York City Department of Environmental Protection (DEP) maintains extensive systems of reservoirs and aqueducts for water collection, storage, and transport; it supplies about 1 billion gallons (Ggal) of drinking water daily to more than 9 million people (New York City Department of Environmental Protection, 2016a). The West of Hudson (WOH) reservoirs, in the Delaware and Hudson River drainage basins in New York State, includes six reservoirs (fig. 1): Ashokan, Cannonsville, Neversink, Pepacton, Rondout, and Schoharie, which were constructed from the early 1900s to the 1960s (table 1) with a combined estimated as-built (original) useable storage capacity of more than 460 Ggal (table 2).

The daily and seasonal management of the WOH reservoirs by DEP depends on accurate bathymetry information in several forms, including the mapped bathymetric surfaces, elevation-area-capacity tables, and bathymetric contours. The surfaces are used in several water-quality models, the elevation-area-capacity tables are used to determine current and available reservoir storage, and contours are used in mapping applications. The bathymetry of the reservoirs was initially determined from topographic maps made before a reservoir was completed, the newest of the WOH reservoirs is now more than 50 years old, and the oldest is more than 100 years old. The most recent systematic bathymetric survey of the WOH reservoirs was completed in 1998 with contour intervals of 16.4 feet (ft). Since the initial filling of the reservoirs, bed morphology has likely changed as a result of sedimentation. To provide updated surface, capacity, and contour data, the U.S. Geological Survey (USGS), in cooperation with New York City DEP, conducted bathymetric surveys of the six WOH reservoirs beginning in 2013. These data are available as separate data releases (Nystrom, 2018a–f).

Purpose and Scope

The purpose of this report is to document the methods of data collection, data-processing techniques, assessment of data accuracy, and results of bathymetric surveys of the six WOH reservoirs conducted by the USGS and New York City DEP between 2013 and 2015. The resulting bathymetric maps are not to be used for navigational purposes.

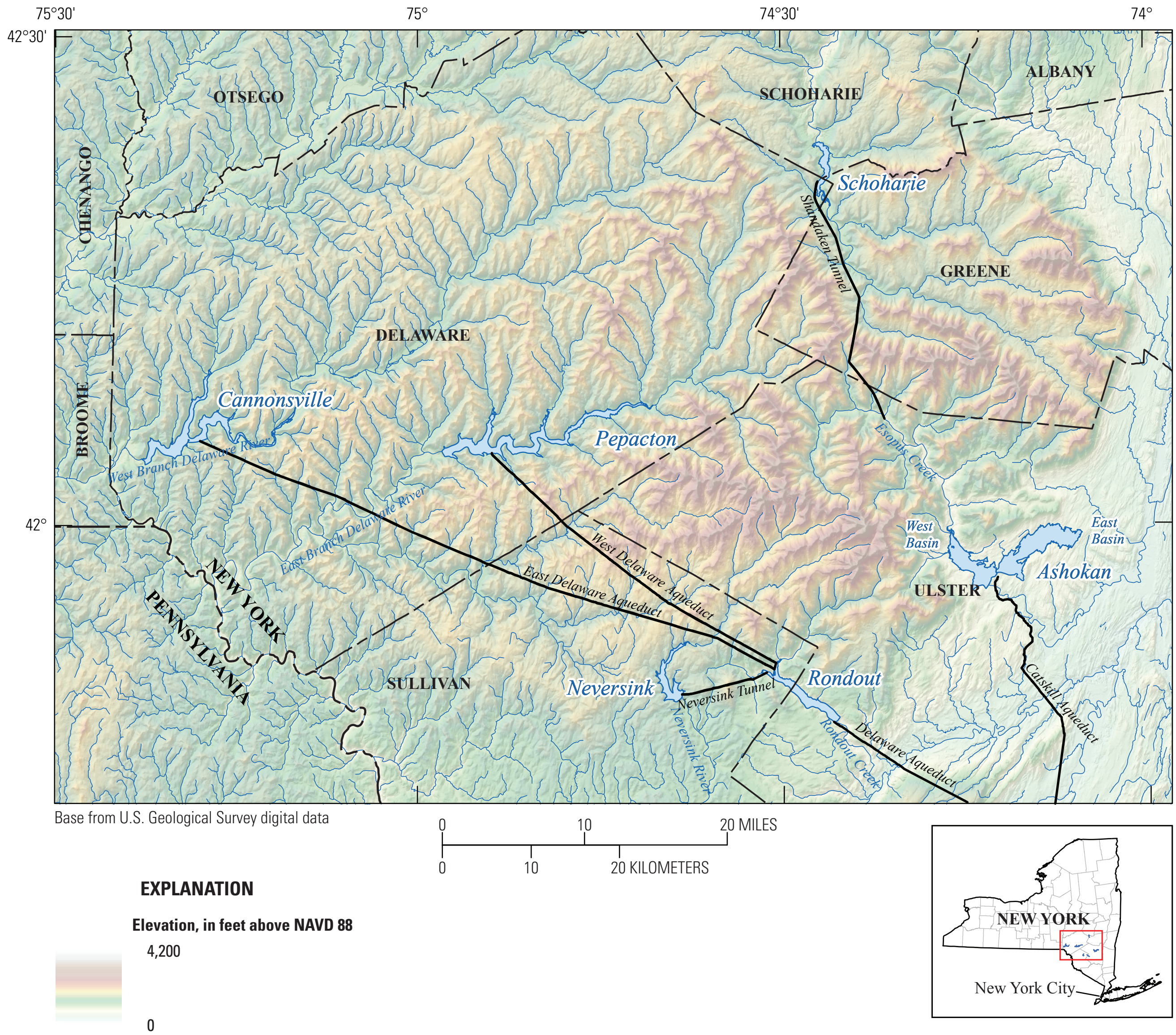

Figure 1. Locations of the West of Hudson reservoirs and connecting aqueducts and tunnels in New York State.

Description of Study Area

The six WOH reservoirs are in Delaware, Greene, Schoharie, Sullivan, and Ulster Counties in upstate New York (fig. 1). Ashokan Reservoir was the first of the WOH reservoirs to be constructed, with storage beginning in 1913 (U.S. Geological Survey, 2016a), and Cannonsville was the last (U.S. Geological Survey 2016b), with storage beginning in 1963 (table 1). Pepacton Reservoir has the largest total capacity of the six WOH reservoirs at approximately 150 Ggal (table 2; U.S. Geological Survey, 2016d) and Schoharie has the smallest at approximately 21 Ggal (U.S. Geological Survey, 2016f). Cannonsville and Pepacton Reservoirs are the longest of the WOH reservoirs, both more than 20 miles long, and Schoharie is the shortest, at slightly more than 5 miles long (table 3).

The WOH reservoirs are grouped into two systems based on the aqueducts that supply New York City. Schoharie and Ashokan Reservoirs are part of the Catskill System, and Cannonsville, Neversink, Pepacton, and Rondout Reservoirs are part of the Delaware System. In the Catskill System, Schoharie Reservoir was formed by damming Schoharie Creek; water from Schoharie Reservoir travels through the Shandaken Tunnel into the Esopus Creek and then into Ashokan Reservoir. Ashokan Reservoir was formed by damming Esopus Creek; the reservoir has two drainage basins (the West Basin and East Basin). Esopus Creek enters the West Basin; water then flows from the West Basin over a dividing weir into the East Basin, where it travels through the Catskill Aqueduct to Kensico

Table 1. Information on West of Hudson reservoirs: U.S. Geological Survey station identifier, year storage began, year in service, and water supply system in New York State.

[Locations of reservoirs shown in figure 1. USGS, U.S. Geological Survey]

Reservoir	USGS station ID	Year storage began[1]	Year in service[2]	Water-supply system
Ashokan	01363400	1913	1915	Catskill
Cannonsville	01424997	1963	1964	Delaware
Neversink	01435900	1953	1954	Delaware
Pepacton	01416900	1954	1955	Delaware
Rondout	01366400	1951	1954	Delaware
Schoharie	01350100	1926	1926	Catskill

[1]Published value from USGS annual summaries (U.S. Geological Survey, 2016a–f).

[2]Published values from New York City Department of Environmental Protection (DEP) watershed protection pages (DEP, 2016b–g).

Reservoir just north of New York City. In the Delaware System, Cannonsville Reservoir was formed by damming the West Branch Delaware River, Pepacton Reservoir was formed by damming the East Branch Delaware River, and Neversink Reservoir was formed by damming the Neversink River. Water from these three reservoirs travels through aqueducts and tunnels to Rondout Reservoir, which was formed by damming the Rondout Creek. From Rondout, water travels through the Delaware Aqueduct to Kensico Reservoir.

Methods

Bathymetric data were collected using a single-beam echo sounder from a moving boat, following methods documented in Wilson and Richards (2006). Echo sounder points were collected along transects that were spaced at intervals determined by the length of the reservoir (table 3). Horizontal positions of the surveyed points were determined by using a real-time kinematic global positioning system (RTK–GPS), and water surface elevations measured by the DEP were used as a vertical reference, from which reservoir-bottom elevations

Table 2. West of Hudson reservoirs as-built capacity values and corresponding elevations of reservoir structures in New York State.

[Locations of reservoirs shown in figure 1. Rows in italics present duplicative information and are not included in calculation of West of Hudson reservoirs total. BWS, New York City Department of Environmental Protection Bureau of Water Supply; NAVD 88, North American Vertical Datum of 1988; total capacity is total volume at spillway elevation including dead storage; useable capacity is the volume between the spillway elevation and the minimum operating level required to deliver full flow for drinking water supply; available capacity is the volume between the spillway elevation and the lowest intake or sill elevation used for drinking water supply; dead storage is the volume below lowest intake height or sill elevation for drinking water supply]

Reservoir	Spillway elevation	Minimum operating level	Intake/sill elevation	Spillway elevation	Minimum operating level	Intake/sill elevation	As-built Total capacity	As-built Useable capacity	As-built Available capacity	As-built Dead storage[1]
	(feet above BWS datum)			(feet above NAVD 88)			(billions of gallons)			
Ashokan (East Basin)	587.00	520.00	500.00	585.68	518.68	498.68	80.678	75.683	80.678	0.000
Ashokan (West Basin)	590.00	520.00	495.50	588.68	518.68	494.18	49.417	43.199	47.180	2.237
Ashokan (Total)							*130.095*	*118.882*	*127.858*	*2.237*
Cannonsville	1,150.00	1,040.00	1,035.00	1,149.58	1,039.58	1,034.58	98.618	95.706	96.726	1.892
Neversink	1,440.00	1,319.00	1,314.00	1,439.21	1,318.21	1,313.21	37.146	34.941	35.466	1.680
Pepacton	1,280.00	1,152.00	1,143.00	1,278.81	1,150.81	1,141.81	149.799	140.190	143.701	6.098
Rondout	840.00	723.00	720.00	838.88	721.88	718.88	52.435	49.617	50.048	2.387
Schoharie (before spillway reconstruction in 2015)	1,130.00	1,065.15	1,050.00	1,128.90	1,064.05	1,048.90	21.551	17.582	19.583	1.968
Schoharie (after spillway reconstruction in 2015)	*1,129.73*	*1,065.15*	*1,050.00*	*1,128.63*	*1,064.05*	*1,048.90*	*21.454*	*17.485*	*19.486*	*1.968*
Total West of Hudson reservoirs							489.644	456.918	473.382	16.262

[1]Published value from U.S. Geological Survey annual summaries (U.S. Geological Survey, 2016a–f, original source from City of New York Department of Water Supply, Gas & Electric values).

Table 3. Transect spacing information used in surveying the West of Hudson reservoirs in New York State.

[Locations of reservoirs shown in figure 1]

Reservoir	Approximate reservoir length (miles)	Transect spacing (feet)	Ratio of transect spacing to reservoir length (percent)	Planned total length of transects (miles)
Ashokan	11.4	410	0.68	188
Cannonsville	21.7	361	0.31	161
Neversink	6.3	262	0.78	60
Pepacton	20.7	459	0.42	134
Rondout	6.3	328	0.98	60
Schoharie	5.2	213	0.78	55

were calculated. Echo sounder data points were supplemented with data from several additional sources including RTK–GPS, acoustic Doppler current profiler (ADCP), aerial orthophotographs, and light detection and ranging (lidar) in select areas to provide improved spatial coverage (table 4). Echo sounder data were processed and edited using the hydrographic software HYPACK (HYPACK Inc., 2016). Bathymetric surfaces were mapped and edited in ArcMap (Esri Inc., 2016) before contours were created and elevation-area capacity was calculated. A second dataset of echo sounder points was collected along transects at oblique angles to the main transects for assessing the accuracy of the elevations.

Survey Planning

Echo sounder transects were laid out using HYPACK (HYPACK Inc., 2016) to achieve a transect spacing to reservoir length ratio of 1 percent or less, as recommended by Wilson and Richards (2006). This ratio was chosen to produce data of sufficient density to accurately calculate bathymetric surfaces, elevation-area-capacity tables, and contours; resulting transect spacings were 213 to 459 ft (table 3). Planned transects were aligned perpendicular to the long axis of the reservoir; as most of WOH reservoirs follow the sinuous course of old river beds, the direction of the planned transects was altered to follow these bends. Schoharie Reservoir transects are shown as an example in figure 2 (main echo sounder transects shown as blue lines). Additional transects were added across bays to ensure that deep spots resulting from the presence of old stream channels were recorded. The total length of planned transects at each reservoir (table 3) ranged from 55 miles (Schoharie) to 188 miles (Ashokan). For quality assurance (QA), a second set of echo sounder transects was planned, with a spacing 10 times that of the main transect spacing, oriented at a 45-degree angle to the main transects (green lines in fig. 2). Collecting data along oblique transects allowed comparison of coincident depth measurements where the main transects and the QA transects intersected.

Data Collection

Data collection began in September 2013, at the West Basin of Ashokan Reservoir, and continued through July 2015, at Pepacton Reservoir (table 4). Most reservoirs were nearly full (the water surface elevation was within a few feet of the spillway elevation) when surveyed (table 4); the water surface elevation during data collection was lowest in relation to the spillway elevation at Schoharie Reservoir (the water surface elevation was about 15–18 ft below the spillway elevation when surveyed.)

Horizontal and Vertical Control

The DEP Western Operations Surveying staff established horizontal and vertical control networks throughout the WOH system. Equipment utilized included Leica Viva GS 15 Smart Antennas paired with Leica Viva CS 15 Field Controllers; data were post-processed with Leica Geo Office version 7.01. Control points were established based upon the North American Datum of 1983 (NAD 83) Geoid 09 (horizontal) and North American Vertical Datum of 1988 (NAVD 88) (vertical).

Horizontal control was established by redundant (two) static observations with observation times of 2 hours. Continuous Operating Reference Stations (CORS) were utilized as primary control points; stations used were Binghamton, Hancock, Oneonta, Kingston, Hudson, Middletown, and Newburgh. Observations were collected between July 2012 and September 2014.

Vertical control was established at or near each spillway, except at Schoharie Reservoir, by static global positioning system (GPS) observations. Additional observations of first-floor elevations of intake and effluent chambers were conducted at the Rondout and Schoharie Reservoirs. Occupation times varied by location based upon distance to the 1st or 2nd order USGS benchmarks that were used for elevation of the control points. Established elevations were compared to elevations determined by the horizontal control networks based upon the CORS stations. Results indicated a 2-centimeter confidence level.

Measurements of water surface elevations at each reservoir were referenced to the DEP Bureau of Water Supply (BWS) datum for each reservoir. Each datum was established during reservoir construction and, due to practical survey limitations at the time of establishment, does not correspond directly to any national vertical datum (for example NAVD 88), and the offset to national datum varies slightly at each reservoir (Terry Ringler, New York City Department of Environmental Protection, oral commun., 2013). Vertical conversion factors between BWS datum and NAVD 88 were calculated for each reservoir based on the vertical control spillway observations (table 5).

Table 4. Data collection dates by type and water surface elevations during surveys of West of Hudson reservoirs in New York State.

[Locations of reservoirs shown in figure 1. GPS, global positioning system; RTK, real-time kinematic; NAVD 88, North American Vertical Datum of 1988, NAIP, National Agriculture Imagery Program; NYSDOP, New York Statewide Digital Orthoimagery Program; --, not used]

Reservoir	Echo sounder and latency correction method: Wide beam transducer and fixed offset latency		Echo sounder and latency correction method: Narrow beam transducer and GPS synchronization		Manual RTK-GPS survey points	Acoustic Doppler current profiler points		Aerial orthophotograph shoreline points		
	Date	Average water surface elevation (feet above NAVD 88)	Date	Average water surface elevation (feet above NAVD 88)	Date	Date	Average water surface elevation (feet above NAVD 88)	Date	Source	Average water surface elevation (feet above NAVD 88)
Ashokan (East Basin)	--	--	5/14/2014	585.94	--	--	--	10/12/2008	NAIP[1]	572.8
			5/15/2014	585.85				8/20/2013	NAIP[1]	581.4
			5/20/2014	586.40				9/24/2013	NAIP[1]	581.4
			5/27/2014	585.91						
			5/28/2014	585.88						
Ashokan (West Basin)	9/9/2013	584.47	5/28/2014	588.80	9/26/2013	--	--	10/12/2008	NAIP[1]	569.8
	9/10/2013	584.19						4/1/2009	NYSDOP[2]	582.5
	9/11/2013	584.07								
	9/12/2013	583.98								
	9/23/2013	582.55								
	9/24/2013	582.37								
	9/25/2013	582.19								
	9/26/2013	582.04								
Cannonsville	--	--	5/4/2015	1,149.34	--	6/2/2015	1,145.78	5/28/2008	NAIP[1]	1,129.80
			5/5/2015	1,149.17				9/1/2008	NAIP[1]	1,128.80
			5/6/2015	1,148.99						
			5/12/2015	1,148.20						
			5/13/2015	1,148.05						
			5/14/2015	1,147.90						
			5/15/2015	1,147.72						
			5/18/2015	1,147.30						
			5/19/2015	1,147.20						
Neversink	--	--	7/1/2014	1,438.42	--	--	--	8/12/2006	NAIP[1]	1,424.60
			7/9/2014	1,437.42						
			7/10/2014	1,437.44						
			7/11/2014	1,437.50						

Table 4. Data collection dates by type and water surface elevations during surveys of West of Hudson reservoirs in New York State.—Continued

[Locations of reservoirs shown in figure 1. GPS, global positioning system; RTK, real-time kinematic; NAVD 88, North American Vertical Datum of 1988, NAIP, National Agriculture Imagery Program; NYSDOP, New York Statewide Digital Orthoimagery Program; --, not used]

Reservoir	Echo sounder and latency correction method				Manual RTK-GPS survey points	Acoustic Doppler current profiler points		Aerial orthophotograph shoreline points		
	Wide beam transducer and fixed offset latency		Narrow beam transducer and GPS synchronization							
	Date	Average water surface elevation (feet above NAVD 88)	Date	Average water surface elevation (feet above NAVD 88)	Date	Date	Average water surface elevation (feet above NAVD 88)	Date	Source	Average water surface elevation (feet above NAVD 88)
Pepacton	--	--	7/6/2015	1,278.59	--	--	--	--	--	--
			7/7/2015	1,278.44						
			7/8/2015	1,278.28						
			7/9/2015	1,278.09						
			7/10/2015	1,278.05						
			7/13/2015	1,277.33						
			7/14/2015	1,277.05						
			7/15/2015	1,276.93						
			7/16/2015	1,276.83						
Rondout	11/6/2013	835.32	4/28/2014	835.15	--	--	--	4/1/2009	NYSDOP[2]	836.3
	11/7/2013	835.25	4/29/2014	835.30						
	11/14/2013	835.03	5/12/2014	835.20						
	11/15/2013	834.95	5/13/2014	835.38						
Schoharie	--	--	9/2/2014	1,113.24	9/30/2014	10/2/2014	--	8/5/2013	NAIP[1]	1,115.90
			9/3/2014	1,112.99	10/2/2014					
			9/4/2014	1,112.81						
			9/5/2014	1,112.59						
			9/12/2014	1,110.84						

[1]U.S. Department of Agriculture (2016).

[2]New York State (2016a).

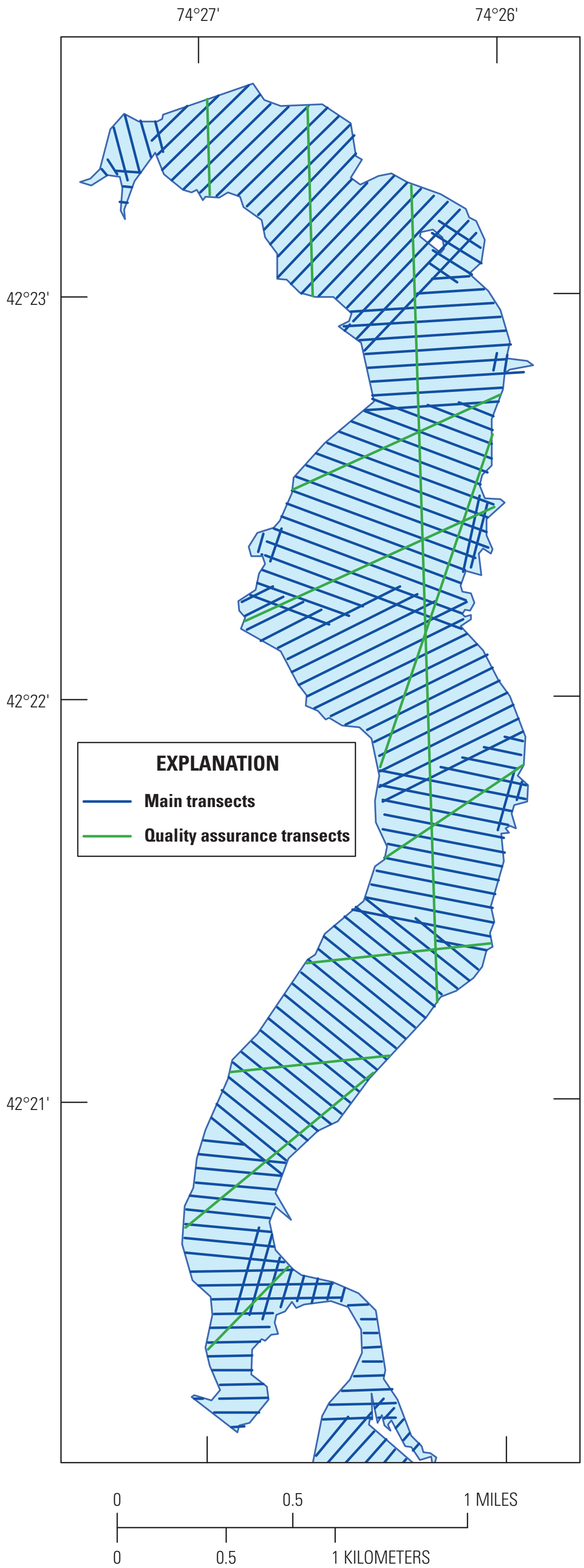

Figure 2. Example of the planned main transects and quality assurance transects, Schoharie Reservoir in New York State. Location of reservoir shown in figure 1.

Table 5. Spillway elevations and conversion factors for the surveyed West of Hudson reservoirs in New York State.

[Locations of reservoirs shown in figure 1. NAVD 88, North American Vertical Datum of 1988; BWS, New York City Department of Environmental Protection Bureau of Water Supply]

Reservoir	Spillway elevation (feet above NAVD 88)	Spillway elevation (feet above BWS datum)	Datum conversion factor (feet)
Ashokan (East Basin)	585.68	587.00	1.32
Ashokan (West Basin)	588.68	590.00	1.32
Cannonsville	1,149.58	1,150.00	0.42
Neversink	1,439.21	1,440.00	0.79
Pepacton	1,278.81	1,280.00	1.19
Rondout	838.88	840.00	1.12
Schoharie (before spillway reconstruction in 2015)	1,128.90	1,130.00	1.10
Schoharie (after spillway reconstruction in 2015)	1,128.63	1,129.73	1.10

Horizontal Position Data

Horizontal position data were collected using RTK–GPS with two Trimble R8 global navigation satellite system (GNSS) receivers and a radio communication link (Trimble, 2016). The base GNSS receiver occupied horizontal control points established and surveyed by DEP using static GPS observations (fig. 3 and table 6). Due to local topography, control point location, reservoir characteristics, and radio range, as few as one control point was required for some reservoirs (Ashokan and Schoharie) and as many as four control points were required for other reservoirs (Cannonsville). The rover GNSS receiver was mounted on the boat directly above the echo sounder transducer (fig. 4).

Water Surface Elevations and Vertical-Position Data

Vertical-position data were determined from water surface elevations supplied by DEP, measured at 5- to 15-minute intervals, typically at reservoir intake structures, using float-tape gages with shaft encoders, recorded digitally to the nearest hundredth of a foot. A 2-hour moving-average window was applied to the instantaneous observed values to smooth the effects of noise and waves in the final processing of the hydrographic data (example observations at Pepacton Reservoir shown in fig. 5). Water surface elevations typically decreased

Figure 3. Base station and radio antenna at control point near Schoharie Reservoir, New York State.

slightly over the course of data collection, usually at a rate not greater than 1 ft over the course of a week of data collection. Water surface elevations as supplied were referenced to DEP BWS datum. To standardize the dataset and because additional spatial data referenced to NAVD 88 were used, all observed water surface elevations were converted to NAVD 88 using the constant conversion factor for each reservoir.

Echo Sounder Data Collection

Depth data were collected with a Syqwest Bathy-500 MF, a survey-grade echo sounder with a resolution of 0.1 ft and a manufacturer-specified accuracy of 0.1 ft plus 0.1 percent of the depth (Syqwest, Inc., 2008). Data collected in 2013 used a 200-kilohertz (kHz) wide-beam transducer (8 degrees wide, measured at 3 decibels [dB]); in 2014 and 2015, data were collected with a 200-kHz narrow-beam transducer (3 degrees at 3 dB). The narrow-beam transducer was acquired to improve measurements made in the extremely steep areas within the WOH reservoirs. The minimum measurable depth varied depending on echo sounder settings but was typically approximately 3 ft. The echo sounder transducer was installed on the boat in a manner that allowed it to be adjusted using bubble levels to account for the trim of the boat; this correction was not dynamic, but rather the transducer was adjusted to be vertical at typical boat operation speeds (around 5 knots). Transducer draft was typically 0.7 ft and was measured using marked tape applied to the echo sounder transducer mount.

Table 6. Control points used in the surveys of the West of Hudson reservoirs in New York State.

[Locations of reservoirs shown in figure 1. NAVD 88, North American Vertical Datum of 1988; UTM18N, Universal Transverse Mercator Zone 18 north]

Point	Reservoir	Elevation (feet above NAVD 88)	Latitude	Longitude	Northing, UTM18N (meters)	Easting, UTM18N (meters)
Ashokan A1	Ashokan	608.442	41.948879	-74.207635	4644403.906	565674.511
BEERS	Cannonsville	1160.608	42.084070	-75.201857	4659130.235	483304.739
CHAMB	Cannonsville	1178.949	42.117752	-75.276912	4662887.302	477109.085
DRYBK	Cannonsville	1169.004	42.131994	-75.299097	4664475.169	475280.736
TURNER	Cannonsville	1237.191	42.070400	-75.364244	4657655.694	469867.390
NeversinkHARN	Neversink	1492.500	41.825295	-74.637255	4630442.860	530123.737
Neversink2	Neversink	1437.310	41.873361	-74.650864	4635774.670	528971.895
ARENA	Pepacton	1315.399	42.109523	-74.741883	4661968.766	521339.923
EDIC	Pepacton	1325.375	42.074256	-74.901567	4658025.497	508142.529
POND	Pepacton	1805.666	42.095323	-74.816583	4660376.188	515167.460
RC1	Rondout	858.570	41.799529	-74.430826	4627675.105	547285.398
RC4	Rondout	842.950	41.846000	-74.514803	4632791.805	540279.653
STIC	Schoharie	1140.490	42.356059	-74.443907	4689460.012	545796.700

Figure 4. Survey boat and global navigation satellite system (GNSS) rover receiver used for the study of the West of Hudson reservoirs in New York State.

Sound Speed

Echo sounders determine depth by transmitting a pulse of sound into the water and measuring the amount of time it takes for an echo to return. In order to calculate the depth, the speed of sound must be known. Sound speed varies with temperature, pressure, and salinity; because reservoirs are often stratified by temperature, the speed of sound typically varies with depth. The sound speed of the echo-sounder control box was set to a value that was representative of the middle to upper layers of the reservoir, and profiles of sound speed over depth were measured for use in post-processing using the hydrographic software. Sound speed profiles were measured using an Applied Microsystems Smart SV Sensor (AML Oceanographic, 2010) at least once per day, and more often when data were collected in different areas during the same day (for example, shallow inlet bays and deep areas near dams). Sound speed was recorded at 5-ft increments over the depth at the location of measurement; below the thermocline in deep water, where the sound speed was stable, the measurement interval was sometimes increased to 10 ft. The maximum depth for which a sound speed was measured was 155 ft at Neversink Reservoir. Water temperature at the reservoir surface was also noted two to three times per day as a QA check.

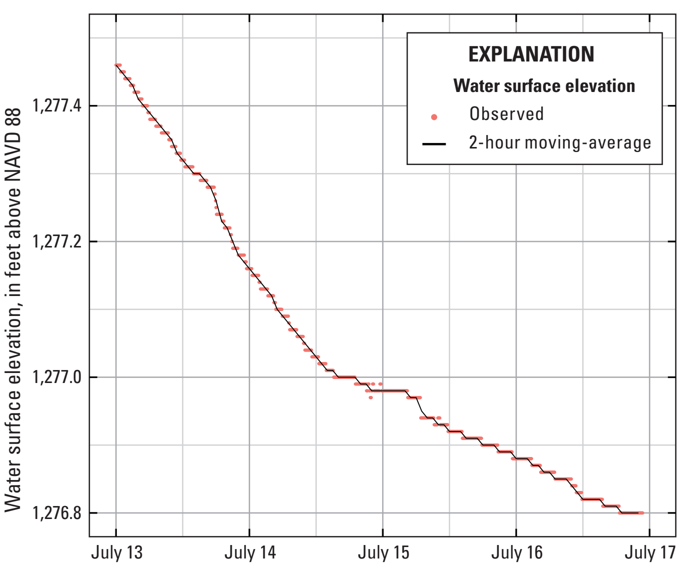

Figure 5. Example of observed 5-minute interval and 2-hour moving-average water surface elevation, Pepacton Reservoir, New York State, July 2015.

Depth-Measurement Checks

Echo sounder depth measurements were regularly checked by performing bar checks, a process in which a bar or plate is suspended at a known depth below the echo sounder, and the depth measured from the echo return off the bar is then compared to the known depth of the bar. A 3-ft by 4-ft perforated aluminum plate (fig. 6) was lowered into the reservoir below the echo sounder to specified depths, typically at 5-ft intervals, to verify live echo sounder readings. Live readings were typically within 0.2 ft of expected values. Variation from expected values can be caused by variable draft, drift of the boat relative to the bar as a result of wind, wave action, variation of the speed of sound with depth, or a combination of effects. Bar checks were performed three times a day (before data collection, at noon, and after data collection) when conditions permitted. The bar check conducted before data collection commenced was used to help set the echo sounder control box for the day, but subsequent bar checks were used as verification only. Windy conditions made conducting bar checks of deeper depths impractical on a fairly regular basis, especially at depths greater than 20 ft, as even slight winds would cause

Figure 6. Bar check plate used during surveys of the West of Hudson reservoirs in New York State.

the boat to drift so that the echo sounder transducer was no longer directly above the bar check plate. Bar checks were typically carried as deep as it was possible to get a readable return in the available depth; they typically went to 30 to 40 ft. The maximum depth of a bar check was 70 ft at Cannonsville, Neversink, and Rondout Reservoirs.

Data Integration (HYPACK)

Live echo sounder readings and RTK–GPS position data were integrated in the field using HYPACK. Latency tests showed that the echo sounder depth measurement for a point was received 1.8 seconds before the RTK–GPS position measurement; without correction, this latency would result in an inaccurate position being applied to each depth measurement. Data collected in 2013 were corrected for this latency using a single, constant time offset. Beginning in 2014, data were corrected for the latency by using the ZDA synchronization function in HYPACK, which synchronized the computer clock with the RTK–GPS clock as data were collected.

Additional Sources of Depth and Elevation Data

Four additional types of depth or elevation data were used in conjunction with the echo sounder depth measurements: manual RTK–GPS point measurements, acoustic Doppler current profiler (ADCP) point measurements, edge of water points digitized from aerial orthophotographs, and lidar points (table 4). Elevations were measured using the RTK–GPS rover on a 6.65 or 7.38 ft pole at selected points in the West Basin of Ashokan Reservoir, which were above the water surface during the 2013 survey but were below the water surface at the time of 2009 lidar data collection, and in areas shallow enough for wading near the inlet of Schoharie Reservoir along the channel of Schoharie Creek. The average vertical precision for the manual RTK–GPS points measured at Ashokan Reservoir was 0.31 ft. Depths were measured with the 0.5-megahertz vertical beam of a Sontek RiverSurveyor M9 ADCP (Sontek, 2016) deployed from a remote control boat in small bays at Cannonsville Reservoir that were inaccessible by manned boat and in the areas too deep to wade in the inlet of Schoharie Creek. Position data for the ADCP depths were obtained using a separate RTK–GPS system supplied by the ADCP manufacturer (Sontek, 2016), and vertical control was established using water surface elevations provided by the DEP. The minimum depth measureable with an M9 is 0.66 ft, with a resolution of 0.003 ft and a manufacturer-stated accuracy of 1 percent. Shoreline points were digitized along the edge of water in aerial orthophotographs to help fill in shallow areas inaccessible by boat. The aerial orthophotographs used were collected from 2006 to 2013 (table 4) by the National Agriculture Imagery Program (NAIP, U.S. Department of Agriculture, 2016) and New York State Digital Orthoimagery Program (NYSDOP, New York State, 2016a); an elevation was assigned to water edge points based on the average water level on the date the aerial photo was taken. Lidar data were used to supplement collected data in areas above the water surface elevation at the time of the surveys and to allow calculation of capacity above spillway elevations. The lidar data were collected from March through June 2009, by Sanborn Map Company, Inc., on behalf of DEP (New York City Department of Environmental Protection, 2009). The lidar data were downloaded in tiled form from New York Orthos Online

(New York State, 2016b) and converted from a 6.56-ft raster grid to points. The stated vertical accuracy of the lidar dataset is 0.305 ft (Terry Spies, New York City Department of Environmental Protection, oral commun., 2016).

Data Processing

Data processing included editing of echo sounder depth data, assembly of data into a geographic information system (GIS) database, bathymetric map editing, creation of contours, and generation of elevation-area-capacity tables.

Echo Sounder Data Processing

Echo sounder data were processed in HYPACK before output for use in a GIS. Processing in HYPACK included application of sound-speed corrections, application of water surface elevation data for calculation of point elevations from measured depths, and screening for errors and spikes in the data.

All of the reservoirs except Rondout were moderately to strongly stratified at the time of field surveys, with the largest range in sound speed observed at Pepacton Reservoir (table 7). Stratification was stable at Neversink, Pepacton, and Schoharie Reservoirs but varied with time at Ashokan, Cannonsville, and Rondout Reservoirs (fig. 7). Corrections for sound-speed variation over depth were applied to all reservoirs except Rondout, where substantial stratification was not present, and measured speed of sound was never more than 0.6 percent different from the value used by the echo sounder. Observed sound-speed profiles (dots in fig. 7) were grouped by date and averaged into representative profiles (solid lines in fig. 7) for application to observed depths. The median correction to observed depths ranged from 0.04 ft in the West Basin of Ashokan to 0.38 ft in Pepacton; the maximum speed of sound correction was almost 4 ft (Pepacton Reservoir; table 7).

Measured depths were converted to elevations in HYPACK by subtracting the depth, corrected for the speed of sound, from processed water surface elevations. After conversion to elevation, each transect was screened for spikes and measurement errors. Spikes and errors can occur in the echo sounder data in the digitization process (the process by which the echo sounder determines a depth value from the analog echo signal received by the transducer). For example, a strong return from objects in the water column such as debris, fish, or vegetation can be digitized as the measured depth, or the second acoustic return can be digitized instead of the first. In shallow water, sound can be reflected off the water surface as well as the reservoir bottom; the second return would travel from echo sounder to reservoir bottom, to water surface, to reservoir bottom, and back to the echo sounder before being digitized; the recorded value is then approximately twice as deep as the actual value. An example of an edited echo sounder transect is shown in figure 8, with red points marking the removed spikes. After processing and editing, position and elevation data were exported from HYPACK to a comma-delimited text file for import to a GIS. From 184,000 to 550,000 main echo sounder points per reservoir were used (table 8).

Geographic Information System Database Creation and Linear Enforcement Editing

The edited bathymetry points were combined in a GIS with ADCP point measurements, the manual RTK–GPS point measurements, points digitized from aerial orthophotographs (table 8), and lidar points for creation of a triangulated irregular network (TIN). All data were projected into a common horizontal datum (NAD 83) and vertical datum (NAVD 88). The TINs were created by connecting each point with its two nearest neighbors; for single-beam echo sounder data collected in transects, this creates a three-dimensional array of thin triangles. Because the nearest neighbors are connected

Table 7. Sound-speed corrections by depth applied to the West of Hudson reservoirs surveyed in New York State.

[Locations of reservoirs shown in figure 1. --, not used]

Reservoir	Average difference between		Sound-speed correction			
	shallowest and deepest measured sound speed (percent)	deepest measured sound speed and echo sounder value (percent)	Applied	Median (feet)	Maximum (feet)	Standard deviation (feet)
Ashokan (East Basin)	1.7	0.7	Yes	0.13	0.78	0.14
Ashokan (West Basin)	1.3	1.0	Yes	0.04	3.40	0.42
Cannonsville	3.2	1.5	Yes	0.17	2.06	0.22
Neversink	3.5	1.2	Yes	0.25	2.19	0.42
Pepacton	4.2	2.0	Yes	0.38	3.93	0.73
Rondout	0.6	0.2	No	--	--	--
Schoharie	2.2	1.4	Yes	0.05	1.72	0.28

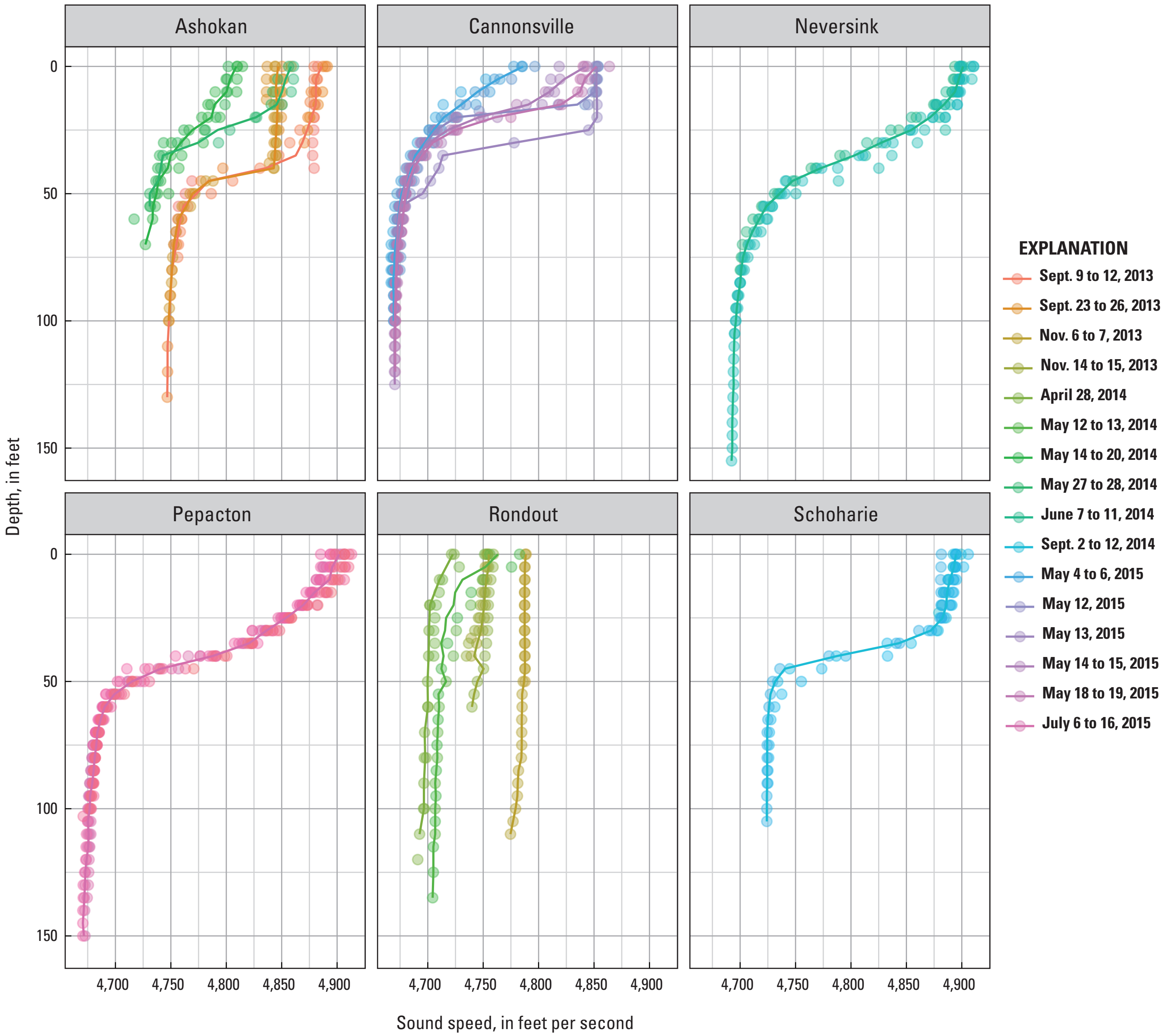

Figure 7. Sound-speed profiles, measured points, and processing averages (lines) for each West of Hudson reservoir surveyed in New York State. Dots represent individual observations; lines represent averaged profiles. Profiles are color coded by date with oranges being the earliest measurements and purples and pinks being the latest measurements. Ashokan East Basin (green) and Ashokan West Basin (orange) Reservoirs are shown combined. Averaged profiles from Rondout Reservoir were not applied to data during processing. Locations of reservoirs shown in figure 1.

in the GIS without reference to linear geomorphic features, often the TIN surface does not accurately reflect features such as channels and steep slopes (fig. 9). These linear features were enforced by manually adding breaklines to the raw TIN surfaces, creating edited TIN surfaces (fig. 10). The breaklines were hand drawn along features observed in the survey data—for example, to connect the deepest observations in old channels and to connect points along lines running parallel to the reservoir shore or along slopes. Most breaklines were added based solely on observations in the surveyed data. Topographic maps created before reservoir construction were also used to draw breaklines in some locations. In areas that had highly nonlinear features, breaklines were added and the resulting points were adjusted horizontally to produce smooth transitions in the edited TIN surface, or points were added directly to the TIN surface at interpolated elevations to allow formation of triangles that better conformed to a realistic bathymetric surface. Points were also added to the edited TIN along spillways to allow mapped contours at spillway elevations (depth of zero ft) to close.

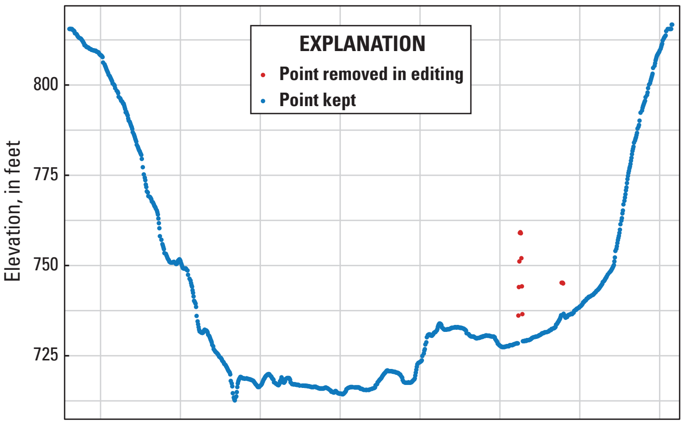

Figure 8. Profile of an echo sounder point screening and editing example from Rondout Reservoir, New York State.

Table 8. Number of data points used per West of Hudson reservoir in New York State after data editing, classified by data source.

[Locations of reservoirs shown in figure 1. ADCP, acoustic Doppler current profiler; RTK-GPS, real-time kinematic global positioning system; --, not used]

Reservoir	Echo sounder		ADCP points	Manual RTK-GPS survey points	Aerial orthophotograph edge of water points
	Main points	Quality assurance points			
Ashokan (East Basin)	490,764	57,641	--	--	6,404
Ashokan (West Basin)	258,911	36,153	--	41	7,699
Cannonsville	550,270	76,522	3,787	--	813
Neversink	198,062	28,246	--	--	1,469
Pepacton	464,231	69,479	--		--
Rondout	296,375	23,673	--	--	202
Schoharie	183,560	26,450	4,127	295	307

Contour Creation and Elevation-Area-Capacity Table Computations

Bathymetic contours were created at 2-ft intervals to match existing above-water contours (which were calculated by DEP from 2009 lidar data). The TIN surface for each reservoir was converted to a 6.56-ft cell-size raster using the TIN-to-Raster natural neighbor interpolation tool in the ArcGIS (Esri, Inc., 2016). The raster was then smoothed using a low-pass filter, and contours were created at 2-ft elevation increments that correspond to even-foot depth-below-spillway increments; an example low-pass filtered raster and contours are shown in figure 11.

Elevation-area-capacity tables were calculated at 0.1-meter intervals using the 3-dimensional analyst surface-volume tool in ArcMap (Esri Inc., 2016) and were expanded using linear interpolation to 0.01-ft increments. Tabular values of surface area and volume are presented for NAVD 88 elevations, BWS reservoir datum elevations, and depth below spillway (see tables in the “Results of Surveys” section).

Accuracy Assessment

The accuracy of the bathymetric data was evaluated using a QA dataset collected along transects oriented at oblique angles to the main echo sounder transects, as described by Wilson and Richards (2006). About 23,000 to 76,000 QA points were collected at each reservoir (table 8). The points from the QA dataset were spatially intersected with the main echo sounder data points, the TIN and raster surfaces, and the mapped contours. The elevations from the QA points were then compared with the matching elevations from the points, surfaces, and contours for each reservoir (fig. 12).

The National Standard for Spatial Data Accuracy (NSSDA), published by the Federal Geographic Data Committee (FGDC; 1998), defines a standard for assessing map accuracy based on the root mean square error (RMSE) of the data, calculated with the following equations:

$$RMSE_z = \sqrt{\frac{\sum_{i=1}^{n}\left(Z_{data_i} - Z_{check_i}\right)^2}{n}} \quad (1)$$

where
- $RMSE_z$ is the vertical root mean square error,
- Z_{data_i} is the vertical coordinate of the ith check point in the dataset,
- Z_{check_i} is the vertical coordinate of the ith check point in the QA dataset,
- i is an integer from 1 to n, and
- n is the number of points being checked.

Assuming the errors are normally distributed, the vertical accuracy of the map product can be calculated at the 95-percent accuracy level based on the RMSE:

$$A_z = 1.960 * RMSE_z \quad (2)$$

where
- A_z is the fundamental vertical accuracy calculated at the 95-percent confidence level.

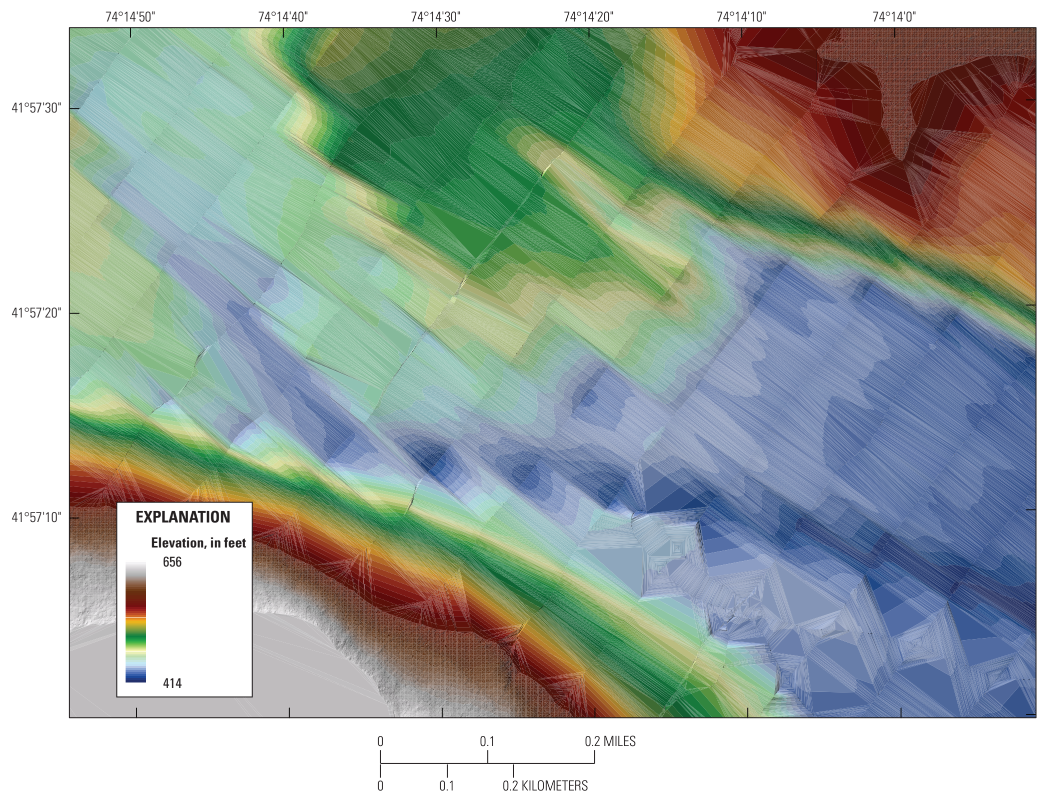

Figure 9. An example of a raw triangulated irregular network in the West Basin of Ashokan Reservoir in New York State. Location of reservoir is shown in figure 1.

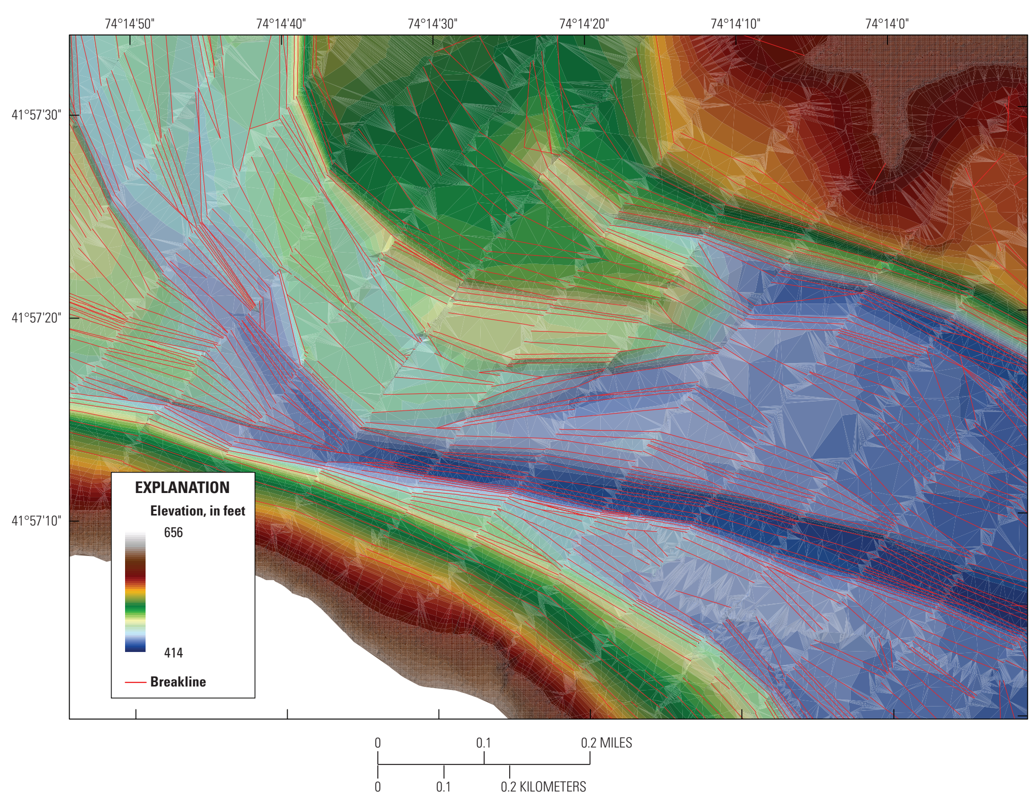

Figure 10. An example of breakline additions and edited triangulated irregular network in the West Basin of Ashokan Reservoir in New York State. Location of reservoir is shown in figure 1.

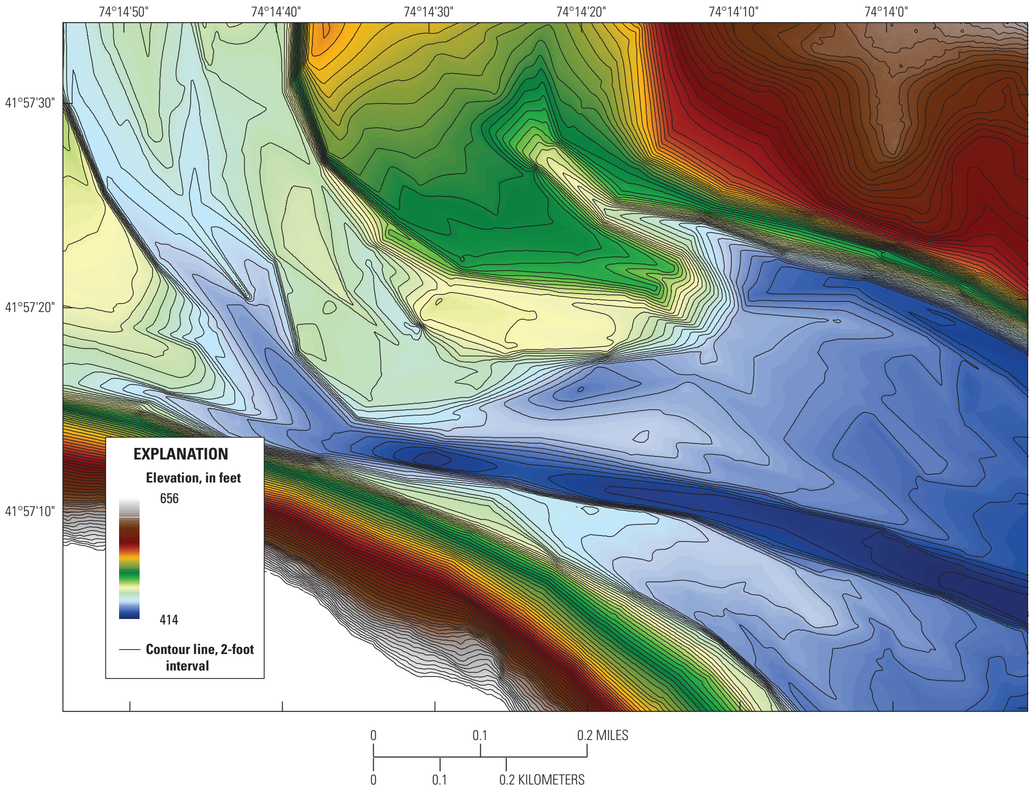

Figure 11. Example low-pass filtered raster and contours in the West Basin of Ashokan Reservoir in New York State. Location of reservoir is shown in figure 1.

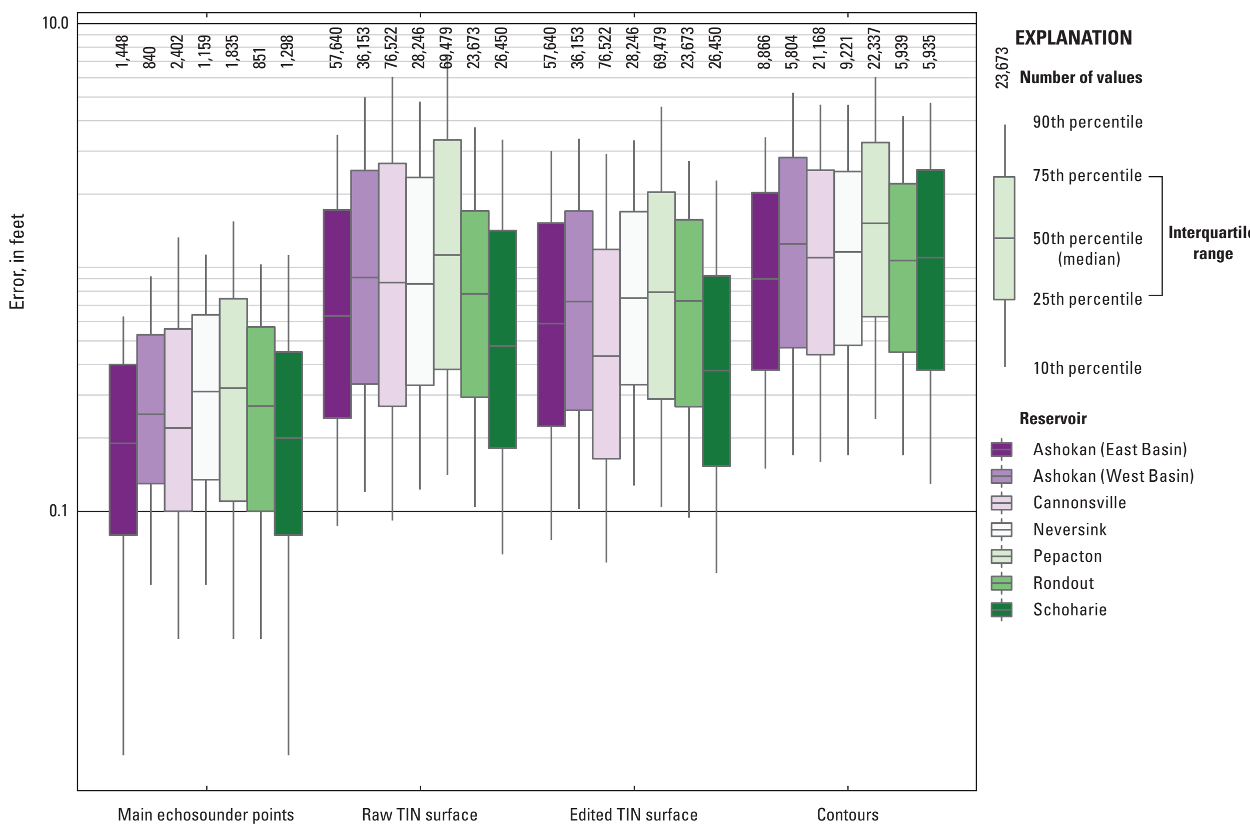

Figure 12. Accuracy assessment of survey data—elevation error calculated by comparing quality assurance points to main echo sounder points, triangulated irregular network (TIN) surfaces, and contours by reservoir in New York State.

Because it is not possible to separate the effects of many different factors on each measured point in the dataset, this accuracy assessment includes the cumulative effects of many potential sources of errors or inaccuracies, including those associated with the measurements of depth, horizontal position, and water surface elevation, as well as those arising from the motion of the boat, including pitch, roll, or heave.

As might be expected, the accuracy of the measured points was higher than that of the TIN surfaces and contours (fig. 12). The linear-enforcement editing process provided a moderate improvement in the accuracy of the bathymetric surfaces (fig. 12). The accuracy of the mapped surfaces (and therefore also the resulting contours) was highest close to the measured echo sounder points (median error of about 0.2 ft) and lowest between transects farthest from the measured echo sounder points (median error of about 1 ft; fig. 13).

Because the capacity tables represent a spatial average of the depth measurements, the accuracy of the capacity tables can be assessed by calculating confidence intervals around the mean of the depth measurement error of the TIN surfaces from which capacity values were calculated, as in Helsel and Hirsch (2002). A symmetric confidence interval around the mean error can be calculated by

$$\bar{x} - t_{(\alpha/2,\ n-1)} \bullet \sqrt{s^2 / n} \le \mu \le \bar{x} + t_{(\alpha/2,\ n-1)} \bullet \sqrt{s^2 / n} \qquad (3)$$

where

$\bar{x}$ is the sample mean error,

t is the Student's t value,

α is (1 – confidence interval),

n is the number of observations,

s^2 is the sample variance, and

μ is the population mean error.

In this case, a 95-percent confidence interval was calculated, and equation 3 becomes

$$\bar{x} - 1.96 \bullet \sqrt{s^2 / n} \le \mu \le \bar{x} + 1.96 \bullet \sqrt{s^2 / n} \qquad (4)$$

Survey Data Accuracy—Echo Sounder Points

The QA points were spatially joined to the nearest main echo sounder point occurring within a 3-ft radius, resulting in 840 to 2,402 paired points per reservoir and 9,833 points total (table 9). The elevation of the main point was subtracted

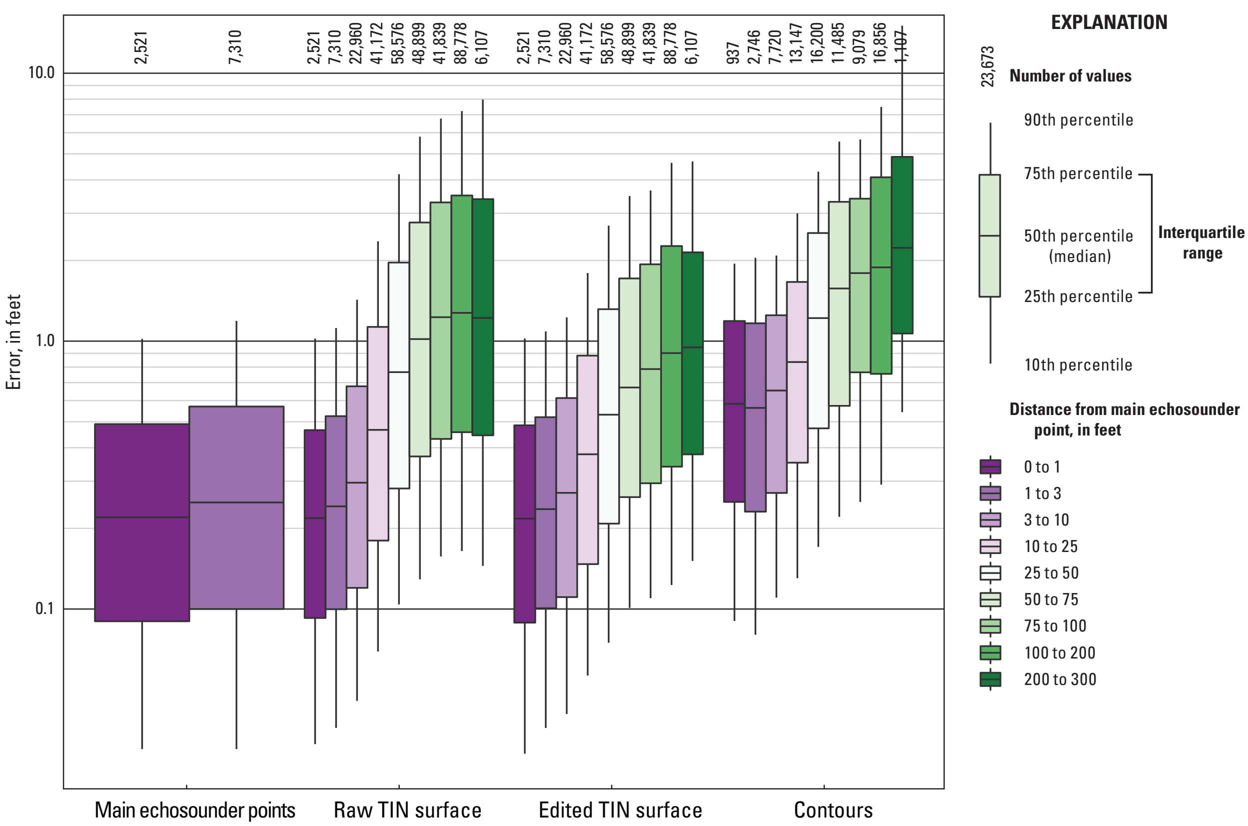

Figure 13. Accuracy assessment of survey data—elevation error calculated by comparing quality assurance points to main echo sounder points, triangulated irregular network (TIN) surfaces, and contours, by distance from main echo sounder point in the West of Hudson reservoirs in New York State.

Table 9. Accuracy of point elevations for quality assurance echo sounder points compared to main echo sounder points for the West of Hudson reservoirs, New York State.

[Locations of reservoirs shown in figure 1. n, number of points—each quality assurance point was compared to the nearest main point within 3 feet; RMSEz, vertical root mean square error; accuracy$_z$, National Standard for Spatial Data Accuracy fundamental vertical accuracy calculated at the 95-percent confidence level; WOH, West of Hudson]

Reservoir	n	Median signed error (feet)	Median absolute error (feet)	RSME$_z$ (feet)	Accuracy$_z$, 95-percent confidence level (feet)
Ashokan (East Basin)	1,448	-0.06	0.19	0.79	1.55
Ashokan (West Basin)	840	-0.05	0.25	0.75	1.48
Cannonsville	2,402	-0.02	0.22	1.29	2.53
Neversink	1,159	-0.07	0.31	0.78	1.53
Pepacton	1,835	0.07	0.32	0.94	1.84
Rondout	851	-0.01	0.27	0.74	1.44
Schoharie	1,298	-0.02	0.20	1.55	3.04
All WOH reservoirs	9,833	-0.02	0.24	1.07	2.10

from the elevation of the QA point, and descriptive statistics were calculated on the signed error and the absolute value of the error. A map of the point-to-point comparison errors for Schoharie Reservoir is shown as an example in figure 14; the largest errors tend to occur near steep features in the reservoir. The median signed error between QA point elevation and main point elevation (which addresses potential bias between datasets) ranged from 0.07 ft at Pepacton Reservoir to -0.07 ft at Neversink Reservoir and was -0.02 ft overall. The median absolute error (which assesses reproducibility of the data or an average vertical distance between the main points and the QA points) was 0.24 ft overall and ranged from 0.19 ft at the East Basin of Ashokan Reservoir to 0.32 ft at Pepacton Reservoir (table 9). The NSSDA accuracy of the point measurements at 95-percent confidence level was 2.10 ft for all points combined and ranged from 1.44 ft at Rondout Reservoir to 3.04 ft at Schoharie Reservoir (table 9).

Survey Product Accuracy—Bathymetric Surfaces, Contours, and Capacity Tables

The QA points were spatially joined to the raw and edited TINS, the elevations were compared, and descriptive statistics were calculated (table 10; a map of the point-to-TIN comparison errors for Schoharie Reservoir is shown as an example in

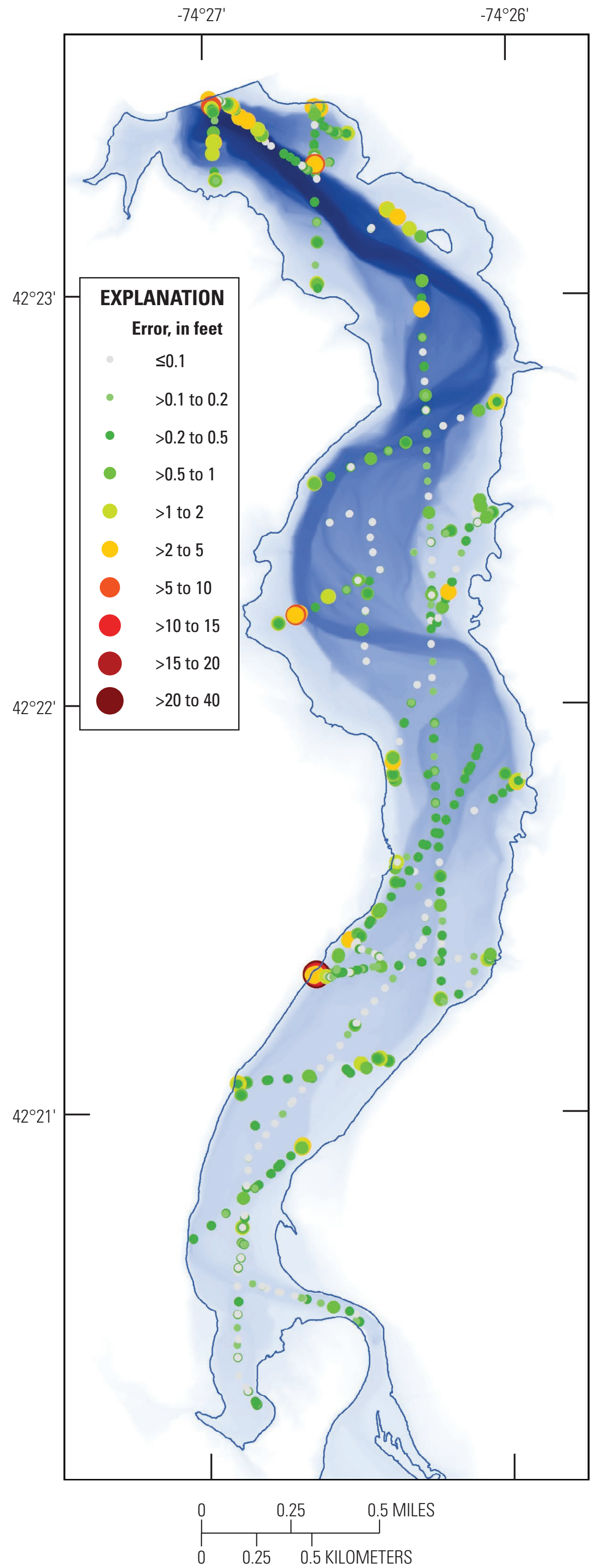

Figure 14. Quality assurance echo sounder points compared to main echo sounder points, Schoharie Reservoir, New York State. Location of reservoir is shown in figure 1.

Table 10. Accuracy of triangulated irregular network (TIN) elevations for quality assurance echo sounder points compared to edited and raw TIN surfaces for the West of Hudson reservoirs, New York State.

[Locations of reservoirs shown in figure 1. n, number of points—each quality assurance point was compared to the corresponding elevation of the edited and raw TINs; TIN, triangulated irregular network; $RMSE_z$, vertical root mean square error; $accuracy_z$, National Standard for Spatial Data Accuracy fundamental vertical accuracy calculated at the 95-percent confidence level; WOH, West of Hudson]

Reservoir	n	Edited TIN				Raw TIN				Improvement from editing			
		Mean signed error (feet)	Median absolute error (feet)	$RSME_z$ (feet)	$Accuracy_z$ (feet)	Mean signed error (feet)	Median absolute error (feet)	$RSME_z$ (feet)	$Accuracy_z$ (feet)	Mean signed error (feet)	Median absolute error (feet)	$RMSE_z$ (feet)	$Accuracy_z$ (feet)
Ashokan (East Basin)	57,641	-0.26	0.59	2.00	3.92	-0.60	0.63	2.40	4.70	0.34	0.04	0.4	0.78
Ashokan (West Basin)	36,153	0.15	0.73	2.28	4.48	-0.48	0.91	3.48	6.82	0.63	0.18	1.2	2.34
Cannonsville	76,522	0.02	0.43	2.21	4.33	-1.32	0.87	4.02	7.89	1.34	0.44	1.81	3.56
Neversink	28,246	0.00	0.75	2.17	4.26	-0.86	0.86	4.18	8.19	0.86	0.11	2.01	3.93
Pepacton	69,479	-0.01	0.79	3.59	7.04	-1.29	1.12	4.96	9.72	1.28	0.33	1.37	2.68
Rondout	23,673	0.13	0.73	1.98	3.88	-0.37	0.78	2.46	4.83	0.50	0.05	0.48	0.95
Schoharie	26,450	-0.15	0.38	1.71	3.36	-0.52	0.48	2.77	5.43	0.37	0.10	1.06	2.07
All WOH reservoirs	318,164	-0.03	0.59	2.50	4.91	-0.91	0.82	3.78	7.42	0.87	0.23	1.28	2.51

figure 15). The median absolute error for the edited TINs was 0.59 ft overall and ranged from 0.38 ft at Schoharie Reservoir to 0.79 ft at Pepacton Reservoir. The NSSDA accuracy of the edited TINs was 4.91 ft and ranged from 3.36 ft at Schoharie Reservoir to 7.04 ft at Pepacton Reservoir. The linear-enforcement editing process improved the NSSDA accuracy by 2.51 ft overall, with a minimum improvement of 0.78 ft at the East Basin of Ashokan Reservoir and a maximum improvement of 3.93 ft at Neversink Reservoir. The mean signed error for raw TINs was -0.91 ft overall and was negative for all reservoirs, indicating that the raw TIN surface elevations were on average higher than the elevations of the QA points. The linear-enforcement editing process reduced the mean signed error for the TINs to -0.03 ft overall, with a minimum improvement of 0.34 ft at the East Basin of Ashokan Reservoir and a maximum improvement of 1.34 ft at Cannonsville Reservoir. The comparison of QA points and low-pass filtered rasters was almost identical to that for the edited TINs (table 11).

The QA points were spatially joined to the nearest mapped contour occurring within 3 ft of each QA point, the elevations were compared and descriptive statistics were calculated (table 12; a map of the point-to-contour comparison errors for Schoharie Reservoir is shown as an example in figure 16). The median absolute error for the contours was 1.19 ft overall and ranged from 0.90 ft at the East Basin of Ashokan Reservoir to 1.52 ft at Pepacton Reservoir. The NSSDA accuracy was 6.80 ft overall and ranged from 4.52 ft at the East Basin of Ashokan Reservoir to 9.05 ft at Pepacton Reservoir. The decrease in accuracy from the surfaces to the contours is because contours are closely spaced in steep areas; as a result of this close spacing, steep areas are oversampled in the assessment of contours as compared to the assessment of surfaces. In steep areas, small errors in horizontal-position measurement can create large vertical errors, and even small distances between a QA point and its paired contour can result in relatively large elevation errors. Bathymetric contours were mapped at a 2-ft interval to emulate existing topographic maps, but the user should be aware that the 95-percent confidence level accuracy of these contours is much larger than the mapped contour interval at all of the WOH reservoirs.

The accuracy of the capacity at the spillway elevation for each reservoir was assessed using the comparison of the QA points to the edited TINs because capacity was calculated using the TIN surfaces. The volume of a reservoir represents the spatial integration of depth over area; therefore, the accuracy of the calculated capacity can be represented by putting confidence intervals on the signed mean depth error. This assessment, however, does not include any potential bias in measurement of water surface elevation. A more conservative estimate of the accuracy of the capacity can be calculated by putting confidence intervals on the mean absolute depth error. Using the mean signed error, the 95-percent confidence interval calculated using equation 4 for all WOH reservoirs was 0.6 percent or less of total capacity at spillway elevation; using the mean absolute error, the 95-percent confidence interval for all WOH reservoirs was 3.0 percent or less of total capacity at spillway elevation (table 13).

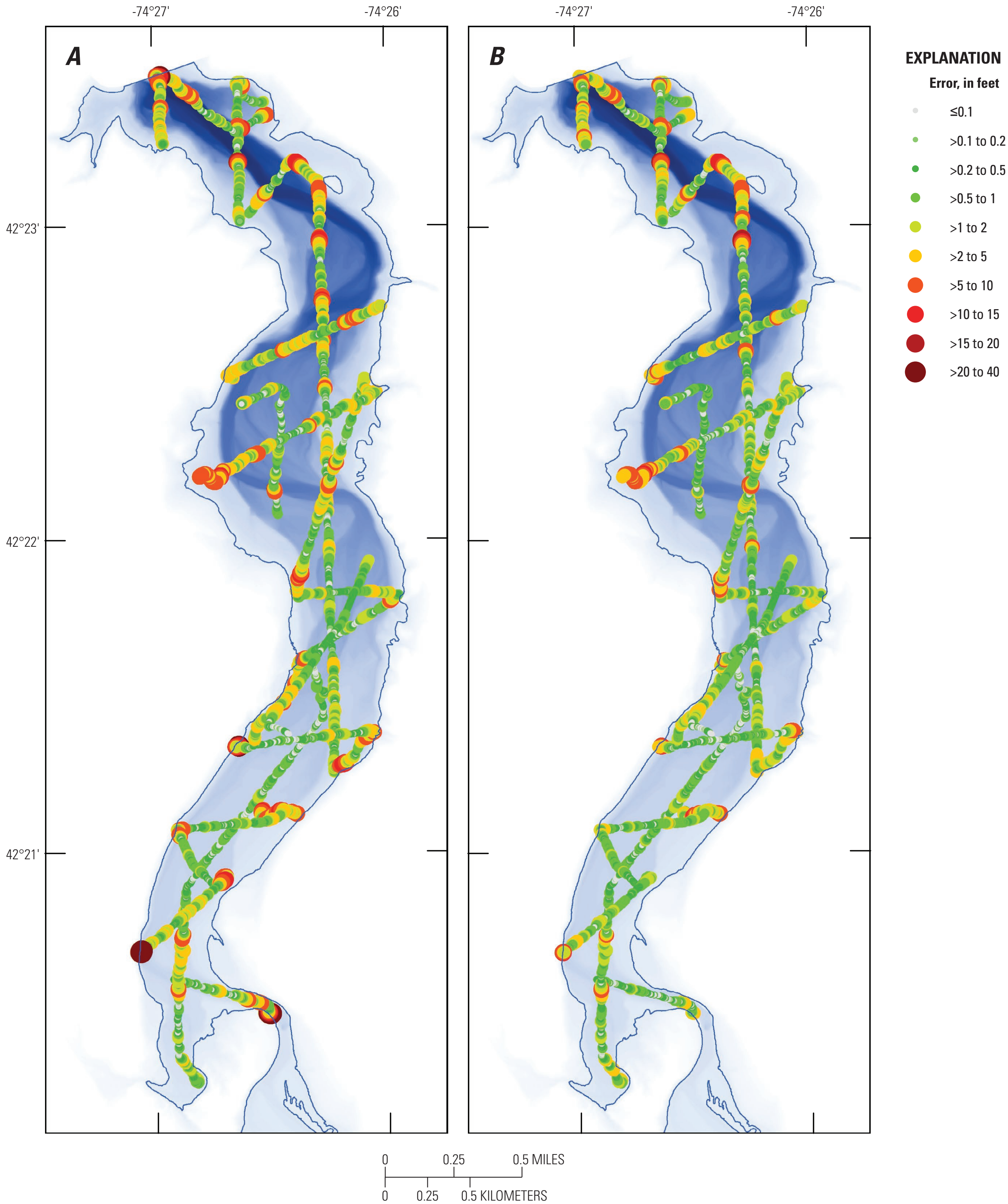

Figure 15. Quality assurance echo sounder points compared to *A*, raw and *B*, edited triangular irregular networks (TINs), Schoharie Reservoir in New York State. Location of reservoir is shown in figure 1.

Table 11. Accuracy of raster elevations for quality assurance echo sounder points compared to raster surfaces for West of Hudson reservoirs, New York State.

[Locations of reservoirs shown in figure 1. n, number of points—each quality assurance point was compared to the corresponding elevation of the low-pass filtered rasters; RMSE$_z$, vertical root mean square error; accuracy$_z$, National Standard for Spatial Data Accuracy fundamental vertical accuracy calculated at the 95-percent confidence level; WOH, West of Hudson]

Reservoir	n	Median absolute error (feet)	RSME$_z$ (feet)	Accuracy$_z$, 95-percent confidence level (feet)
Ashokan (East Basin)	57,641	0.59	1.99	3.90
Ashokan (West Basin)	36,153	0.73	2.27	4.45
Cannonsville	76,522	0.45	2.19	4.30
Neversink	28,246	0.74	2.16	4.24
Pepacton	69,479	0.79	3.55	6.96
Rondout	23,673	0.72	1.97	3.86
Schoharie	26,450	0.39	1.74	3.41
All WOH reservoirs	318,164	0.60	2.48	4.87

Table 12. Accuracy of contour elevations for quality assurance echo sounder points compared to contours for West of Hudson reservoirs, New York State.

[Locations of reservoirs shown in figure 1. n, number of points—each quality assurance point was compared to the elevation of the nearest contour within 3 feet; RMSE$_z$, vertical root mean square error; accuracy$_z$, National Standard for Spatial Data Accuracy fundamental vertical accuracy calculated at the 95-percent confidence level; WOH, West of Hudson]

Reservoir	n	Median absolute error (feet)	RSME$_z$ (feet)	Accuracy$_z$, 95-percent confidence level (feet)
Ashokan (East Basin)	8,866	0.90	2.31	4.52
Ashokan (West Basin)	5,804	1.25	3.37	6.60
Cannonsville	21,168	1.10	3.03	5.94
Neversink	9,221	1.16	2.95	5.79
Pepacton	22,345	1.52	4.62	9.05
Rondout	5,939	1.07	2.63	5.15
Schoharie	5,935	1.10	2.91	5.70
All WOH reservoirs	79,278	1.19	3.47	6.80

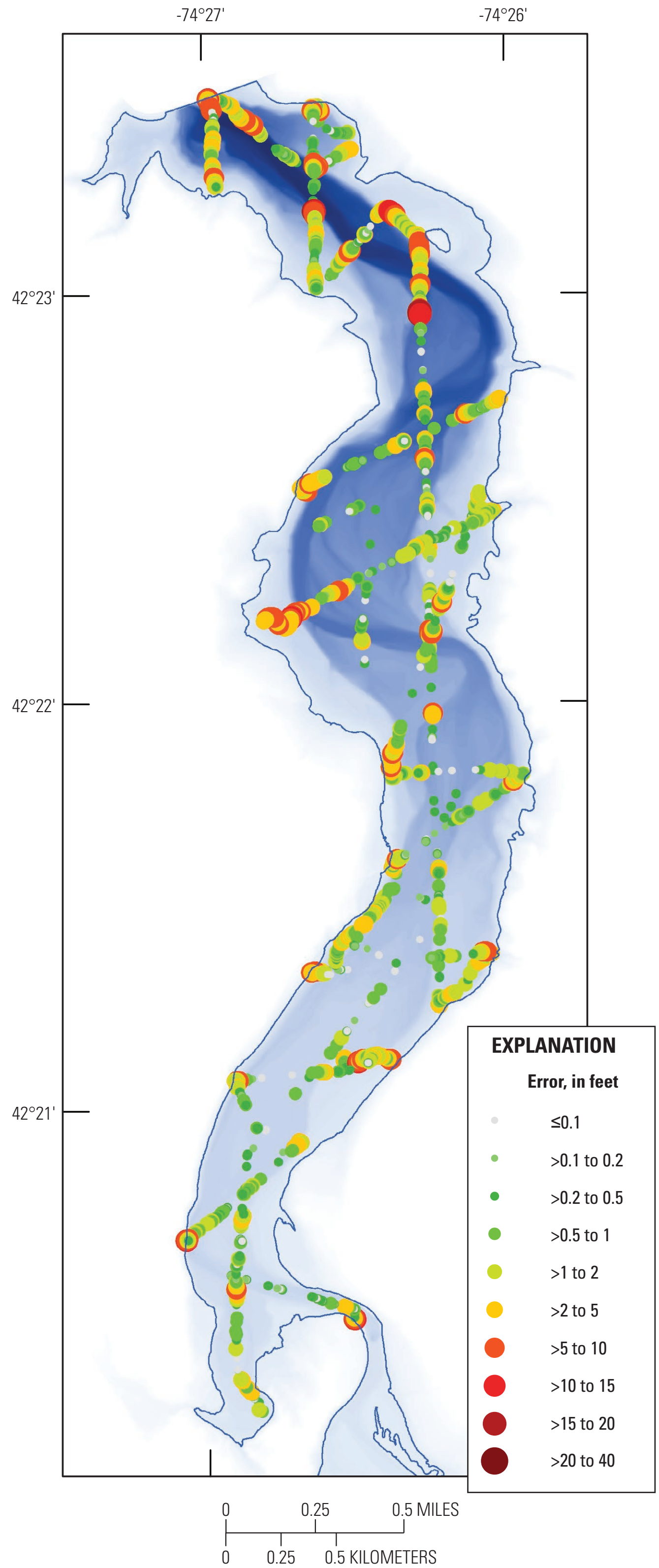

Figure 16. Quality assurance echo sounder points compared to contours for Schoharie Reservoir in New York State. Location of reservoir is shown in figure 1.

Table 13. Accuracy of reservoir capacity at spillway elevations for the West of Hudson reservoirs, New York State.

[Locations of reservoirs shown in figure 1. n, number of points—each quality assurance point was compared to the corresponding elevation of the edited triangulated irregular networks (TINs); CI, 95-percent confidence interval]

Reservoir	TIN surface elevation						Capacity at spillway elevation			
	n	Mean signed error (feet)	Mean absolute error (feet)	Variance of error (feet²)	CI, mean signed error (feet)	CI, mean absolute error (feet)	CI, mean signed error (billion gallons)	CI, mean absolute error (billion gallons)	CI, mean signed error (percent of total capacity)	CI, mean absolute error (percent of total capacity)
Ashokan (East Basin)	57,641	-0.258	1.18	3.94	±0.281	±1.21	±0.46	±2.00	±0.59	±2.5
Ashokan (West Basin)	36,153	0.151	1.36	5.20	±0.174	±1.38	±0.18	±1.39	±0.37	±3.0
Cannonsville	76,522	0.020	1.11	4.87	±0.036	±1.12	±0.06	±1.73	±0.06	±1.8
Neversink	28,246	0.003	1.35	4.73	±0.029	±1.37	±0.01	±0.68	±0.04	±1.9
Pepacton	69,479	-0.011	1.82	12.90	±0.037	±1.85	±0.07	±3.40	±0.05	±2.3
Rondout	23,673	0.125	1.21	3.91	±0.151	±1.24	±0.10	±0.85	±0.20	±1.6
Schoharie	26,450	-0.146	0.89	2.91	±0.166	±0.91	±0.06	±0.33	±0.31	±1.7

Results of Surveys

Echo sounder points, TINs, raster surfaces, contours, elevation-area-capacity tables, and associated metadata are available for download as digital data online (Nystrom 2018a–f) at https://dx.doi.org/10.5066/F7P26W7P (Ashokan Reservoir), https://dx.doi.org/10.5066/F7WM1BJK (Cannonsville Reservoir), https://dx.doi.org/10.5066/F71C1V1W (Neversink Reservoir), https://dx.doi.org/10.5066/F7DJ5CSM (Pepacton Reservoir), https://dx.doi.org/10.5066/F7542KR6 (Rondout Reservoir), and https://dx.doi.org/10.5066/F7J964HB (Schoharie Reservoir). Elevation-area-capacity tables at 10-ft increments of depth for each reservoir are in tables 14–20.

Effect of Linear Enforcement on Capacity Estimation

To assess the effect that linear enforcement of the TINs had on estimation of the WOH reservoir capacities, the capacities of the raw TINs were calculated and compared to those calculated from the linearly enforced (or edited) TINs (table 21). The calculated capacity of the raw TIN was less than the calculated capacity of the linearly enforced TIN for all of the WOH reservoirs, with a difference totaling more than 5 Ggal (1.1 percent) of the combined total capacity at spillway elevations. The effect of linear enforcement on total volume was smallest at the Schoharie Reservoir (about 0.1 Ggal) and largest at Pepacton Reservoir (about 2.2 Ggal). The relative effect of linear enforcement on volume was smallest at Rondout Reservoir (about 0.6 percent) and largest at Pepacton Reservoir (about 1.5 percent).

Change in Reservoir Capacity Over Time

Comparison of newly calculated reservoir capacities to previously published as-built capacities (U.S. Geological Survey, 2016a–f) shows a decrease in the total capacity of all six WOH reservoirs over time (table 22). The total calculated storage capacity at spillway elevations of the WOH reservoirs decreased by 11.5 Ggal, or 2.3 percent. The largest changes in total reservoir capacity were in Ashokan Reservoir, which decreased about 4.8 Ggal (about 2.6 Ggal in the West Basin and about 2.2 Ggal in the East Basin) and Cannonsville Reservoir, which decreased by about 2.6 Ggal. The largest percent change in total capacity was at Schoharie Reservoir, which decreased by about 8.6 percent. The change in total capacity at spillway elevation was greater than the 95-percent confidence interval calculated using the mean signed error at all reservoirs (table 13). The change in total capacity was greater than the more conservative confidence interval calculated using mean absolute error at Ashokan Reservoir (both basins), Cannonsville Reservoir, and Schoharie Reservoir. The useable capacity (the volume between the spillway elevation and the minimum operating level required to deliver full flow for drinking water supply) of the WOH reservoirs decreased by 7.9 Ggal (1.7 percent). The largest decreases in useable capacity were at Ashokan Reservoir, which decreased about 3.1 Ggal, and Cannonsville Reservoir, which decreased by about 2.3 Ggal; the largest percent decrease in useable capacity was at Schoharie Reservoir, which decreased by about 5 percent. The available capacity (the volume between the spillway elevation and the lowest intake or sill elevation used for drinking water supply) of the WOH reservoirs decreased by 10.0 Ggal (2.1 percent). Dead storage (the volume below the lowest intake or sill elevation) decreased by 1.5 Ggal (9.0 percent).

Table 14. Reservoir area and capacity at specified elevations for Ashokan Reservoir, East Basin, New York State.

[Location of reservoir shown in figure 1. Expanded elevation-area-capacity table is available for download at https://dx.doi.org/10.5066/F7P26W7P. NAVD 88, North American Vertical Datum of 1988; BWS, New York City Department of Environmental Protection Bureau of Water Supply; total capacity is total volume at spillway elevation (including dead storage); dead storage is the volume below minimum intake height or sill elevation for drinking water supply; useable capacity is the volume between the spillway elevation and the minimum operating level required to deliver full flow for drinking water supply; available capacity is the volume between the spillway elevation and the lowest intake or sill elevation used for drinking water supply]

Elevation (feet above NAVD 88)	Elevation (feet above BWS reservoir datum)	Depth below spillway (feet)	Area (square miles)	Total capacity (billion gallons)	Useable capacity (billion gallons)	Available capacity (billion gallons)
585.68	587.00	0	7.94	78.526	74.339	78.526
575.68	577.00	10	7.31	62.589	58.402	62.589
565.68	567.00	20	6.36	48.345	44.158	48.345
555.68	557.00	30	5.64	35.790	31.603	35.790
545.68	547.00	40	4.81	24.893	20.706	24.893
535.68	537.00	50	4.11	15.602	11.415	15.602
525.68	527.00	60	2.91	8.061	3.874	8.061
515.68	517.00	70	2.07	2.790	0.000	2.790
505.68	507.00	80	0.60	0.286	0.000	0.286

Table 15. Reservoir area and capacity at specified elevations for Ashokan Reservoir, West Basin, New York State.

[Location of reservoir shown in figure 1. Expanded elevation-area-capacity table is available for download at https://dx.doi.org/10.5066/F7P26W7P. NAVD 88, North American Vertical Datum of 1988; BWS, New York City Department of Environmental Protection Bureau of Water Supply; total capacity is total volume at spillway elevation (including dead storage); dead storage is the volume below minimum intake height or sill elevation for drinking water supply; useable capacity is the volume between the spillway elevation and the minimum operating level required to deliver full flow for drinking water supply; available capacity is the volume between the spillway elevation and the lowest intake or sill elevation used for drinking water supply]

Elevation (feet above NAVD 88)	Elevation (feet above BWS reservoir datum)	Depth below spillway (feet)	Area (square miles)	Total capacity (billion gallons)	Useable capacity (billion gallons)	Available capacity (billion gallons)
588.68	590.00	0	4.81	46.816	41.475	45.101
578.68	580.00	10	4.26	37.353	32.012	35.638
568.68	570.00	20	3.69	29.004	23.663	27.289
558.68	560.00	30	3.14	21.906	16.565	20.191
548.68	550.00	40	2.49	16.041	10.700	14.326
538.68	540.00	50	1.96	11.414	6.073	9.699
528.68	530.00	60	1.43	7.860	2.518	6.145
518.68	520.00	70	1.05	5.341	0.000	3.626
508.68	510.00	80	0.75	3.477	0.000	1.762
498.68	500.00	90	0.52	2.161	0.000	0.446
488.68	490.00	100	0.38	1.251	0.000	0.000
478.68	480.00	110	0.23	0.596	0.000	0.000
468.68	470.00	120	0.10	0.263	0.000	0.000
458.68	460.00	130	0.04	0.127	0.000	0.000
448.68	450.00	140	0.02	0.061	0.000	0.000
438.68	440.00	150	0.01	0.027	0.000	0.000
428.68	430.00	160	0.01	0.010	0.000	0.000

Table 16. Reservoir area and capacity at specified elevations for Cannonsville Reservoir, New York State.

[Location of reservoir shown in figure 1. Expanded elevation-area-capacity table is available for download at https://dx.doi.org/10.5066/F7WM1BJK. NAVD 88, North American Vertical Datum of 1988; BWS, New York City Department of Environmental Protection Bureau of Water Supply; total capacity is total volume at spillway elevation (including dead storage); dead storage is the volume below minimum intake height or sill elevation for drinking water supply; useable capacity is the volume between the spillway elevation and the minimum operating level required to deliver full flow for drinking water supply; available capacity is the volume between the spillway elevation and the lowest intake or sill elevation used for drinking water supply]

Elevation (feet above NAVD 88)	Elevation (feet above BWS reservoir datum)	Depth below spillway (feet)	Area (square miles)	Total capacity (billion gallons)	Useable capacity (billion gallons)	Available capacity (billion gallons)
1,149.58	1,150.00	0	7.37	96.004	93.448	94.379
1,139.58	1,140.00	10	6.68	81.427	78.871	79.802
1,129.58	1,130.00	20	6.16	68.046	65.490	66.421
1,119.58	1,120.00	30	5.66	55.718	53.162	54.093
1,109.58	1,110.00	40	5.09	44.497	41.941	42.872
1,099.58	1,100.00	50	4.47	34.508	31.952	32.883
1,089.58	1,090.00	60	3.77	25.878	23.322	24.253
1,079.58	1,080.00	70	3.13	18.702	16.146	17.077
1,069.58	1,070.00	80	2.48	12.859	10.303	11.234
1,059.58	1,060.00	90	1.87	8.365	5.808	6.739
1,049.58	1,050.00	100	1.36	5.062	2.506	3.437
1,039.58	1,040.00	110	1.05	2.556	0.000	0.931
1,029.58	1,030.00	120	0.57	0.952	0.000	0.000
1,019.58	1,020.00	130	0.19	0.159	0.000	0.000

Table 17. Reservoir area and capacity at specified elevations for Neversink Reservoir, New York State.

[Location of reservoir shown in figure 1. Expanded elevation-area-capacity table is available for download at https://dx.doi.org/10.5066/F71C1V1W. NAVD 88, North American Vertical Datum of 1988; BWS, New York City Department of Environmental Protection Bureau of Water Supply; total capacity is total volume at spillway elevation (including dead storage); dead storage is the volume below minimum intake height or sill elevation for drinking water supply; useable capacity is the volume between the spillway elevation and the minimum operating level required to deliver full flow for drinking water supply; available capacity is the volume between the spillway elevation and the lowest intake or sill elevation used for drinking water supply]

Elevation (feet above NAVD 88)	Elevation (feet above BWS reservoir datum)	Depth below spillway (feet)	Area (square miles)	Total capacity (billion gallons)	Useable capacity (billion gallons)	Available capacity (billion gallons)
1,439.21	1,440.00	0	2.38	36.647	34.692	35.163
1,429.21	1,430.00	10	2.20	31.871	29.916	30.387
1,419.21	1,420.00	20	2.02	27.478	25.523	25.994
1,409.21	1,410.00	30	1.85	23.455	21.500	21.971
1,399.21	1,400.00	40	1.67	19.771	17.816	18.287
1,389.21	1,390.00	50	1.50	16.465	14.510	14.981
1,379.21	1,380.00	60	1.34	13.506	11.551	12.022
1,369.21	1,370.00	70	1.19	10.868	8.913	9.384
1,359.21	1,360.00	80	1.04	8.543	6.588	7.059
1,349.21	1,350.00	90	0.91	6.513	4.558	5.029
1,339.21	1,340.00	100	0.79	4.734	2.779	3.250
1,329.21	1,330.00	110	0.65	3.224	1.269	1.739
1,319.21	1,320.00	120	0.49	2.055	0.100	0.571
1,309.21	1,310.00	130	0.37	1.153	0.000	0.000
1,299.21	1,300.00	140	0.25	0.505	0.000	0.000
1,289.21	1,290.00	150	0.12	0.130	0.000	0.000

Table 18. Reservoir area and capacity at specified elevations for Pepacton Reservoir, New York State.

[Location of reservoir shown in figure 1. Expanded elevation-area-capacity table is available for download at https://dx.doi.org/10.5066/F7DJ5CSM. NAVD 88, North American Vertical Datum of 1988; BWS, New York City Department of Environmental Protection Bureau of Water Supply; total capacity is total volume at spillway elevation (including dead storage); dead storage is the volume below minimum intake height or sill elevation for drinking water supply; useable capacity is the volume between the spillway elevation and the minimum operating level required to deliver full flow for drinking water supply; available capacity is the volume between the spillway elevation and the lowest intake or sill elevation used for drinking water supply]

Elevation (feet above NAVD 88)	Elevation (feet above BWS reservoir datum)	Depth below spillway (feet)	Area (square miles)	Total capacity (billion gallons)	Useable capacity (billion gallons)	Available capacity (billion gallons)
1,278.81	1,280.00	0	8.82	148.690	139.320	142.372
1,268.81	1,270.00	10	8.25	130.890	121.520	124.572
1,258.81	1,260.00	20	7.68	114.270	104.900	107.952
1,248.81	1,250.00	30	7.00	98.946	89.576	92.628
1,238.81	1,240.00	40	6.36	85.047	75.677	78.729
1,228.81	1,230.00	50	5.72	72.468	63.098	66.150
1,218.81	1,220.00	60	5.19	61.089	51.719	54.771
1,208.81	1,210.00	70	4.74	50.766	41.396	44.448
1,198.81	1,200.00	80	4.31	41.312	31.942	34.994
1,188.81	1,190.00	90	3.88	32.778	23.408	26.460
1,178.81	1,180.00	100	3.39	25.179	15.809	18.861
1,168.81	1,170.00	110	2.88	18.643	9.273	12.325
1,158.81	1,160.00	120	2.42	13.098	3.728	6.780
1,148.81	1,150.00	130	1.96	8.532	0.000	2.214
1,138.81	1,140.00	140	1.53	4.904	0.000	0.000
1,128.81	1,130.00	150	1.07	2.165	0.000	0.000
1,118.81	1,120.00	160	0.50	0.515	0.000	0.000
1,108.81	1,110.00	170	0.05	0.028	0.000	0.000

Table 19. Reservoir area and capacity at specified elevations for Rondout Reservoir, New York State.

[Location of reservoir shown in figure 1. Expanded elevation-area-capacity table is available for download at https://dx.doi.org/10.5066/F7542KR6. NAVD 88, North American Vertical Datum of 1988; BWS, New York City Department of Environmental Protection Bureau of Water Supply; total capacity is total volume at spillway elevation (including dead storage); dead storage is the volume below minimum intake height or sill elevation for drinking water supply; useable capacity is the volume between the spillway elevation and the minimum operating level required to deliver full flow for drinking water supply; available capacity is the volume between the spillway elevation and the lowest intake or sill elevation used for drinking water supply]

Elevation (feet above NAVD 88)	Elevation (feet above BWS reservoir datum)	Depth below spillway (feet)	Area (square miles)	Total capacity (billion gallons)	Useable capacity (billion gallons)	Available capacity (billion gallons)
838.88	840.00	0	3.27	51.770	49.060	49.480
828.88	830.00	10	3.03	45.221	42.511	42.931
818.88	820.00	20	2.83	39.115	36.405	36.825
808.88	810.00	30	2.60	33.442	30.732	31.152
798.88	800.00	40	2.38	28.261	25.551	25.971
788.88	790.00	50	2.23	23.457	20.747	21.167
778.88	780.00	60	2.05	18.991	16.281	16.701
768.88	770.00	70	1.82	14.938	12.228	12.648
758.88	760.00	80	1.55	11.432	8.722	9.142
748.88	750.00	90	1.30	8.450	5.740	6.160
738.88	740.00	100	1.10	5.947	3.236	3.657
728.88	730.00	110	0.88	3.873	1.163	1.583
718.88	720.00	120	0.64	2.290	0.000	0.000
708.88	710.00	130	0.43	1.188	0.000	0.000
698.88	700.00	140	0.25	0.489	0.000	0.000
688.88	690.00	150	0.10	0.137	0.000	0.000
678.88	680.00	160	0.02	0.018	0.000	0.000

Table 20. Reservoir area and capacity at specified elevations for Schoharie Reservoir, New York State.

[Location of reservoir shown in figure 1. Expanded elevation-area-capacity table is available for download at https://dx.doi.org/10.5066/F7J964HB. NAVD 88, North American Vertical Datum of 1988; BWS, New York City Department of Environmental Protection Bureau of Water Supply; total capacity is total volume at spillway elevation (including dead storage); dead storage is the volume below minimum intake height or sill elevation for drinking water supply; useable capacity is the volume between the spillway elevation and the minimum operating level required to deliver full flow for drinking water supply; available capacity is the volume between the spillway elevation and the lowest intake or sill elevation used for drinking water supply]

Elevation (feet above NAVD 88)	Elevation (feet above BWS reservoir datum)	Depth below spillway[1] (feet)	Area (square miles)	Total capacity (billion gallons)	Useable capacity (billion gallons)	Available capacity (billion gallons)
1,128.63	1,129.73	0	1.76	19.599	16.601	18.240
1,118.63	1,119.73	10	1.56	16.155	13.157	14.796
1,108.63	1,109.73	20	1.43	13.049	10.051	11.690
1,098.63	1,099.73	30	1.31	10.189	7.191	8.830
1,088.63	1,089.73	40	1.17	7.604	4.606	6.245
1,078.63	1,079.73	50	0.94	5.361	2.363	4.002
1,068.63	1,069.73	60	0.72	3.653	0.655	2.294
1,058.63	1,059.73	70	0.57	2.306	0.000	0.947
1,048.63	1,049.73	80	0.37	1.338	0.000	0.000
1,038.63	1,039.73	90	0.23	0.726	0.000	0.000
1,028.63	1,029.73	100	0.12	0.373	0.000	0.000
1,018.63	1,019.73	110	0.08	0.167	0.000	0.000
1,008.63	1,009.73	120	0.03	0.049	0.000	0.000

[1]After spillway reconstruction, completed 2015.

Table 21. Effect of linear enforcement on calculated capacity at spillway elevations in the West of Hudson reservoirs in New York State.

[Location of reservoir shown in figure 1. Rows in italics present duplicative information and are not included in calculation of West of Hudson reservoirs total. TIN, triangulated irregular network]

Reservoir	Capacity at spillway, linearly enforced TIN (billion gallons)	Capacity at spillway, unedited TIN, (billion gallons)	Difference (billion gallons)	Difference (percent)
Ashokan (East Basin)	78.526	78.086	-0.440	-0.6
Ashokan (West Basin)	46.816	46.149	-0.667	-1.4
Ashokan (Total)	*125.342*	*124.235*	*-1.107*	*-0.9*
Cannonsville	96.004	94.935	-1.069	-1.1
Neversink	36.647	36.326	-0.321	-0.9
Pepacton	148.690	146.530	-2.160	-1.5
Rondout	51.770	51.454	-0.316	-0.6
Schoharie[1]	19.599	19.467	-0.132	-0.7
Total	478.052	472.947	-5.105	-1.1

[1]After spillway reconstruction, completed 2015.

Table 22. Summary of change in reservoir capacity since construction in the West of Hudson reservoirs in New York State.

[Location of reservoir shown in figure 1. Rows in italics present duplicative information and are not included in calculation of West of Hudson reservoirs total. Total capacity is total volume at spillway elevation (including dead storage); useable capacity is the volume between the spillway elevation and the minimum operating level required to deliver full flow for drinking water supply; available capacity is the volume between the spillway elevation and the lowest intake or sill elevation used for drinking water supply; dead storage is the volume below minimum intake height or sill elevation for drinking water supply; green shaded cells, change in total capacity at spillway elevation exceeds the 95-percent confidence interval computed using both the mean signed error and the mean absolute error (table 13); blue shaded cells, change in total capacity at spillway elevation exceeds the 95-percent confidence interval computed using the mean signed error but not the mean absolute error (table 13); --, not applicable]

Reservoir	As built[1] (billions of gallons)				At time of survey (billions of gallons)				Change (billions of gallons)				Change (percent)			
	Total capacity at spillway	Useable capacity	Available capacity	Dead storage	Total capacity at spillway	Useable capacity	Available capacity	Dead storage	Total capacity at spillway	Useable capacity	Available capacity	Dead storage	Total capacity at spillway	Useable capacity	Available capacity	Dead storage
Ashokan (East Basin)	80.678	75.683	80.678	0.000	78.526	74.339	78.526	0.000	-2.152	-1.344	-2.152	0.000	-2.7	-1.8	-2.7	--
Ashokan (West Basin)	49.417	43.199	47.180	2.237	46.816	41.475	45.101	1.715	-2.601	-1.724	-2.079	-0.522	-5.3	-4.0	-4.4	-23.3
Ashokan (Total)	*130.095*	*118.882*	*127.858*	*2.237*	*125.342*	*115.814*	*123.627*	*1.715*	*-4.753*	*-3.068*	*-4.231*	*-0.522*	*-3.7*	*-2.6*	*-3.3*	*-23.3*
Cannonsville	98.618	95.706	96.726	1.892	96.004	93.448	94.379	1.625	-2.614	-2.258	-2.347	-0.267	-2.7	-2.4	-2.4	-14.1
Neversink	37.146	34.941	35.466	1.680	36.647	34.692	35.163	1.484	-0.499	-0.249	-0.303	-0.196	-1.3	-0.7	-0.9	-11.7
Pepacton	149.799	140.190	143.701	6.098	148.690	139.320	142.372	6.318	-1.109	-0.870	-1.329	0.220	-0.7	-0.6	-0.9	3.6
Rondout	52.435	49.617	50.048	2.387	51.770	49.060	49.480	2.290	-0.665	-0.557	-0.568	-0.097	-1.3	-1.1	-1.1	-4.1
Schoharie (before spillway reconstruction in 2015)	21.551	17.582	19.583	1.968	19.698	16.700	18.339	1.359	-1.853	-0.882	-1.244	-0.609	-8.6	-5.0	-6.4	-30.9
Schoharie (after spillway reconstruction in 2015)	*21.454*	*17.485*	*19.486*	*1.968*	*19.599*	*16.601*	*18.240*	*1.359*	*-1.855*	*-0.884*	*-1.246*	*-0.609*	*-8.6*	*-5.1*	*-6.4*	*-30.9*
Total	489.644	456.918	473.382	16.262	478.151	449.034	463.360	14.791	-11.493	-7.884	-10.022	-1.471	-2.3	-1.7	-2.1	-9.0

[1]From published U.S. Geological Survey annual summaries (U.S. Geological Survey, 2016a–f).

Summary

Bathymetric surveys of the six West of Hudson (WOH) reservoirs that supply water to New York City—Ashokan, Cannonsville, Neversink, Pepacton, Rondout, and Schoharie—were completed by the U.S. Geological Survey, in cooperation with the New York City Department of Environmental Protection, from 2013 to 2015 to provide updated and more accurate elevation-area-capacity tables and bathymetric maps. Depths were measured using a single-beam echo sounder, horizontal positions were measured using a real-time kinematic global positioning system, and reservoir-bottom elevations were referenced to observed water surface elevations. Planned transects were spaced to achieve a ratio of transect spacing to reservoir length of 1 percent or less and were aligned to be perpendicular to the long axis of the reservoir. A second quality assurance set of echo sounder data was collected at oblique angles to the main transects for elevation-accuracy assessment. Data were integrated and processed using HYPACK, including corrections for speed of sound, before being imported to a geographic information system. Surfaces were created using triangulated irregular networks (TINs) and were edited to more accurately represent geomorphic features; without this editing for linear enforcement, the total capacity of the WOH reservoirs would have been underestimated by about 5 Ggal, or 1.1 percent. Elevation-area-capacity tables were calculated at 0.01-foot (ft) intervals from the edited TINs, and contours were mapped at 2-ft intervals from a raster conversion of the edited TINs.

Quality assurance data points were compared with the main data points, mapped surfaces, and contours and showed that for the combined results of the six reservoir surveys the directly measured points have better accuracy (2.10 ft at the 95-percent confidence level as defined by the National Standard for Spatial Data Accuracy [NSSDA]) than mapped surfaces (4.91 ft for edited TINs) or mapped contours (6.80 ft). Linear enforcement of the TIN surfaces improved accuracy by 2.51 ft overall. Users should be aware that the 95-percent confidence level accuracy of the mapped contours is larger than the contour interval (that is, greater than 2 ft) at all of the WOH reservoirs. The 95-percent confidence interval calculated for total capacity at spillway elevations was 0.6 percent or less when calculated using the mean signed error of the TIN surfaces and 3.0 percent or less when calculated using the mean absolute error of the TIN surfaces.

The results of the surveys show that the total capacity of the WOH reservoirs has decreased 11.5 Ggal (2.3 percent) since construction. The largest changes in capacity occurred at Cannonsville and Ashokan Reservoirs; the largest percent change in capacity occurred at Schoharie Reservoir. The useable capacity of the WOH reservoirs decreased by 7.9 Ggal (1.7 percent). Digital data products, including echo sounder points, TIN and raster surfaces, contour maps, and elevation-area-capacity tables are available for download online at https://dx.doi.org/10.5066/F7P26W7P (Ashokan Reservoir), https://dx.doi.org/10.5066/F7WM1BJK (Cannonsville Reservoir), https://dx.doi.org/10.5066/F71C1V1W (Neversink Reservoir), https://dx.doi.org/10.5066/F7DJ5CSM (Pepacton Reservoir), https://dx.doi.org/10.5066/F7542KR6 (Rondout Reservoir), and https://dx.doi.org/10.5066/F7J964HB (Schoharie Reservoir).

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