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

Prepared in cooperation with the
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Scientific Investigations Map 3409

Figure 1. Location of Clearwater Lake near Piedmont, Missouri.

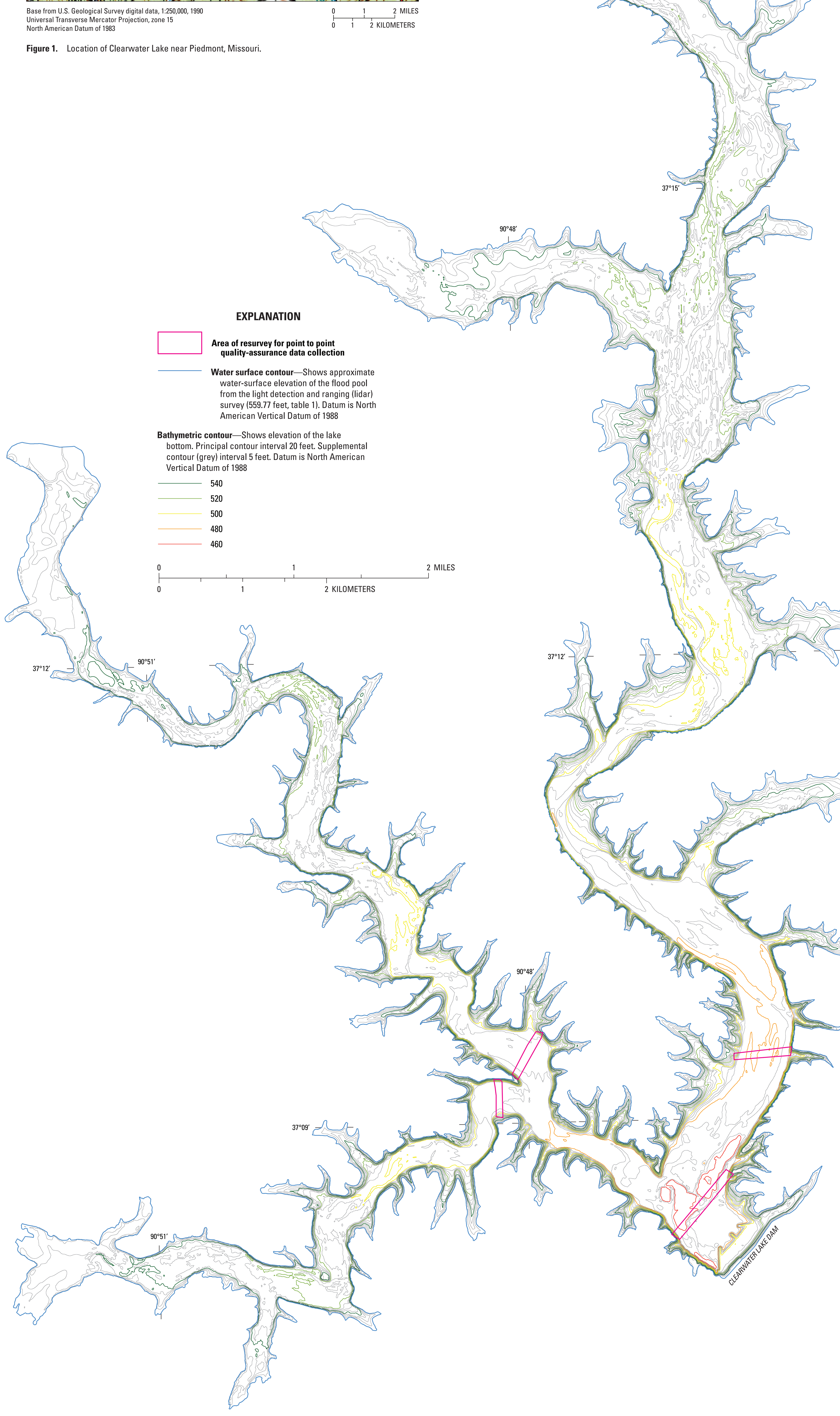

Figure 2. Bathymetric contours for Clearwater Lake near Piedmont, Missouri, resulting from survey made May 3–11, 2017.

Introduction

Clearwater Lake, on the Black River near Piedmont in Reynolds County, Missouri, (fig. 1) was constructed in 1948 and is operated by the U.S. Army Corps of Engineers (USACE) for flood-risk reduction, recreation, and fish and wildlife habitat (U.S. Army Corps of Engineers, [n.d.]). The lake area is about 1,800 acres with about 34 miles of shoreline at the conservation pool elevation of 498 feet (ft). Since the completion of the lake in 1948, sedimentation likely has caused the storage capacity of the lake to decrease gradually. The loss of storage capacity can decrease the effectiveness of the lake to mitigate flooding, and excessive sediment accumulation also can reduce aquatic habitat in some areas of the lake. Many lakes operated by the USACE have periodic bathymetric and sediment surveys to monitor the status of the lake. The U.S. Geological Survey completed one such survey of Clearwater Lake in 2008 during a period of high lake level using bathymetric surveying equipment consisting of a multibeam echosounder (MBES), a singlebeam echosounder, 1/3 arc-second National Elevation Dataset data (used outside the MBES survey extent; https://nationalmap.gov/elevation.html), and the waterline derived from 2008 aerial light detection and ranging (lidar) data (Richards, 2013). In May 2017, the U.S. Geological Survey, in cooperation with the USACE, surveyed the bathymetry of Clearwater Lake to prepare an updated bathymetric map and a surface area and capacity table. The 2008 survey was contrasted with the 2017 survey to document the changes in the bathymetric surface of the lake.

Methods

A bathymetric survey was done from May 3 to 11, 2017, at Clearwater Lake using similar methods to the previous survey completed in 2008 (Richards, 2013). The average water-surface elevation of the lake during the 2017 survey was 559.77 ft. A bathymetric surface, a bathymetric contour map, and a difference map were created from the survey data.

Bathymetric Data Collection

Bathymetric data (water depths and positions) were collected (fig. 2) using a high-resolution multibeam mapping system (MBMS). The various components of the MBMS used for this study are described in more detail in reports about studies on the Missouri and Mississippi Rivers in Missouri (for example, see Huizinga, 2010, 2017; Huizinga and others, 2010) and for the City of Cameron water supply lakes (Huizinga, 2014). The survey methods used to obtain the data for Clearwater Lake were similar to those of these other studies, as were the methods used to ensure data quality. A brief description of the equipment and methods follows.

An MBMS is an integration of several individual components: the MBES, an inertial navigation system (INS), and a data-collection and data-processing computer. The INS provides position in three-dimensional space and measures the heave, pitch, roll, and heading of the vessel (and, thereby, the MBES) to accurately position the data received by the MBES.

Real-time navigation during the survey used a Differential Global Position System (DGPS) solution; however, the navigation information from the Clearwater Lake survey was postprocessed using the POS-Pac™ Mobile Mapping Suite (MMS™) software (Applanix Corporation, 2009) to mitigate the effects of the degraded positional accuracy of the vessel from the DGPS solution. POS-Pac™ MMS™ provides tools to identify and compensate for sensor and environmental errors and computes an optimally blended navigation solution from the Global Navigation Satellite Systems (GNSS) and inertial measurement unit raw data from the INS. The location solution was further enhanced by collecting static GNSS data with a GNSS base receiver set up over a documented benchmark at the dam, using techniques detailed in Rydlund and Densmore (2012). The blended navigation solution (called a “smoothed best estimate of trajectory” or “SBET” file) generated by postprocessing the daily navigation data was applied to the respective day of data collection in the survey.

Bathymetric data within the conservation pool area of Clearwater Lake (fig. 3) were collected with the MBES sound navigation and ranging (sonar) head oriented horizontally. However, along the banks in the conservation pool area and in the area above the conservation pool, the MBES head was tilted at 30 degrees to port to enhance acquisition of bathymetric data in the shallow areas near the banks, in coves, and in the upper reaches of the lake arms and to cover a wider swath of the bottom compared to when the head was not tilted.

The bathymetric data were collected along transect lines oriented longitudinally in the main lake area. In the conservation pool area, the transect lines were spaced to create about 10- to 25-percent overlap of the survey swaths to attempt to ensure complete coverage of the lake bottom and minimize sonic shadows. In the areas above the conservation pool, the transect lines were about 250 ft apart, resulting in partial lake-bottom coverage in these areas because it was shallower, had less bathymetric relief, and had more surface obstructions to navigation. Shoreline data were collected by travelling along the edge of the data collected along the longitudinal survey lines to ensure overlap of the shoreline data with the main body data. Cove data were collected by navigating into a cove along the approximate centerline of the cove as far as practical (usually, the point at which forward progress was blocked by thick timber, or water depth decreased to less than about 3 ft), pivoting the boat 180 degrees, and egressing the cove along the ingress line.

In a lake, it is not unusual for the speed of sound in the water to change over time and to vary spatially. The speed of sound also can vary over the water column because of water temperature variations with depth. Although sound velocity data are collected at the MBES head throughout the survey to mitigate these variations near the water surface, the changes in the speed of sound with depth needs to be known to accurately determine the depths acquired by the MBES. Therefore, sound velocity profiles were measured at various locations throughout each survey day and applied during postprocessing in the HYPACK®/HYSWEEP® software.

Preparation for the bathymetric survey was done in HYPACK®/HYSWEEP® (HYPACK, Inc., 2015). To collect the survey data, a computer onboard the survey vessel ran HYPACK®/HYSWEEP® data acquisition software. After completing the surveys, the acquired depth data were processed further to apply sound velocity profiles and to remove data spikes and other spurious points in the MBES swath trace, georeferenced using the navigation and position solution data from the SBET file from POS-Pac™ MMS™, and visualized in HYPACK®/HYSWEEP® as a triangulated irregular network (TIN) surface or a point cloud. The georeferenced data were output to a comma-delimited file that was filtered and reduced to a 3.28-ft data resolution.

Bathymetric Surface and Contour Map Creation

The data collected by the 2017 MBES survey represented about 56 percent of the flood pool lake area (fig. 2), whereas the 2008 survey represented about 40 percent. About 19,000,000 data points (Richards and Huizinga, 2018), spaced 3.28-ft horizontally, were exported from the raw data collected in the 2017 survey. The vertical datum for the survey was the North American Vertical Datum of 1988, and the horizontal datum was the North American Datum of 1983. Geographic information system (GIS) software was used to filter the 3.28-ft spaced bathymetric data points so that the points would be no closer than about 16.4 ft apart. The data reduction retained about 715,000 surveyed data points from the 2017 MBES survey.

Data for the remaining 44 percent of the flood pool area (fig. 2), where direct surveying with the MBES was not possible (for example, where wooded or too shallow), was obtained from the 2008 bathymetric surface and sampled at a 16.4-ft spacing (about 581,000 points). In addition, about 600 additional points were added to the dataset based on surrounding 2017 data values using the linear enforcement techniques described in Wilson and Richards (2006). These data were added to anchor the surface in areas of sparse data such as in the upper ends of coves and along near vertical bluffs where the 16.4-ft spacing could not constrain the steep elevation change.

These three point datasets, in combination with the water-surface elevation line derived from 2008 lidar data, were used to produce a three-dimensional TIN surface of the lake-bottom elevations. A surface area and capacity table was produced from the three-dimensional TIN surface showing surface area and capacity at specified lake water-surface elevations (table 1). The surface was contoured at a 5-ft interval using GIS software, and the contours were cartographically smoothed and edited to create a bathymetric contour map (fig. 2) using the techniques of Wilson and Richards (2006).

Bathymetric Difference Map Creation

The bathymetric difference map (fig. 3) was computed as the difference between the 2008 and 2017 bathymetric surfaces. The 2008 map was based on a 16.4-ft gridded set of points, and the 2017 map was based on a similar spacing of data. To compute the bathymetric difference, 16.4-ft raster surfaces were interpolated linearly from the bathymetric TIN surfaces for each survey, and then the 2008 16.4-ft raster surface was subtracted from the 2017 16.4-ft raster surface. The bathymetric difference map was limited to the intersection of the 2008 and 2017 MBES survey extents so that only data that were surveyed by the MBES were compared. Because the uncertainty is larger and vertical accuracy of the MBES typically is worse in areas of steep slope (see “Uncertanty Estimation” section, fig. 4; and “Bathymetric Surface and Contour Map Quality Assurance” section, fig. 5) and bathymetric change was assumed to be minor in these areas, raster cells that had a 2017 slope greater than 16.6 degrees (about 5 percent of the 2017 slope values) also were removed from the map.

Bathymetric Data Collection Quality Assurance

For the MBMS, the principal quality-assurance measures were assessed in real time during the survey. The MBMS operator continuously assessed the quality of the data collected during the survey by making observations of across-track swaths (such as convex, concave, or skewed bed returns in flat, smooth bottoms), noting data quality flags and alarms from the MBES and the INS, and inspecting comparisons between adjacent overlapping swaths. In addition to the real-time quality-assurance assessments during the survey, beam angle checks and a suite of patch tests were done on May 3 before the survey to ensure quality data were acquired from the MBMS. These tests were completed in the deepest part of Clearwater Lake near Clearwater Lake Dam. Additional patch tests were completed on May 4, after a substantial strike of the MBES head on a submerged stob, and on May 8, at the beginning of a new survey week with a different boat operator.

Beam Angle Check

A beam angle check is used to determine the accuracy of the depth readings obtained by the outer beams (greater than 25 degrees from nadir [vertical]) of the MBES (U.S. Army Corps of Engineers, 2013), which may change with time because of inaccurate sound velocities, physical configuration changes, and water depth. On the first day of surveying on May 3, a beam angle check was done, and the results were within the recommended performance standards used by the U.S. Army Corps of Engineers for hydrographic surveys for all the representative angles below 50 degrees (U.S. Army Corps of Engineers, 2013), permitting the use of the central 100 degrees of the sonar swath with confidence.

Patch Tests

Patch tests are a series of dynamic calibration tests that are used to check for subtle variations in the orientation and timing of the MBES with respect to the INS and real-world coordinates. The patch tests are used to determine timing offsets caused by latency between the MBES and the INS, and angular offsets to roll, pitch, and yaw caused by the alignment of the transducer head (Huizinga, 2017). These offsets have been observed to be essentially constant for a given survey, barring an event that causes the mount to change such as striking a floating or submerged object (see Huizinga, 2017). The offsets determined in the patch test are applied when processing the data collected during a survey. Patch tests were completed on May 3, 4, and 8, 2017, at Clearwater Lake, and angular offsets were updated in the data collection software as appropriate. For this study, there was no measured timing offset, which is consistent with latency test results for this boat and similar equipment configurations used in other surveys (Huizinga, 2010, 2017; Huizinga and others, 2010).

Uncertainty Estimation

Similar to the previous studies of bathymetry in Missouri (Huizinga, 2010, 2017), uncertainty in the survey was estimated by computing the total propagated uncertainty (TPU) for each 3.28-ft survey-grid cell in the surveyed area using the Combined Uncertainty and Bathymetric Estimator (CUBE) method (Calder and Mayer, 2003). The CUBE method allows all random system component uncertainties and resolution effects to be combined and propagated through the data processing steps, which provides a robust estimate of the spatial distribution of possible uncertainty within the survey area (Czuba and others, 2011). Thus, the TPU of a point is a measure of the accuracy to be expected for such a point when all relevant error sources are taken into account (Czuba and others, 2011).

Most of the TPU values (93 percent) were less than 0.50 ft, which is within the specifications for a “Special Order” survey, the most-stringent survey standard of the International Hydrographic Organization (International Hydrographic Organization, 2008). The median TPU value of the data was about 0.20 ft. The largest TPU in this survey was about 2.69 ft; however, TPU values of this magnitude typically are found near high-relief features, such as the nearly vertical banks that exist on some parts of the lake (fig. 2). The TPU values were larger near moderate-relief features (steep banks and submerged channels and ridges; fig. 2). The TPU values also were sometimes larger (1.00 ft or greater) in the outermost beam extents of the MBES swath in the overlap with an adjacent swath, particularly when the MBES head was tilted for the survey lines along the banks or in the upper extent of the lake (fig. 4).

Bathymetric Surface and Contour Map Quality Assurance

Accuracy of the bathymetric surface and contours is a function of the survey data accuracy, density of the survey data, and the processing steps involved in the surface and contour creation. The process of data reduction done to obtain the 3.28-ft gridded dataset from the raw survey data likely degraded the accuracy of the 3.28-ft gridded dataset relative to the raw data. Four areas of the lake were surveyed twice (fig. 2) to collect a dataset that could be used to estimate the accuracy of the 3.28-ft gridded dataset used to produce the bathymetric surface. The four areas had a combined total of about 2,930,000 raw survey points. Raw points that were within a horizontal distance of 0.33 ft of a 3.28-ft gridded point were selected as quality-assurance data points, and the elevation values of these points were compared to the 3.28-ft gridded points. The 93,361 selected raw points were compared to 3.28-ft gridded points, and the data tested at a vertical accuracy of 0.77 ft at a 95-percent confidence level; the median absolute vertical error was about 0.23 ft.

The quality-assurance dataset used to evaluate the bathymetric surface included about 910,000 data points selected at random from the about 19,000,000, 3.28-ft data points. Points that were used to create the bathymetric surface were not included as quality-assurance points. The three-dimensional bathymetric surface was tested against the quality-assurance dataset to determine the vertical accuracy of the surface using methods described in Wilson and Richards (2006). The surface tested at a vertical accuracy of 1.33 ft at the 95-percent confidence level; the median absolute vertical error was about 0.12 ft. The three-dimensional bathymetric surface was used as the source for the computation of the surface area and capacity values in table 1, the source for the development of the bathymetric contour map (fig. 2), and the source for the bathymetric difference map (fig. 3).

The process of smoothing and cartographic editing of the bathymetric contours to produce an aesthetic map degrades the positional and vertical accuracy of the contours; however, the contours are used primarily for visualization of the surface in an illustration, so some accuracy degradation is expected. The bathymetric contours (fig. 2) were tested with the same quality-assurance dataset used to evaluate the bathymetric surface. A point was considered a contour elevation evaluation point if it was within a horizontal distance of 0.66 ft of a given contour line. Of the about 910,000 quality-assurance points, 18,607 points were selected as evaluation points for the contour lines, and the contour vertical accuracy was computed to be 5.85 ft at the 95-percent confidence level; the median absolute vertical error was about 0.92 ft.

Bathymetry, Capacity, and Bathymetric Change

A bathymetric surface was created from the current (2017) surveyed data and used to produce a bathymetric contour map (fig. 2). The bathymetric map is similar to the map produced from the 2008 survey (appendix of Richards, 2013). The lake bathymetric contours show that the submerged Black River channel and the tributary stream channels are still present and are still well-defined in some areas at and below the 500-ft contour (fig. 2). There is evidence of the Black River channel, although somewhat muted, all the way to Clearwater Lake Dam (fig. 2).

A surface area and capacity table (table 1) was computed from the bathymetric surface. At the conservation pool elevation of 498 ft, the surface area of the lake is 1,800 acres and the capacity is 26,800 acre-feet (table 1). The area and capacity table is similar to the previous 2008 survey; however, on average, the survey areas shown on table 1 are about 2 percent larger and capacities are about 1 percent larger than the survey completed in 2008. The differences in the table may exist, in part, because a somewhat larger area of the lake was surveyed in 2017 because the lake level was higher in 2017 than in 2008, and because parts of the lake were surveyed with the MBES head tilted that allowed greater MBES data collection in shallow water where values were estimated in 2008.

The area of bathymetric change below the tested accuracy of the 2017 bathymetric surface (1.33 ft) is shown as a light tan color on the map (fig. 3). This large area of the bathymetric difference map indicated change below the tested accuracy of the 2017 bathymetric surface, so the changes in these areas may or may not be the result of deposition and erosion or a survey or data processing artifact. The bathymetric difference map shows some erosional and depositional areas along the Black River and some of the tributary channels along the upper reaches of the conservation pool elevation of about 498 ft. Areas of erosion and deposition on the map, particularly in the upper reaches of the lake and along the edge of the bathymetric difference map that are collocated with areas of greater survey uncertainty (fig. 4) and areas of larger vertical accuracy differences (fig. 5), are less likely to represent real change between the 2008 and 2017 surveys and more likely to be the result of some survey or data processing artifacts.

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Table 1. Surface area and capacity at specified water surface elevations for Clearwater Lake near Piedmont, Missouri, May 3–11, 2017.

[Conservation pool elevation is about 498 feet (fig. 3); the approximate flood-pool water-surface elevation during the survey was 559.77 feet (fig. 2)]

Water surface elevation, in feet	Surface area, in acres	Capacity, in acre-feet
458.0	30.2	32.8
460.0	60.5	126
462.0	73.9	262
464.0	84.9	421
466.0	102	607
468.0	118	826
470.0	159	1,090
472.0	258	1,500
474.0	335	2,100
476.0	428	2,860
478.0	538	3,820
480.0	642	5,000
482.0	761	6,400
484.0	885	8,050
486.0	1,020	9,950
488.0	1,170	12,100
490.0	1,300	14,600
492.0	1,390	17,300
494.0	1,500	20,200
496.0	1,650	23,400
498.0	1,800	26,800
500.0	1,970	30,600
502.0	2,160	34,700
504.0	2,360	39,200
506.0	2,570	44,200
508.0	2,750	49,500
510.0	2,950	55,200
512.0	3,150	61,300
514.0	3,340	67,800
516.0	3,550	74,600
518.0	3,770	82,000
520.0	3,980	89,700
522.0	4,190	97,900
524.0	4,400	106,000
526.0	4,620	116,000
528.0	4,850	125,000
530.0	5,080	135,000
532.0	5,320	145,000
534.0	5,540	156,000
536.0	5,790	167,000
538.0	6,040	179,000
540.0	6,300	192,000
542.0	6,580	205,000
544.0	6,930	218,000
546.0	7,260	232,000
548.0	7,610	247,000
550.0	7,960	263,000
552.0	8,250	279,000
554.0	8,530	296,000
556.0	8,830	313,000
558.0	9,260	331,000
559.77	9,630	348,000

[1]Elevations are referenced to the North American Vertical Datum of 1988.

[2]Capacities were calculated from surface testing at 1.33-foot vertical accuracy at a 95-percent confidence level.

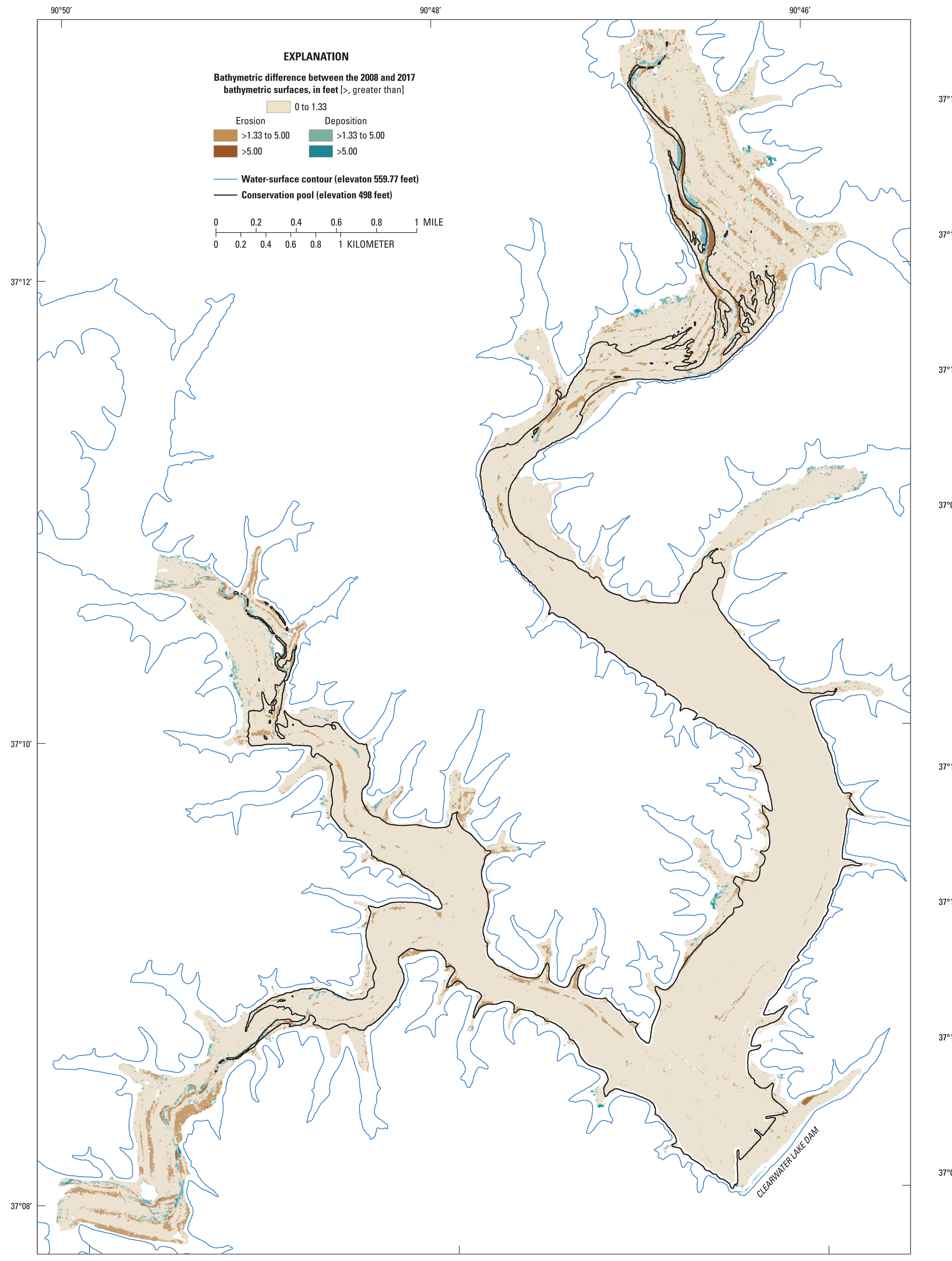

Figure 3. Bathymetric difference between the 2008 survey and the 2017 survey of Clearwater Lake near Piedmont, Missouri.

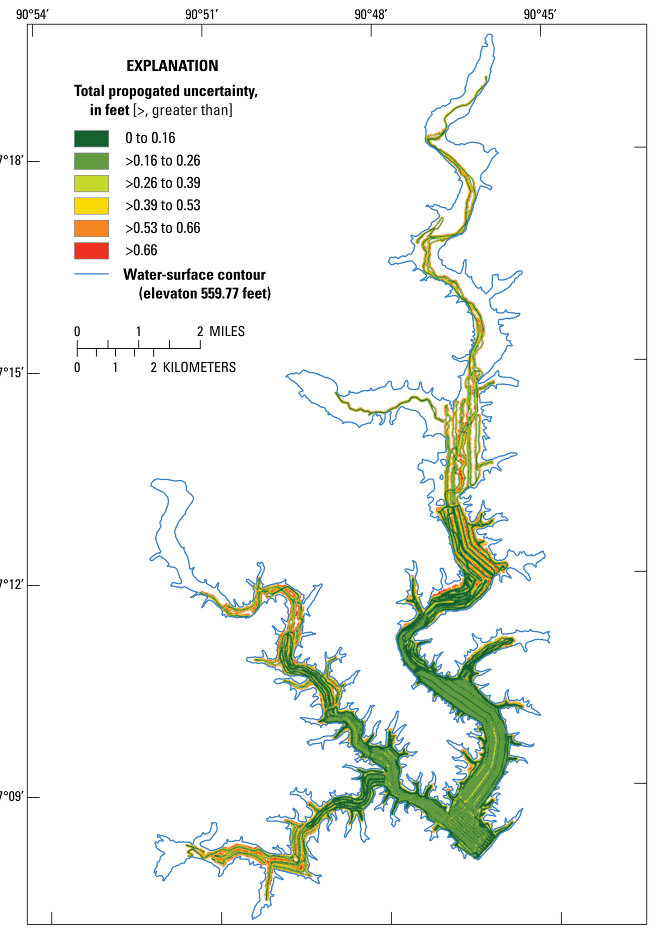

Figure 4. Total propagated uncertainty of bathymetric data from the survey of Clearwater Lake near Piedmont, Missouri, 2017.

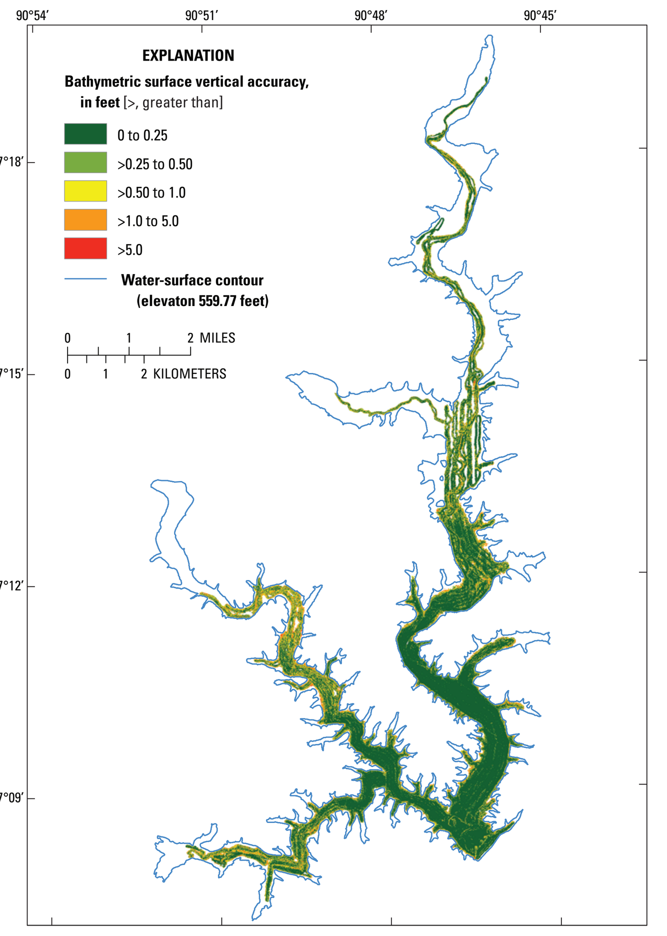

Figure 5. Vertical accuracy of the bathymetric surface of Clearwater Lake near Piedmont, Missouri, 2017.

Bathymetric Contour Map, Surface Area and Capacity Table, and Bathymetric Difference Map for Clearwater Lake near Piedmont, Missouri, 2017

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