Prepared in cooperation with the Missouri Department of Natural Resources

Bathymetric Contour Maps, Surface Area and Capacity Tables, and Bathymetric Change Maps for Selected Water-Supply Lakes in Northeastern Missouri, 2021

Scientific Investigations Report 2023–5108

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

Cover. Top: Photograph showing an acoustic Doppler current profiler being towed by a kayak collecting single beam data, taken at Hazel Creek Lake on May 4, 2021, by Richard Huizinga, U.S. Geological Survey.

Lower left: Photograph showing Global Positioning System equipment, taken at New Marceline City Lake on March 31, 2021, by Richard Huizinga, U.S. Geological Survey.

Lower right: Photograph showing a remote-controlled boat being used for data collection, taken at Memphis Lake (Lake Showme) on April 23, 2021, by Richard Huizinga, U.S. Geological Survey.

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By Benjamin C. Rivers, Richard J. Huizinga, Joseph M. Richards, and
Garett J. Waite

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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	
acre	4046.86	square meter (m^2)
	Volume	
acre-foot (acre-ft)	1233.48	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
	Flux rate	
acre-foot per year (acre-ft/yr)	1,233.48	Cubic meter per year (m^3/yr)
foot per year (ft/yr)	0.3048	Meter per year (m/yr)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88), using the geoid model GEOID18.

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

Supplemental Information

Frequency is given in kilohertz (kHz).

Data were collected, processed, and output in the International System of Units, and converted to U.S. customary units for presentation in the maps at the request and for the convenience of the cooperator.

Abbreviations

ADCP	acoustic Doppler current profiler
CUBE	Combined Uncertainty and Bathymetry Estimator
DGPS	Differential Global Positioning System
GIS	geographic information system
GNSS	Global Navigation Satellite System
IMU	inertial measurement unit
INS	inertial navigation system
lidar	light detection and ranging
MBES	multibeam echosounder
MBMS	multibeam mapping system
MMS	Mobile Mapping Suite
MoDNR	Missouri Department of Natural Resources
NAVD 88	North American Vertical Datum of 1988
RTK	real-time kinematic
SBET	smoothed best estimate of trajectory
sonar	sound navigation and ranging
TIN	triangulated irregular network
USGS	U.S. Geological Survey

Bathymetric Contour Maps, Surface Area and Capacity Tables, and Bathymetric Change Maps for Selected Water-Supply Lakes in Northeastern Missouri, 2021

By Benjamin C. Rivers, Richard J. Huizinga, Joseph M. Richards, and Garett J. Waite

Abstract

Bathymetric data were collected at 12 water-supply lakes in northeastern Missouri by the U.S. Geological Survey (USGS) in cooperation with the Missouri Department of Natural Resources (MoDNR) and various local agencies, as part of a multiyear effort to establish or update the surface area and capacity tables for the surveyed lakes. The lakes were surveyed in March through May 2021. Ten of the lakes had been surveyed previously by the USGS, and the recent surveys were compared to the earlier surveys to document the changes in the bathymetric surface and capacity of the lakes.

Bathymetric data were collected using a high-resolution multibeam mapping system mounted on a boat. Supplemental depth data at five of the lakes were collected in shallow areas with an acoustic Doppler current profiler on a remote-controlled boat. Data points from the various sources were exported at a gridded data resolution appropriate to each lake, either 0.82 foot, 1.64 feet, or 3.28 feet. Data outside the multibeam survey extent and greater than the surveyed water-surface elevation were obtained from data collected using aerial light detection and ranging (lidar) point cloud data. A linear enforcement technique was used to add points to the dataset in areas of sparse data (the upper ends of coves where the water was shallow or aquatic vegetation precluded data acquisition) based on surrounding multibeam and upland data values. The various point datasets were used to produce a three-dimensional triangulated irregular network surface of the lake-bottom elevations for each lake. A surface area and capacity table was produced from the three-dimensional surface for each lake showing surface area and capacity at specified lake water-surface elevations. Various quality-assurance tests were conducted to ensure quality data were collected with the multibeam, including beam angle checks and patch tests. Additional quality-assurance tests were conducted on the gridded bathymetric data from the survey, the bathymetric surface created from the gridded data, and the contours created from the bathymetric survey.

If there were data from a previous bathymetric survey for a given lake, a bathymetric change map was generated from the elevation difference between the previous survey and the 2021 bathymetric survey data points. After reconciling any vertical datum disagreement between the previous survey data and the 2021 survey datum, coincident points between the surveys were identified, and a bathymetric change map was generated using the coincident point data.

The mean elevation change between all repeat surveys at most lakes was positive, indicating sedimentation. Relative to previous surveys, the change in capacity at the primary spillway elevation ranged from a 7.7-percent decrease at Memphis Reservoir to a 3.9-percent increase at Old Lake (Bowling Green West). The mean bathymetric change ranged from 0.03 foot at Hazel Creek and 0.07 foot at Shelbina Lake and Bowling Green Reservoir (Jack Floyd Memorial Lake) to 0.63 at Memphis Lake (Lake Showme) and 0.88 at Memphis Reservoir. The time-averaged mean bathymetric change ranged from 0.002 foot per year at Hazel Creek Lake to 0.044 foot per year at Memphis Reservoir. The computed volumetric sedimentation rate generally ranged from 0.14 to 6.80 acre-feet per year at Shelbina Lake and Memphis Lake (Lake Showme), respectively; however, Forest Lake had a substantially larger sedimentation rate of 17.0 acre-feet per year. Some changes observed in some bathymetric change maps are believed to result from the difference in data collection equipment and techniques between the previous and present bathymetric surveys, whereas other erosional features around the perimeter of certain lakes may be the result of wave action during low-water years.

Introduction

Managers of water-supply lakes need an accurate estimate of the lake capacity to ensure that enough water is available for consistent recreation pool levels, preserving downstream aquatic habitat, flood abatement, water supply, and power generation. Lake capacity is particularly important for managers of water-supply lakes during periods of drought, population growth, or exceptionally high water use in the area supplied by the lake. Typically, surveys are conducted to map the bathymetric (underwater) surface of the lake, from which the capacity, or volume, of the lake is determined at specified elevations in a capacity table. Sedimentation, primarily from runoff into the lake, will cause a loss of storage capacity with time; as a result, the capacity of the lake will tend to decrease with time. Therefore, repeat surveys are needed to update the map of the bathymetric surface and capacity table. Repeat surveys also can be used to quantify the bathymetric change and estimate sediment accumulation rates so that managers can better regulate and utilize the water supply.

In cooperation with several Federal, State, and local agencies, the U.S. Geological Survey (USGS) completed bathymetric surveys of several water-supply lakes in Missouri in the early 2000s (Richards, 2013) to determine the capacity of the lakes. All but one of these surveys were completed using a boat-mounted survey-grade singlebeam echosounder and Differential Global Positioning System (DGPS) equipment. Beginning in 2008, the USGS began using a multibeam echosounder (MBES) and a multibeam mapping system (MBMS) to survey river and lake bathymetry (for example, Huizinga and others, 2010; Clearwater Lake in Richards, 2013; Richards and others, 2019; Huizinga, 2022). Multibeam mapping systems collect bathymetric data at much higher resolution and density than singlebeam echosounders. In September 2018, the USGS, in cooperation with Missouri Department of Natural Resources (MoDNR) and the City of Moberly, Missouri, used an MBMS to survey Sugar Creek Lake to prepare an updated bathymetric map and a surface area and capacity table (Richards and Huizinga, 2019; Richards and others, 2019). The 2018 survey also was compared with the previous singlebeam survey in 2003 (Richards, 2013) to document the changes in the bathymetric surface of the lake and produce a bathymetric change map to exemplify the ability to compare MBMS and singlebeam beam survey data.

In 2019, the USGS, in cooperation with MoDNR and in collaboration with various local agencies, began a 5-year project to resurvey many of the water-supply lakes from the previous study (Richards, 2013), as well as to survey several lakes that had not been previously surveyed. From July 2019 to June 2020, 12 lakes in northwestern Missouri were surveyed to prepare new or updated bathymetric maps and surface area and capacity tables for those lakes (Huizinga and others, 2022). In June and July 2020, 10 additional lakes in north-central and west-central Missouri were surveyed to prepare new or updated bathymetric maps and surface area and capacity tables for those lakes (Huizinga and others, 2023). The data for these lakes were presented in Huizinga and others (2021) and Huizinga and Rivers (2023).

In March through May 2021, 12 additional lakes in northeastern Missouri were surveyed to prepare new or updated bathymetric maps and surface area and capacity tables for those lakes (fig. 1; table 1). As with the 2019 and 2020 surveys, if a previous survey was completed at a given lake (Richards, 2013), that survey was compared with the 2021 survey to document the changes in the bathymetric surface of the lake and produce a bathymetric change map.

Purpose and Scope

The purpose of this report is to document the results of bathymetric surveys using an MBMS completed at water-supply lakes in northeastern Missouri during the spring of 2021 (fig. 1; table 1). Equipment and methods used to process and assure quality of the data are described. Bathymetric surface contours from each lake survey are presented, as well as the surface area and capacity table of the surveyed lake. Maps showing various quality-assurance metrics also are presented. Lakes previously surveyed, as documented in Richards (2013), were compared to the most recent MBMS survey data and results are presented on additional maps.

Description of Study Area

The study area for this report encompasses 12 water-supply system lakes in northeastern Missouri (fig. 1; table 1). The locations of the 12 lakes in Missouri investigated in this report at the State scale are shown in figure 1, and the locations of each lake at the local scale are shown in figures 2–8.

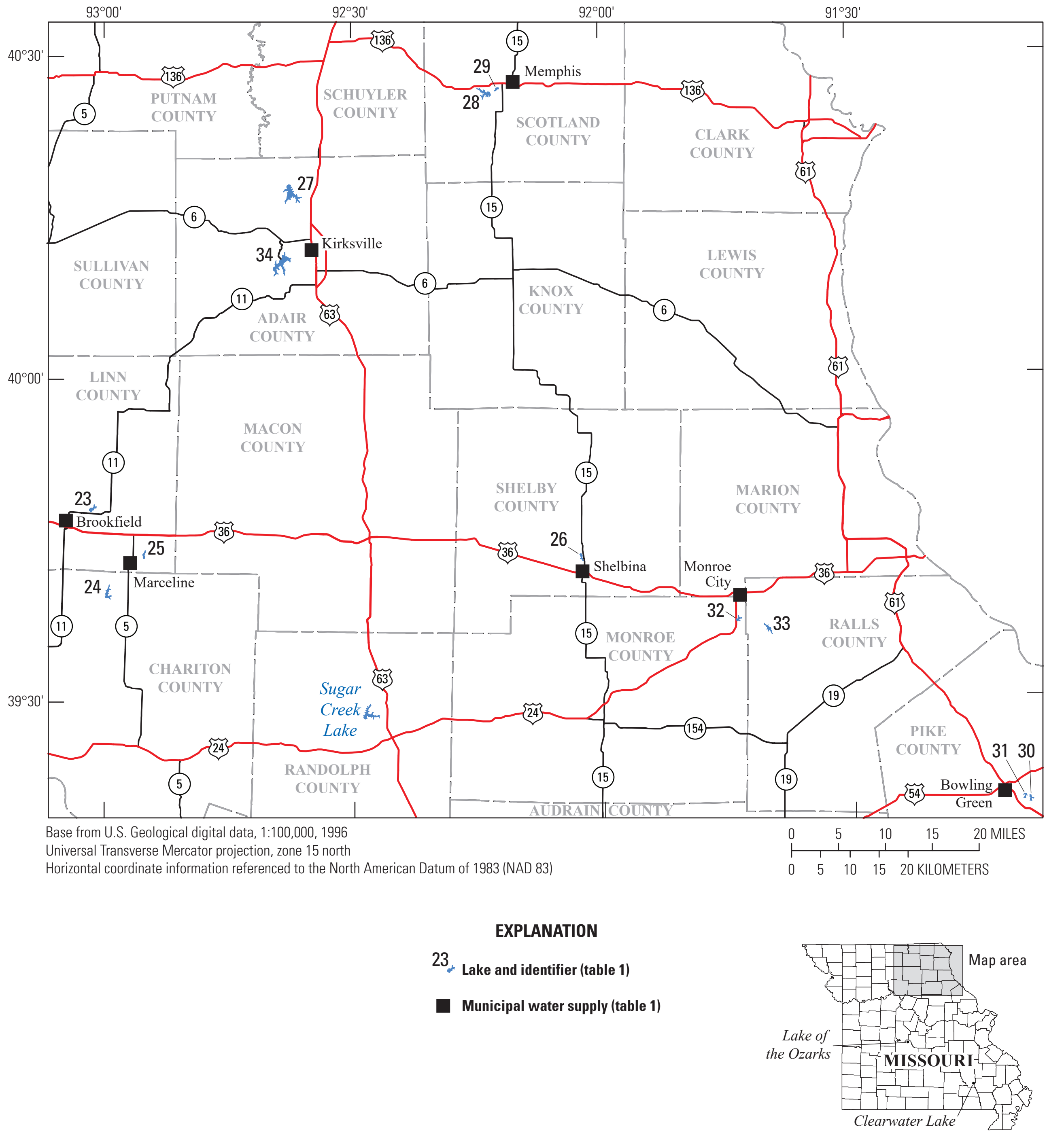


Figure 1. Location of water-supply lakes in northeastern Missouri surveyed in 2021.

Table 1. Water-supply lakes in northeastern Missouri surveyed in 2021.

[Dates are shown as month/day/year. All elevations are referenced to the North American Vertical Datum of 1988. --, no data/not applicable]

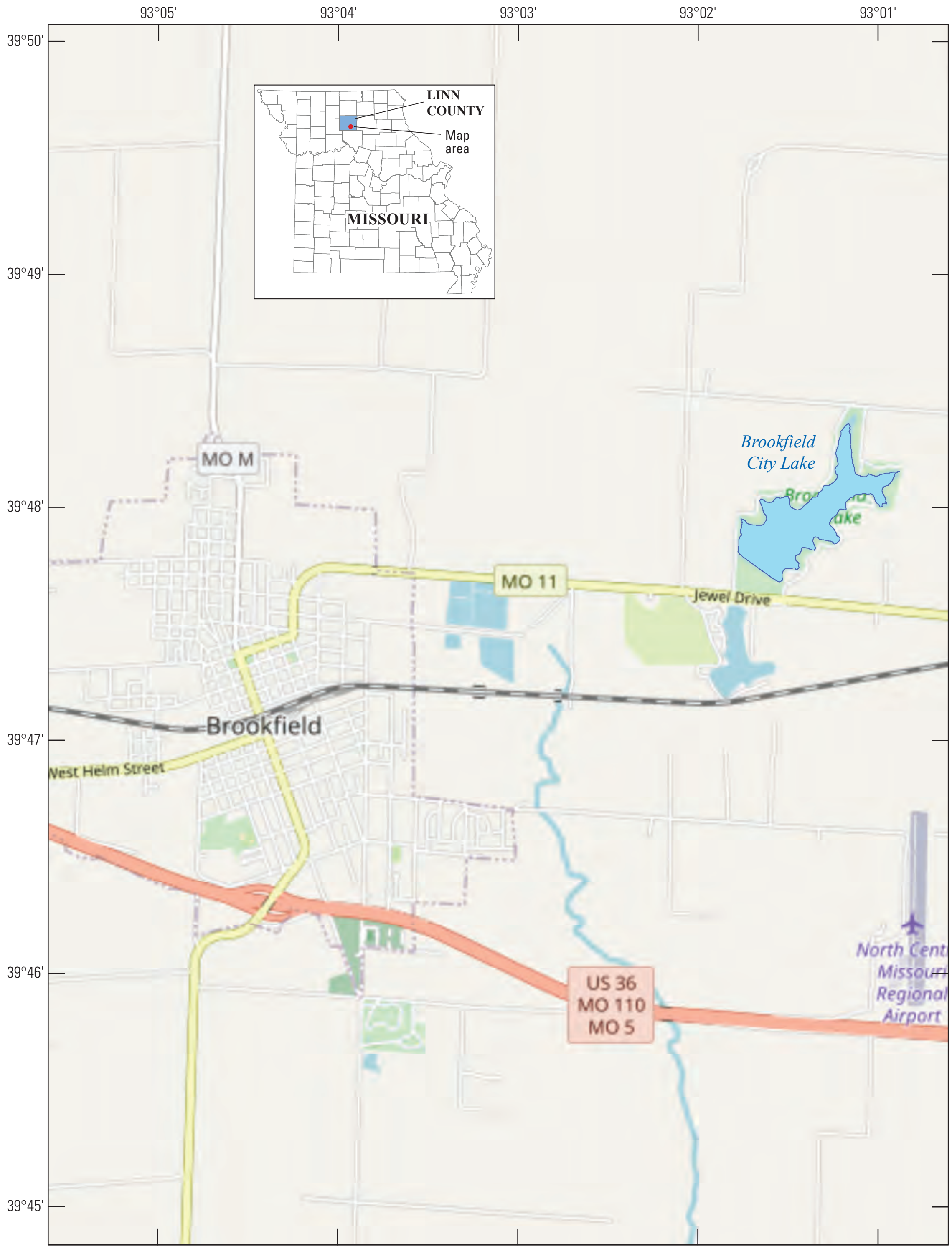
Lake name	Lake number[a] (fig. 1)	County	Municipal water supply	Survey date(s)	Previous survey date(s)	Mean water-surface elevation at time of survey, in feet	Primary spillway/ inlet elevation, in feet	Emergency/ overflow spillway elevation,[b] in feet	Plate number
Brookfield City Lake	23	Linn	Brookfield	03/30/2021	07/13/2000	799.32	802.51[c]	802.51[c]	1
New Marceline City Lake	24	Chariton	Marceline	03/31/2021	05/19/2003	757.16	757.16	761.57	2
Marceline Old Reservoir	25	Linn	Marceline	03/31/2021	--	817.70	817.70[c]	817.70[c]	3
Shelbina Lake[d]	26	Shelby	Shelbina	04/01/2021	06/20/2001	715.14	715.14[c]	715.14[c]	4
Hazel Creek Lake	27	Adair	Kirksville	04/19/2021–04/20/2021	03/02/2005–03/04/2005	847.89	847.89	851.86	5
Memphis Lake (Lake Showme)	28	Scotland	Memphis	04/21/2021	06/03/2002	769.77	769.77	773.81	6
Memphis Reservoir	29	Scotland	Memphis	04/22/2021	06/19/2001	718.15	718.09[c]	718.09[c]	7
Bowling Green Reservoir (Jack Floyd Memorial Lake)	30	Pike	Bowling Green	04/26/2021	02/23/2005	794.79	795.00[c]	795.00[c]	8
Old Lake (Bowling Green West)	31	Pike	Bowling Green	04/26/2021	02/24/2005–02/25/2005	773.93	773.93	779.56	9
Monroe Lake B (Monroe City South)	32	Monroe	Monroe City	04/27/2021	--	712.82	712.82[c]	712.82[c]	10
Monroe City Lake	33	Ralls	Monroe City	04/27/2021	06/05/2002	669.67	669.67[c]	669.67[c]	11
Forest Lake	34	Adair	Kirksville	05/03/2021–05/04/2021	03/01/2005–03/02/2005	799.79	799.79[c]	799.79[c]	12

[a]Lake numbers are a continuation of the numbering started in Huizinga and others (2022).

[b]Emergency/overflow spillway elevation is the elevation at which uncontrolled overflow occurs as opposed to flow into an inlet drop structure. If the primary and emergency/overflow spillway elevations are the same, the lake did not have a drop inlet structure or did not have a clear indication of an inlet lip.

[c]The primary spillway is an uncontrolled overflow spillway at this site.

[d]Encompasses a system of two impoundments that are hydraulically connected, so they were analyzed together. The upper impoundment exists as a sediment catchment and was surveyed, but the area and capacity are not included in the results; nevertheless, contours are included for the upper impoundment.



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(*http://www.openstreetmap.org/copyright*)
Universal Transverse Mercator projection, zone 15 north
North American Datum of 1983

Figure 2. Location of Brookfield City Lake (lake 23) near Brookfield, Missouri.

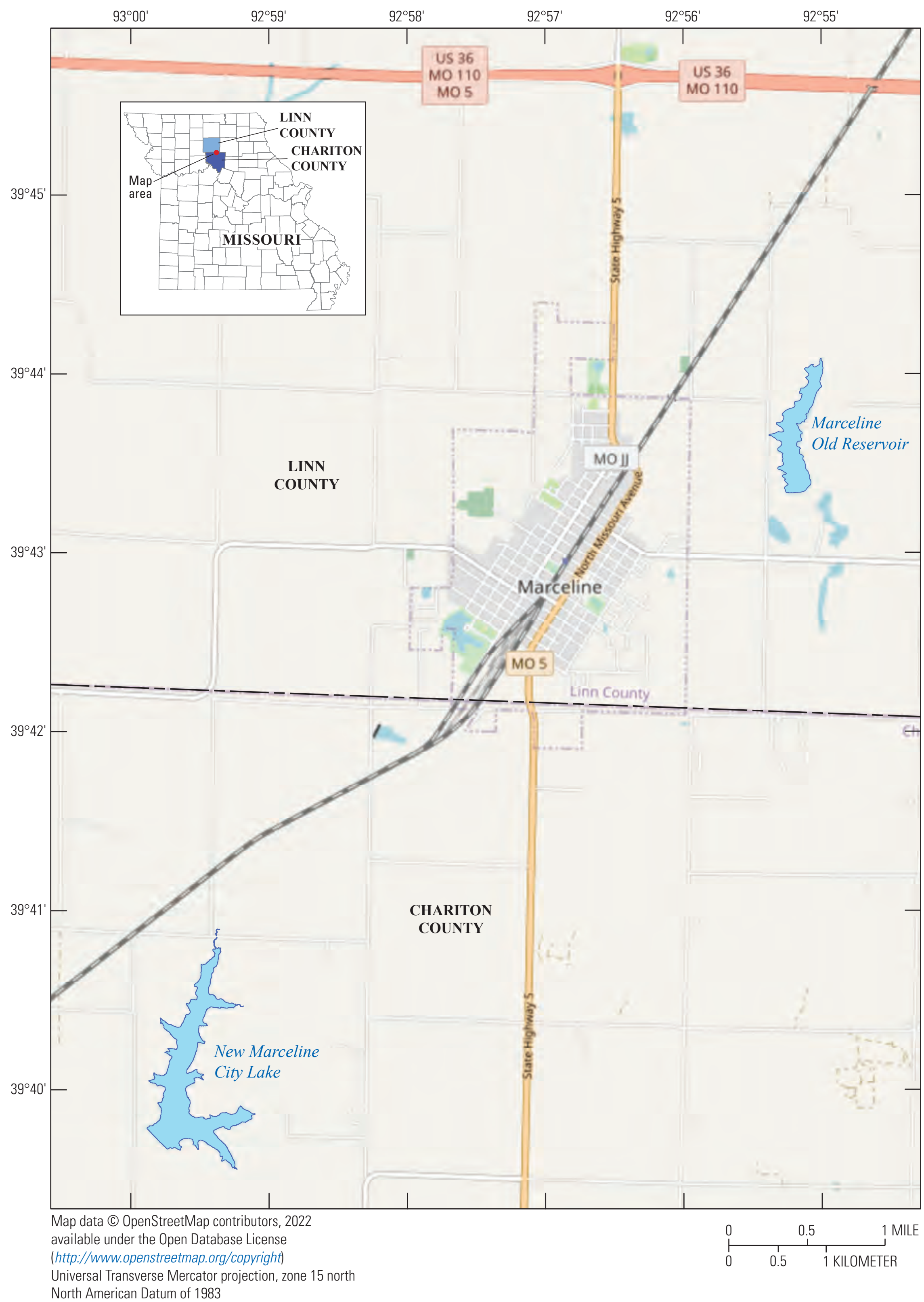
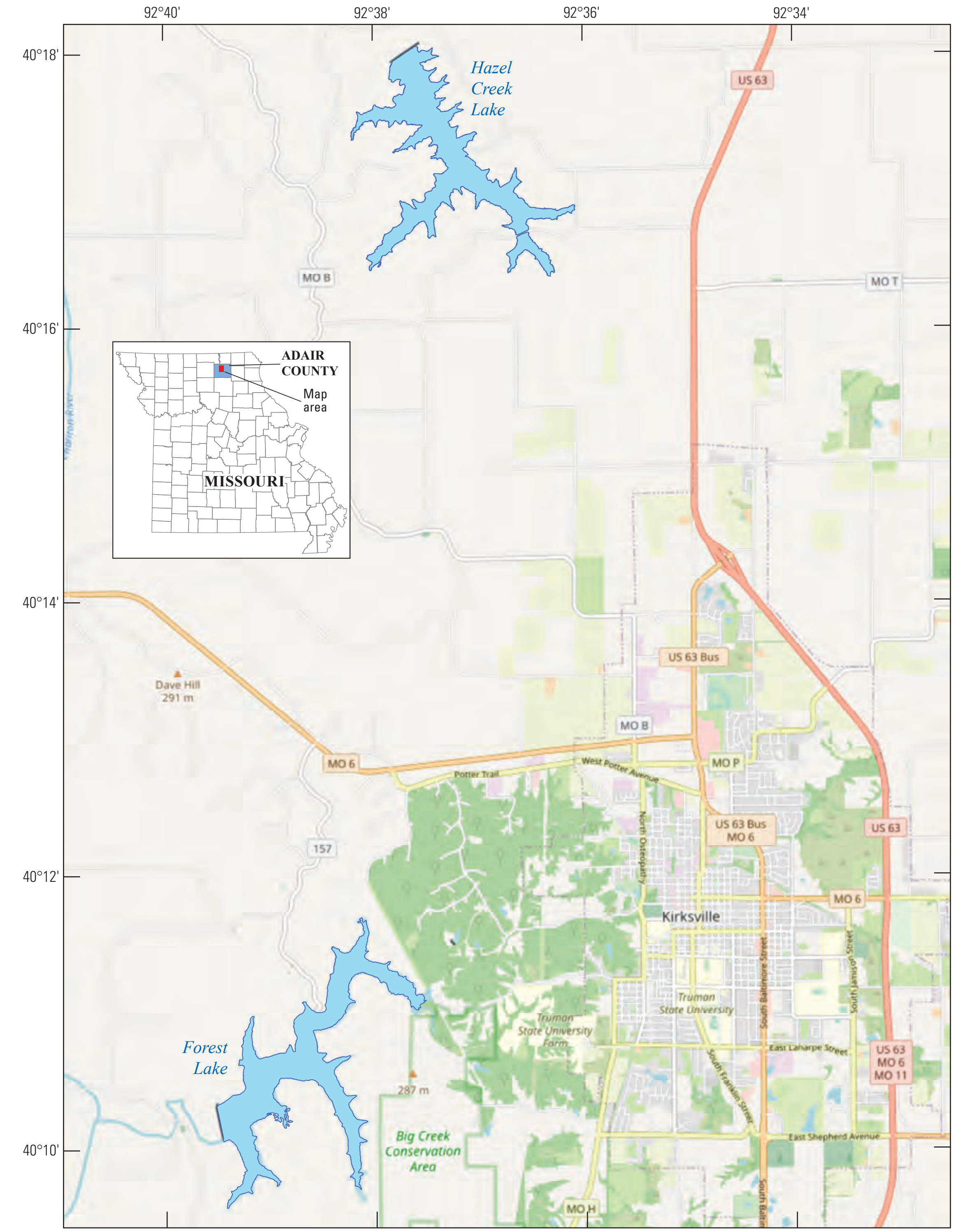


Figure 3. Location of New Marceline City Lake (lake 24) and Marceline Old Reservoir (lake 25) near Marceline, Missouri.

Figure 4. Location of Shelbina Lake (lake 26) near Shelbina, Missouri.



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Universal Transverse Mercator projection, zone 15 north
North American Datum of 1983

0 1 2 MILES
0 1 2 KILOMETERS

Figure 5. Location of Hazel Creek Lake (lake 27) and Forest Lake (lake 34) near Kirksville, Missouri.

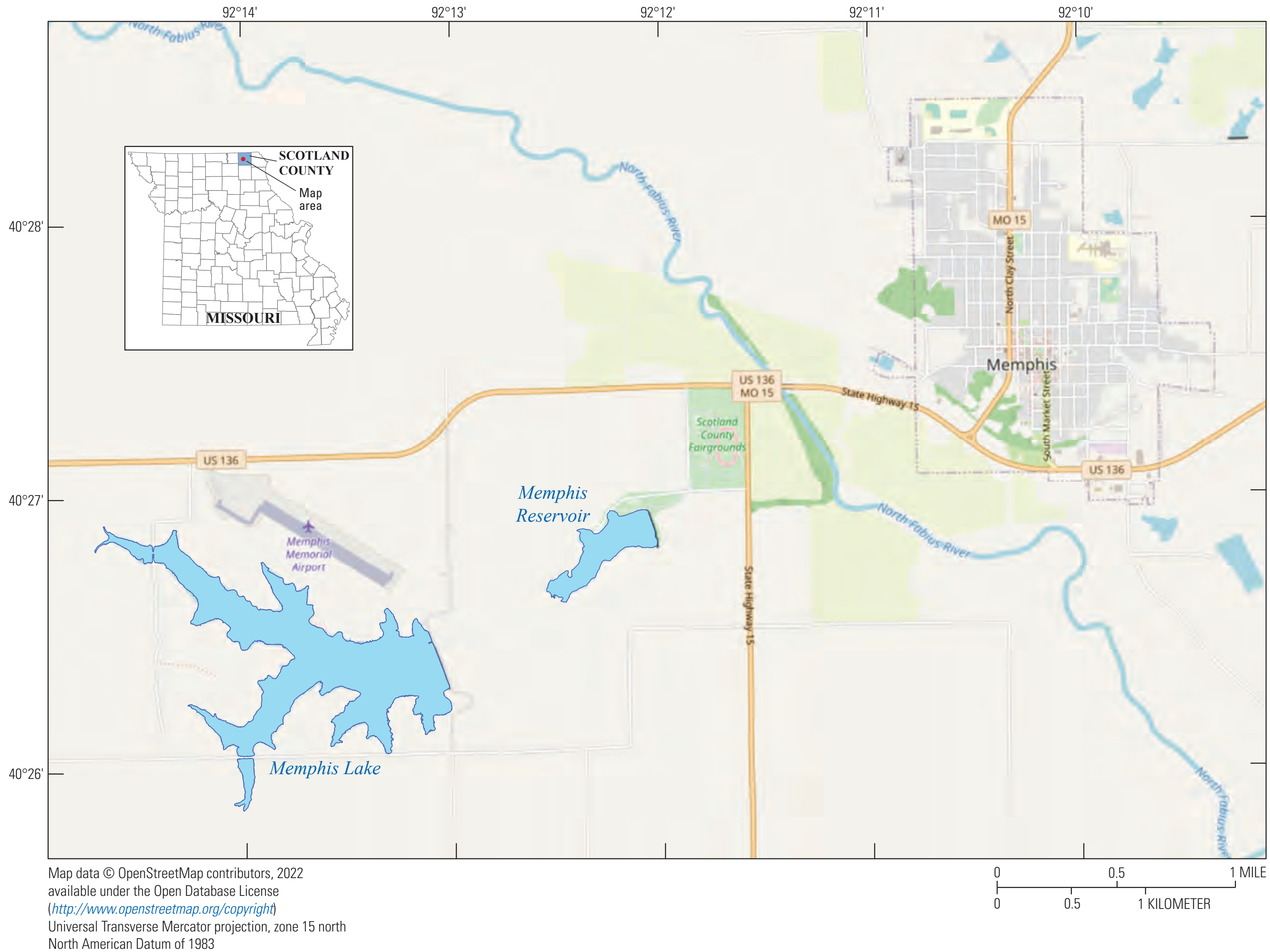
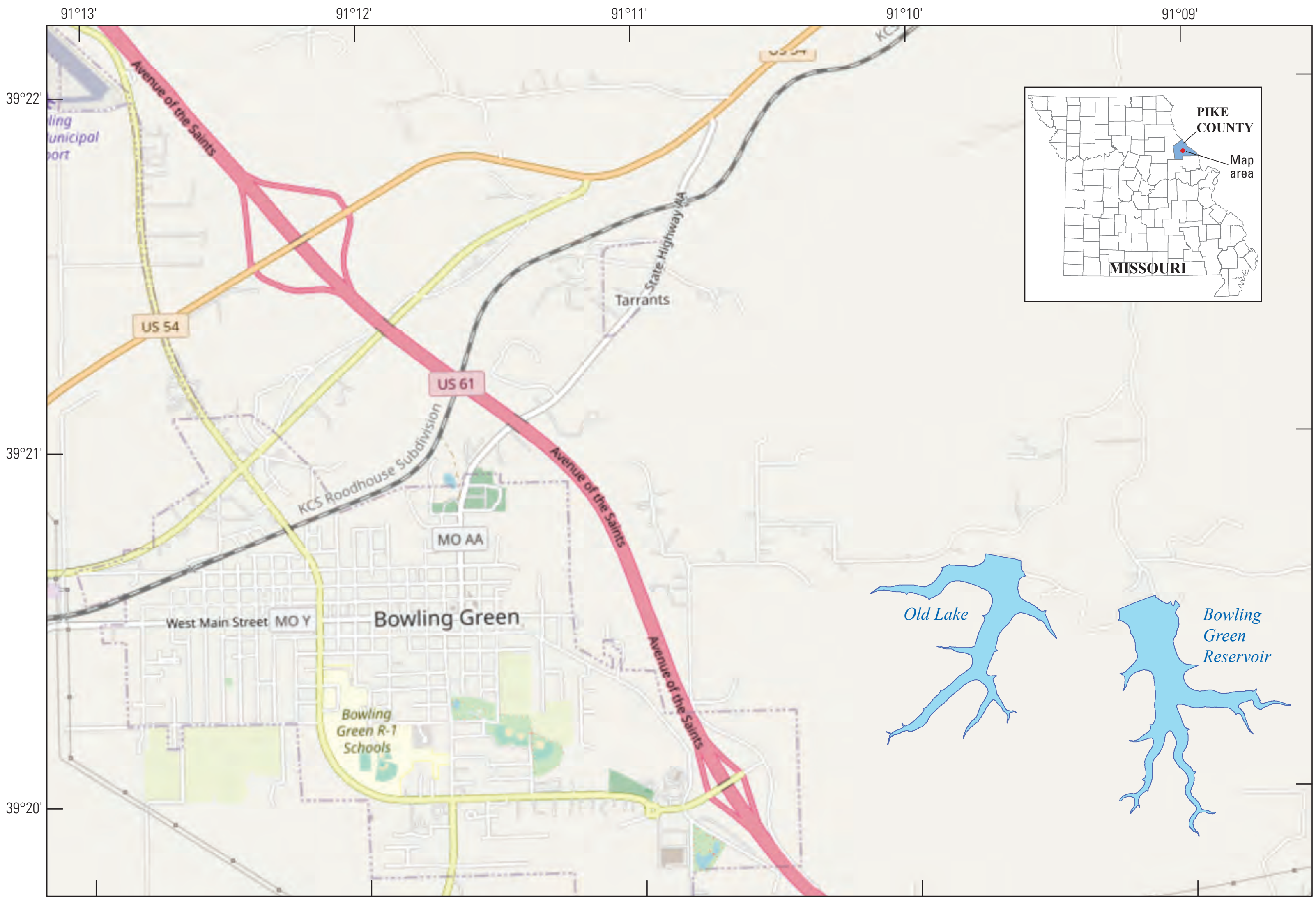


Figure 6. Location of Memphis Lake (Lake Showme; lake 28) and Memphis Reservoir (lake 29) near Memphis, Missouri.



0 0.5 1 MILE
0 0.5 1 KILOMETER

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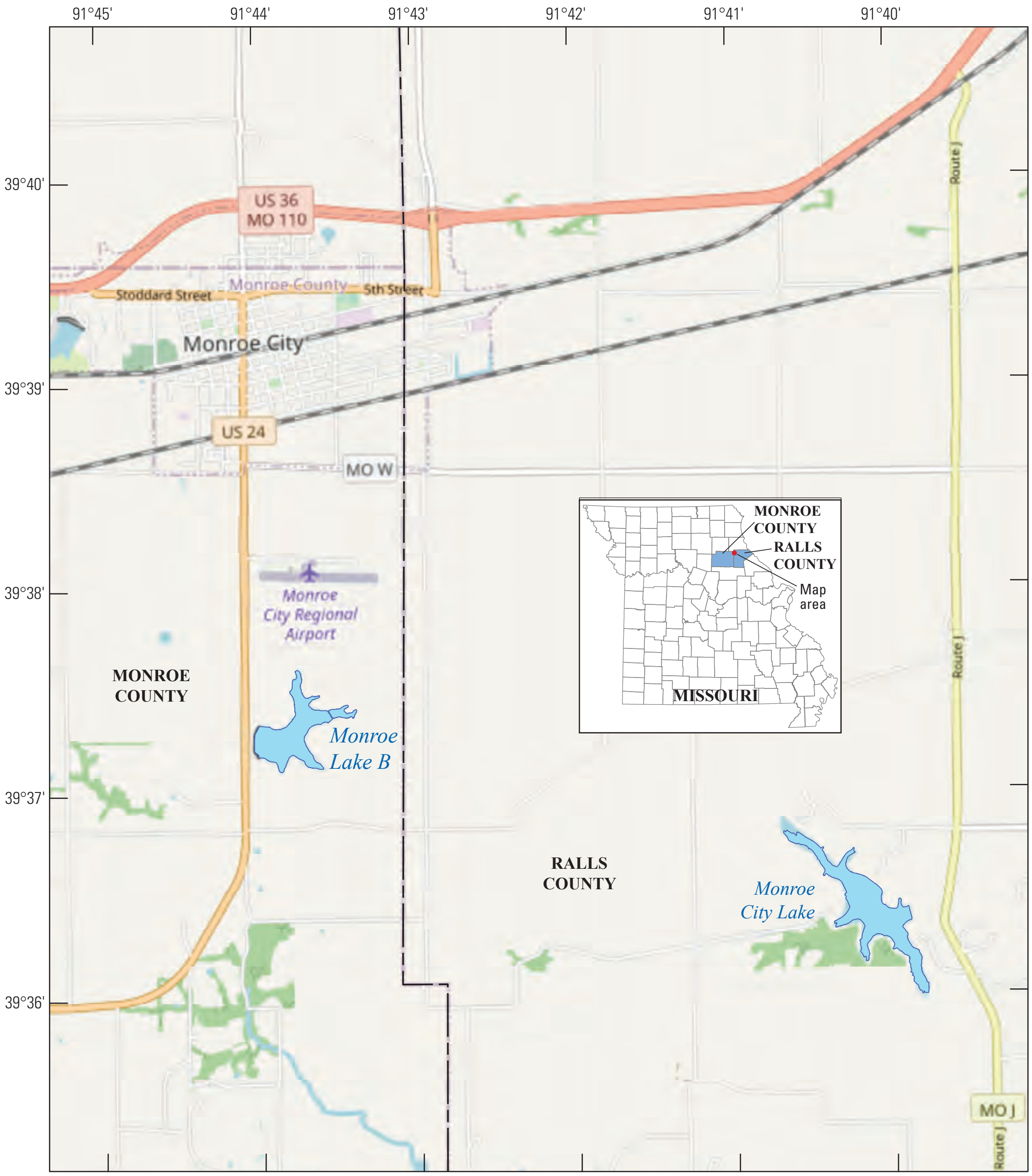
Universal Transverse Mercator projection, zone 15 north
North American Datum of 1983

Figure 7. Location of Bowling Green Reservoir (Jack Floyd Memorial Lake; lake 30) and Old Lake (Bowling Green West; lake 31) near Bowling Green, Missouri.



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Universal Transverse Mercator projection, zone 15 north
North American Datum of 1983

Figure 8. Location of Monroe Lake B (Monroe City South; lake 32) and Monroe City Lake (lake 33) near Monroe City, Missouri.

Methods

Bathymetric surveys for the lakes in northeastern Missouri included in this report were conducted from March 30 to May 4, 2021 (table 1), using similar methods to the survey at Clearwater Lake near Piedmont, Mo., in 2017 (Richards and Huizinga, 2018; fig. 1) and Sugar Creek Lake near Moberly, Mo., in 2018 (Richards and others, 2019; fig. 1). This work is a continuation of the surveys at 22 water-supply lakes in Missouri completed in 2019 and 2020 (Huizinga and others, 2022, 2023). The mean water-surface elevation of each lake during the 2021 surveys detailed in this report is shown in table 1. A bathymetric surface and a bathymetric contour map were created from the survey data for each lake. For lakes at which a previous survey had been completed (Richards, 2013), a bathymetric change map was created from the survey data.

Bathymetric Data Collection

Bathymetric data (water depths and positions) were collected using an MBMS mounted on a boat (fig. 9). Two different boats were used for the 2021 surveys: a 24-foot (ft) flat-bottom cabin boat (fig. 9*B*), and a smaller 16-ft flat-bottom, open-cabin jon boat (fig. 9*C*), which could be more easily launched and retrieved from the bank of a lake. Supplemental depth data were collected in shallow areas with an acoustic Doppler current profiler (ADCP) on a remote-controlled boat either operated remotely or towed by motorized boat. 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, Huizinga, 2010, 2022; Huizinga and others, 2010). The survey methods used to obtain the data for the 2021 lakes were similar to these river studies and the study at Sugar Creek Lake near Moberly, Mo. (Richards and others, 2019), 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. The MBES that was used was the Norbit iWBMSh, operated at a frequency of 400 kilohertz (kHz; fig. 9*A*). The iWBMSh has a curved receiver array, which enables bathymetric data to be collected throughout a swath range of 210 degrees. Optimum data usually are collected in a swath of less than 160 degrees (80 degrees on each side of nadir, or straight down below the MBES); nevertheless, the swath can be electronically rotated to either side of nadir, enabling data along sloping banks to be captured up to a depth just below the water surface.

As with the 2019 and 2020 surveys, the bathymetric survey data were collected using the following generalized methods:

- Positioning was provided by Global Navigation Satellite System (GNSS) systems, using real-time kinematic (RTK) corrections from the Missouri Department of Transportation real-time network whenever possible.
- Data from a static GNSS base receiver set up over a temporary reference mark near each survey launch area were used to enhance the postprocessed navigation solution; coordinates of each reference mark are included in the USGS data release for these lakes (Rivers and others, 2023).
- All navigation information was postprocessed using POS-Pac Mobile Mapping Suite (MMS) software (Applanix Corporation, 2021) to mitigate any degraded positional accuracy of the vessel during the survey.
- The blended navigation solution (called a “smoothed best estimate of trajectory” or “SBET” file) generated by postprocessing the navigation data was applied to the respective data collection in the survey.
- Most data in the main body of each lake were collected with the swath range limited to 140 degrees, 70 degrees on each side of nadir, along lines oriented longitudinally in the main lake area and spaced to create about 10- to 25-percent overlap of the adjacent survey swaths.
- The swath range was widened to 160 degrees and electronically tilted to port or starboard as needed to enhance acquisition of bathymetric data in the shallow areas near the banks, in coves, and in the upper reaches of the lake arms. Data along the shoreline were collected by navigating the boat parallel to the shore while overlapping the data collected in the main body of the lake.
- 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 vegetation, or water depth below the MBES decreased to less than about 3 ft), pivoting the boat 180 degrees, and egressing the cove along the ingress line.
- Sound velocity data were collected at the MBES head with a sound velocity probe (fig. 9*A*) throughout the survey, and sound velocity profiles were routinely measured with an AML Oceanographic Base X2 sound velocity probe at various locations throughout each survey day to mitigate potential sound velocity variations with time, location, and depth.

Figure 9. The Norbit iWBMSh multibeam echosounder. *A*, Viewed from the side. *B*, Mounted on the port side of the U.S. Geological Survey 24-foot cabin boat. *C*, Deployed on the port side of the 16-foot jon boat.

Preparation for and collection of each bathymetric survey was done in 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, often caused by fish, submerged woody debris, or other vegetation. The data were georeferenced using the navigation and position solution data from the SBET file from POS-Pac MMS and preliminarily visualized in HYPACK/HYSWEEP as a triangulated irregular network (TIN) surface or a point cloud for editing. The georeferenced data were filtered and projected to a three-dimensional grid using the Combined Uncertainty and Bathymetry Estimator (CUBE) method (Calder and Mayer, 2003), as implemented in the MBMax processing package of the HYPACK/HYSWEEP software (HYPACK, Inc., 2020). The gridded CUBE bathymetry data were output to a comma-delimited file that was reduced to a data resolution appropriate to the size of the lake, with the aim of no more than about 5 million gridded points per lake to ensure the dataset was a computationally manageable size (table 2).

At Shelbina Lake (lake number 26; fig. 1; table 2), Hazel Creek Lake (lake number 27; fig. 1; table 2), Memphis Lake (Lake Showme; lake number 28; fig. 1; table 2), Memphis Reservoir (lake number 29; fig. 1; table 2), and Monroe Lake B (Monroe City South; lake number 32; fig. 1; table 2), a SonTek RiverSurveyor M9 ADCP mounted on a remote-controlled boat was used to collect bathymetric data in shallow, vegetation-free areas that were inaccessible to the MBMS boats. Data from the so-called “bottom-track” mean of the four velocity beams of the ADCP were combined with position and elevation information provided by a DGPS receiver on the top of the boat to provide the equivalent of singlebeam echosounder data in these otherwise inaccessible areas.

Bathymetric Surface and Contour Map Creation

Data points from the MBMS, as well as any supplemental ADCP data, were exported at the gridded data resolution shown in table 2 from the raw data collected in the 2021 surveys (Rivers and others, 2023). The vertical datum for the surveys was the North American Vertical Datum of 1988 (NAVD 88) using the geoid model GEOID18. The horizontal datum was the North American Datum of 1983. Geographic information system (GIS) software was used to filter the bathymetric data points so that the points would be no closer than the mapping minimum point spacing shown in table 2.

Data outside the MBMS survey extent and greater than the surveyed water-surface elevation for all the lakes were obtained from data collected using aerial light detection and ranging (lidar) point cloud data (U.S. Geological Survey, 2017). Only points classified as “ground” were used from the lidar point cloud data. These upland data points were resampled to a linear distance that matched the mapping minimum point spacing of the bathymetric data using GIS software (when needed for the larger lakes) and used to define the upland areas of the lake.

Using the linear enforcement techniques described in Wilson and Richards (2006), points were added to the dataset based on surrounding MBMS and upland data values. These data were added to anchor the surface in areas of sparse data in the upper ends of coves where the water was too shallow for the MBMS equipment or aquatic vegetation precluded data acquisition with the MBMS or ADCP. Topography from a previous survey (if one existed) and recent aerial imagery (Google Earth, 2010–20; https://earth.google.com/) at water levels lower than surveyed in 2021 often were used to guide the linear enforcement in these areas.

The point datasets were used to produce a three-dimensional TIN surface of the lake-bottom elevations for each lake. 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. Each lake surface was contoured at a 2-ft interval using GIS software, and the contours were cartographically smoothed and edited to create a bathymetric contour map for each lake (plates 1–12; available for download at https://doi.org/10.3133/sir20235108) using the techniques of Wilson and Richards (2006).

As indicated in the “Description of Study Area” section above, Shelbina Lake (lake number 26; plate 4) encompasses a system of two impoundments that are hydraulically connected, so they were analyzed together. The upper impoundment exists as a sediment catchment and was surveyed, but the area and capacity are not included in the results.

Bathymetric Change Map Creation

If data from a previous bathymetric survey exist for a given lake, a bathymetric change map was generated from the difference between the previous survey and the 2021 bathymetric survey points where they were coincident. Two lakes—Marceline Old Reservoir (lake number 25), and Monroe Lake B (Monroe City South; lake number 32)—were not previously surveyed and are not included in this discussion. Accurate surface area and capacity determined from bathymetric surveys are independent of the vertical datum used to reference the bathymetric data; however, accurate comparisons between capacities at specific elevations or between bathymetric surfaces from different surveys require that any disagreement between the vertical datums is reconciled. To maximize comparability between surveys, a vertical adjustment was applied to the earlier survey to convert the elevations to the vertical datum of the recent surveys (NAVD 88 using geoid model GEOID18). Although all surveys inherently have embedded systematic and random errors that are difficult to model and quantify, the errors in the recent surveys are assumed to be negligible in comparison to the previous surveys because of the advances in GNSS technology over

Table 2. Summary of gridded and selected bathymetric data points from surveys at water-supply lakes in northeastern Missouri, March 30 to May 4, 2021.

[--, no data]

Lake name	Lake number (fig. 1)	Gridded data resolution, in feet	Number of gridded points in multibeam bathymetric dataset	Number of supplemental points from sources other than multibeam	Mapping point minimum point spacing, in feet	Number of mapping points selected from the gridded bathymetric dataset used to make the bathymetric surface	Number of mapping quality-assurance points randomly selected from gridded bathymetric dataset	Upland survey data year
Brookfield City Lake	23	1.64	1,405,042	--	3.28	273,541	47,662	2008
New Marceline City Lake	24	1.64	2,036,089	--	3.28	391,832	68,763	2006
Marceline Old Reservoir	25	0.82	2,328,796	--	1.64	526,306	74,797	2008
Shelbina Lake	26	0.82	2,303,235	798	1.64	451,723	77,137	2011
Hazel Creek Lake	27	1.64	1,547,578	7,186	3.28	291,679	52,108	2011
Memphis Lake (Lake Showme)	28	1.64	3,126,262	3,396	3.28	602,638	104,976	2014
Memphis Reservoir	29	0.82	1,830,621	473	1.64	354,287	61,617	2014
Bowling Green Reservoir (Jack Floyd Memorial Lake)	30	0.82	2,538,481	--	1.64	475,414	86,185	2014
Old Lake (Bowling Green West)	31	0.82	1,519,818	--	1.64	280,352	51,601	2014
Monroe Lake B (Monroe City South)	32	1.64	823,263	707	3.28	155,279	27,733	2013
Monroe City Lake	33	1.64	1,181,756	--	3.28	222,740	40,065	2013
Forest Lake	34	3.28	1,932,882	--	6.56	362,412	65,281	2011

time. The vertical adjustment was generally based on one reference location per lake with an elevation that is assumed to have not changed over time, such as a recoverable reference mark or spillway crest (refer to reference mark locations on plates 1–12). The elevation of the reference location was acquired with RTK GNSS technology following methods described by Rydlund and Densmore (2012). The magnitude and direction of the vertical adjustment were then determined from the difference between the reference mark elevation in 2021 and the elevation of a point in the earlier survey at (or near) the reference mark location. By assuming the vertical adjustment is spatially constant, vertical change as it is related to natural geomorphic processes can be observed when the earlier, vertically adjusted survey is compared with the more recent survey. Because of the advances in GNSS surveying techniques and accuracy since the previous surveys, it was assumed that the 2021 elevation was the more accurate value. The vertical offsets between the surveys are listed in table 3.

After applying the vertical shift to the previous survey data to ensure a match to the 2021 survey, coincident points between the surveys were identified. A 2021 survey map point was considered “coincident” when it was within a given horizontal distance from a previous survey data point (the “coincident bathymetry point search radius” in table 3), and a bathymetric change TIN was generated using the difference in elevation of the coincident point datasets, which was computed using the following equation:

$$Difference = elevation_{2021} - elevation_{previous} \quad (1)$$

where

Difference is the difference in elevation of a coincident point pair (the bathymetric change),

$elevation_{2021}$ is the elevation of the point in the 2021 survey, and

$elevation_{previous}$ is the elevation of the point in the previous survey.

The TIN was converted to a raster surface with a spacing that matched the mapping minimum point spacing of the 2021 surveys (“Mapping point minimum point spacing” in table 2) for use in further analysis and creation of the change map. The bathymetric change map was limited to the intersection of the previous and 2021 MBES survey extents so that only bathymetric data that were in the area common to both surveys were compared. Minor positional offsets between points within the “Coincident bathymetry point search radius” listed in table 3 located at high-slope areas (observed in the contour maps as areas where the contours are closely spaced in plates 1–12) can bias the observed vertical difference; furthermore, high-slope areas typically are not well represented in rasterization, which could lead to potentially erroneous bathymetric change results. Therefore, areas that corresponded to a terrain slope greater than about 25 degrees, as represented in the 2021 bathymetric surface, were excluded from the bathymetric change map.

Table 3. Summary of adjustments to previous survey elevation to match 2021 surveys at water-supply lakes in northeastern Missouri, March 30 to May 4, 2021.

Lake name	Lake number (fig. 1)	Elevation adjustment to previous survey,[a] in feet	Coincident bathymetry point search radius,[b] in feet
Brookfield City Lake	23	−0.12	0.66
New Marceline City Lake	24	0.15	0.66
Shelbina Lake	26	0.70	0.66
Hazel Creek Lake	27	0.01	1.64
Memphis Lake (Lake Showme)	28	0.03	0.98
Memphis Reservoir	29	−0.11	0.66
Bowling Green Reservoir (Jack Floyd Memorial Lake)	30	0.25	0.66
Old Lake (Bowling Green West)	31	0.27	0.66
Monroe City Lake	33	0.66	0.98
Forest Lake	34	−0.41	1.31

[a]Contour information and surface area and capacity tables for previous surveys in Richards (2013) need to be adjusted by the elevation adjustment value to be comparable to the 2021 data.

[b]The search radius was used to select points from the 2021 gridded data to match to previous survey data points to determine the elevation difference from the previous survey.

Bathymetric Data Collection Quality Assurance

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 adjacent and overlapping swaths for agreement. In addition to the real-time quality-assurance assessments during the survey, beam angle checks and a suite of patch tests were done at various times throughout the surveys to ensure quality data were acquired from the MBMS. These tests generally were completed in the deepest part of a given lake, near the dam, or over a submerged feature such as the old channel or a submerged roadway.

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) of the MBES by comparing results from two full-swath check lines over a reference surface (created from multiple passes over an area using only the high-quality beams near nadir; U.S. Army Corps of Engineers, 2013). Outer beam accuracy may change with time because of inaccurate sound velocities, physical configuration changes or damage, and water depth. A beam angle check was done at Forest Lake (fig. 1) near Kirksville on May 5, 2021, but the results were compromised owing to substantial submerged vegetation. An additional beam angle check was done at Lake of the Ozarks near Camdenton, Missouri (fig. 1), on November 18, 2021, as part of the 2021 survey season, 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 70 degrees (U.S. Army Corps of Engineers, 2013; table 4), permitting the use of the full 140 degrees of the sound navigation and ranging (sonar) swath with confidence. Points acquired outside of the central 100–110 degrees of the sonar swath generally had overlap with adjacent swaths, which increases the quality of the survey in the overlapped areas because of duplication.

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

Table 4. Results of a beam angle check at Lake of the Ozarks near Camdenton, Missouri, on November 18, 2021.

[<, less than; --, no data]

Beam angle limit, in degrees	Maximum outlier, in feet	Mean difference, in feet	Standard deviation, in feet	95-percent confidence, in feet
Beam angle check results				
0	0.24	−0.09	0.04	0.07
5	0.28	−0.09	0.03	0.07
10	0.23	−0.08	0.04	0.07
15	0.22	−0.08	0.04	0.07
20	0.23	−0.08	0.04	0.08
25	0.23	−0.07	0.04	0.08
30	0.27	−0.07	0.04	0.08
35	0.27	−0.07	0.05	0.09
40	0.23	−0.05	0.04	0.08
45	0.21	−0.04	0.04	0.09
50	0.22	−0.04	0.05	0.09
55	0.23	−0.03	0.05	0.10
60	0.21	−0.01	0.05	0.10
65	0.25	0.02	0.06	0.12
70	0.30	0.03	0.06	0.12
Performance standards[a]				
Threshold	1.00	<0.20	--	<0.80
Result	Met	Met	--	Met

[a]Performance standard check values are from U.S. Army Corps of Engineers (2013, table 3-1) for soft sand/silt bottoms.

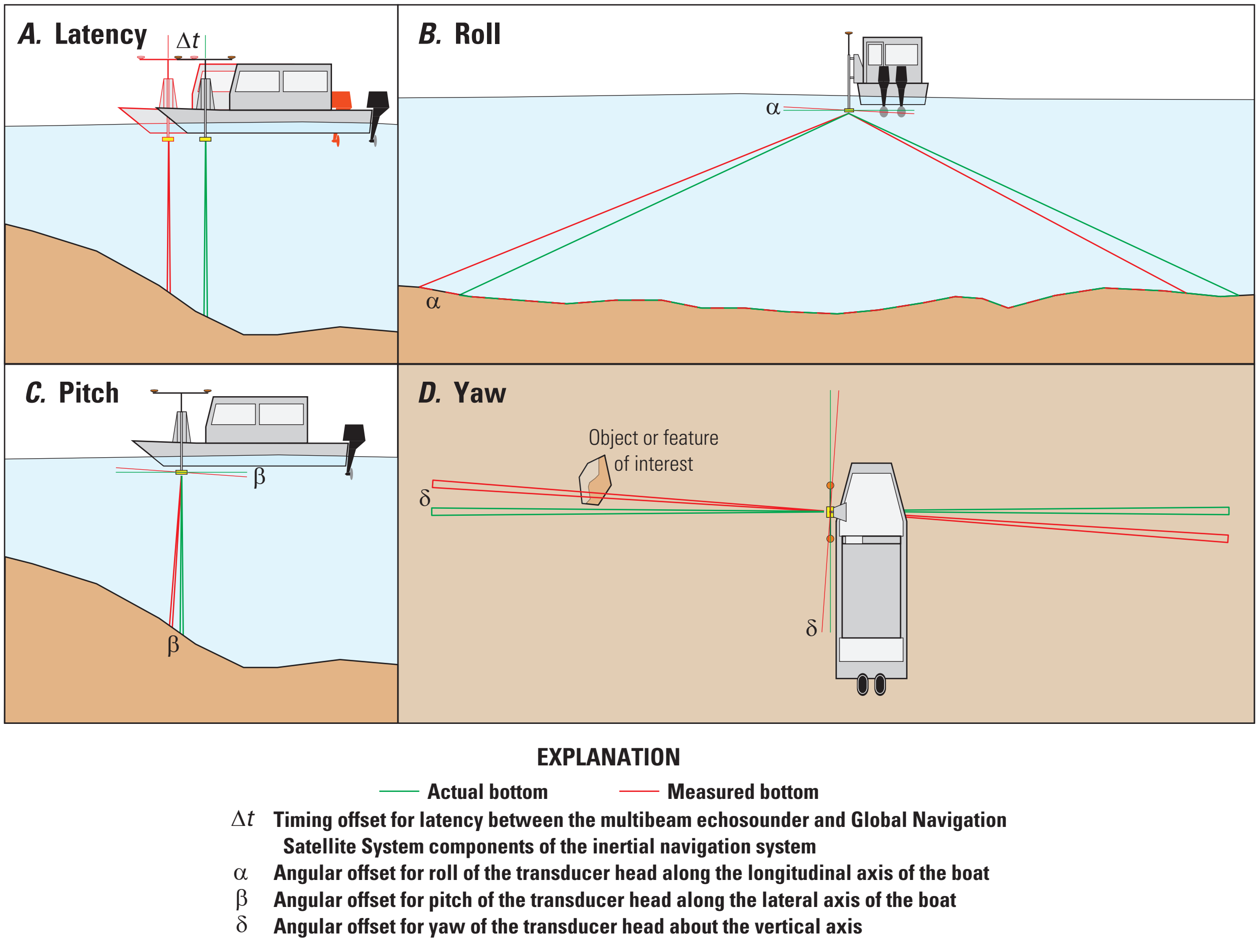


Figure 10. Generalized effects on data from a multibeam echosounder. *A*, Timing offset for latency. *B*, Angular offset for roll. *C*, Angular offset for pitch. *D*, Angular offset for yaw. Figure from Huizinga (2022).

coordinates (fig. 10), and 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, 2022). 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 (Huizinga, 2022). The offsets determined in the patch test are applied when processing the data collected during a survey. Patch tests were completed at various times in various lakes during the surveying projects during the spring of 2021 (table 5), and angular offsets were updated in the data collection and post-processing software as appropriate.

With the Norbit iWBMSh, the INS and MBES are considered to be tightly coupled because the inertial measurement unit (IMU) of the INS is mounted on the same mounting bracket (fig. 9*A*); therefore, there was no measured timing offset and no measured angular offset for pitch (table 5). The yaw is a measure of the alignment of the GNSS receivers relative to the IMU of the INS on the echosounder head, and the measured offset for yaw ranged from 0 to −4 for all the tests (table 5). These values generally are consistent with latency, pitch, and yaw test results for this equipment configuration used in other surveys (Richards and others, 2019; Huizinga, 2022). The variable angular offset for yaw observed in the 2021 surveys is believed to be the result of a combination of a loose connection on the T-pole on which the GNSS receivers were mounted (figs. 9*B*, 9*C*) and an incorrectly applied magnetic variation or grid convergence parameter in the post-processing of the survey data. The measured angular offset for roll remained a constant −0.10 (table 5), which is different from previous results for this equipment configuration in other surveys (Huizinga, 2022; Huizinga and others, 2022); however, the MBES had undergone factory calibration testing in January 2021, which is the likely source of the change. It was noted in the earliest work with the MBMS in Missouri

Table 5. Patch test results at a few locations in Missouri from March 31 to November 18, 2021.

[Dates are shown as month/day/year]

Date of test	Timing offset, in seconds	Angular offset for roll, in degrees	Angular offset for pitch, in degrees	Angular offset for yaw, in degrees	Location
03/31/2021	0	−0.10	0	0	New Marceline City Lake near Marceline, Missouri
04/19/2021	0	−0.10	0	−1.50	Hazel Creek Lake near Kirksville, Missouri, after striking a submerged object
04/26/2021	0	−0.10	0	−4.00[a]	Bowling Green Reservoir near Bowling Green, Missouri
04/27/2021	0	−0.10	0	−2.00	Monroe City Lake near Monroe City, Missouri
05/04/2021	0	−0.10	0	−2.50	Forest Lake near Kirksville, Missouri
11/18/2021	0	−0.10	0	−1.50	Lake of the Ozarks near Camdenton, Missouri

[a]Multibeam echosounder mounted to PORTUS pole on jon boat (fig. 9*C*).

(Huizinga, 2010) that a sensitivity analysis of the four offsets implied that the ultimate position of surveyed points in three-dimensional space was least sensitive to the angular offset for yaw, whereas it was most sensitive to the angular offset for roll. Processing all the data for the lakes detailed in this report with an angular offset for roll of –0.10 degree, no angular offset for pitch, and an angular offset for yaw as determined by incremental patch testing generally yielded good results with no noticeable artifacts caused by incorrect offsets.

Uncertainty Estimation

Similar to the previous studies of bathymetry in Missouri (Huizinga, 2010, 2022; Richards and others, 2019), bathymetry and uncertainty in the multibeam survey was estimated for each survey-grid cell in the surveyed area using the CUBE method (Calder and Mayer, 2003) as implemented in the MBMax processing package of the HYPACK/HYSWEEP software (HYPACK, Inc., 2020). The CUBE uncertainty is a measure of the variability of the individual points in the cell used to determine the CUBE-derived elevation for the cell. Statistics of gridded uncertainty for each of the surveyed lakes are shown in table 6, and the spatial distribution of uncertainty observed in each lake is shown in figures 11–22. The CUBE uncertainty data were output and combined with the three-dimensional bathymetric data and are included with metadata in the USGS data release associated with this study (Rivers and others, 2023). Data from the ADCP do not have an associated CUBE uncertainty.

Mean uncertainty values for all the lakes except Bowling Green Reservoir (Jack Floyd Memorial Lake; lake 30; table 6) were at or less than 0.25 ft, which is within the specifications for a “Special Order” survey, the most-stringent survey standard of the International Hydrographic Organization (International Hydrographic Organization, 2020). The largest mean uncertainty value for the surveys was 0.31 ft, and the largest median uncertainty value was 0.26 ft (table 6). The largest overall uncertainty in these surveys was 4.99 ft; however, uncertainty values were larger near moderate-relief features (steep banks and submerged channels and ridges; portions of the old dam embankment are visible in fig. 19) because the gridded uncertainty as determined by the CUBE method is affected by large variations in raw elevation values in a single grid cell. The uncertainty values also were sometimes larger in the outermost beam extents of the MBES swath in the overlap with an adjacent swath, particularly when the swath was tilted for the survey lines along the banks or widened in the upper extent of a lake (figs. 11–17).

Additional uncertainty at Marceline Old Reservoir (lake 25; fig. 13), Bowling Green Reservoir (Jack Floyd Memorial Lake; lake 30; fig. 18), and Old Lake (Bowling Green West; lake 31; fig. 19) can be linked to the strong winds during data collection. These strong winds cause the surface of the lake to become uneven with waves, thus introducing higher than typical pitch and roll. The two Bowling Green lakes (Bowling Green Reservoir and Old Lake) also had steep terrain with deep valleys or other abrupt topography changes, which can affect uncertainties, particularly when combined with higher-than-normal pitch and roll from wind.

Table 6. Uncertainty results for gridded bathymetric data from surveys at water-supply lakes in northeastern Missouri, March 30 to May 4, 2021.

Lake name	Lake number (fig. 1)	Maximum value of uncertainty, in feet	Mean value of uncertainty, in feet	Median value of uncertainty, in feet	Standard deviation of uncertainty, in feet	Percentage of bathymetric points with uncertainty value less than a given threshold			
						1.00 foot	0.50 foot	0.25 foot	0.10 foot
Brookfield City Lake	23	4.17	0.12	0.07	0.19	99.10	96.97	91.38	78.32
New Marceline City Lake	24	4.13	0.13	0.10	0.19	99.18	96.89	89.40	73.02
Marceline Old Reservoir	25	4.99	0.25	0.16	0.31	97.29	90.79	76.47	22.48
Shelbina Lake	26	3.22	0.18	0.13	0.16	99.49	95.25	82.80	37.84
Hazel Creek Lake	27	4.86	0.08	0.07	0.10	99.86	98.89	96.28	89.29
Memphis Lake (Lake Showme)	28	4.99	0.13	0.10	0.14	99.66	97.93	90.40	61.05
Memphis Reservoir	29	4.56	0.14	0.10	0.17	99.19	96.66	90.43	68.78
Bowling Green Reservoir (Jack Floyd Memorial Lake)	30	4.92	0.31	0.26	0.17	99.74	87.60	45.71	9.61
Old Lake (Bowling Green West)	31	4.99	0.21	0.16	0.18	99.34	95.67	74.84	20.25
Monroe Lake B (Monroe City South)	32	4.20	0.05	0.03	0.06	99.98	99.79	98.54	94.69
Monroe City Lake	33	4.99	0.07	0.07	0.10	99.85	99.15	96.74	90.19
Forest Lake	34	2.36	0.07	0.07	0.06	99.98	99.67	98.42	92.81

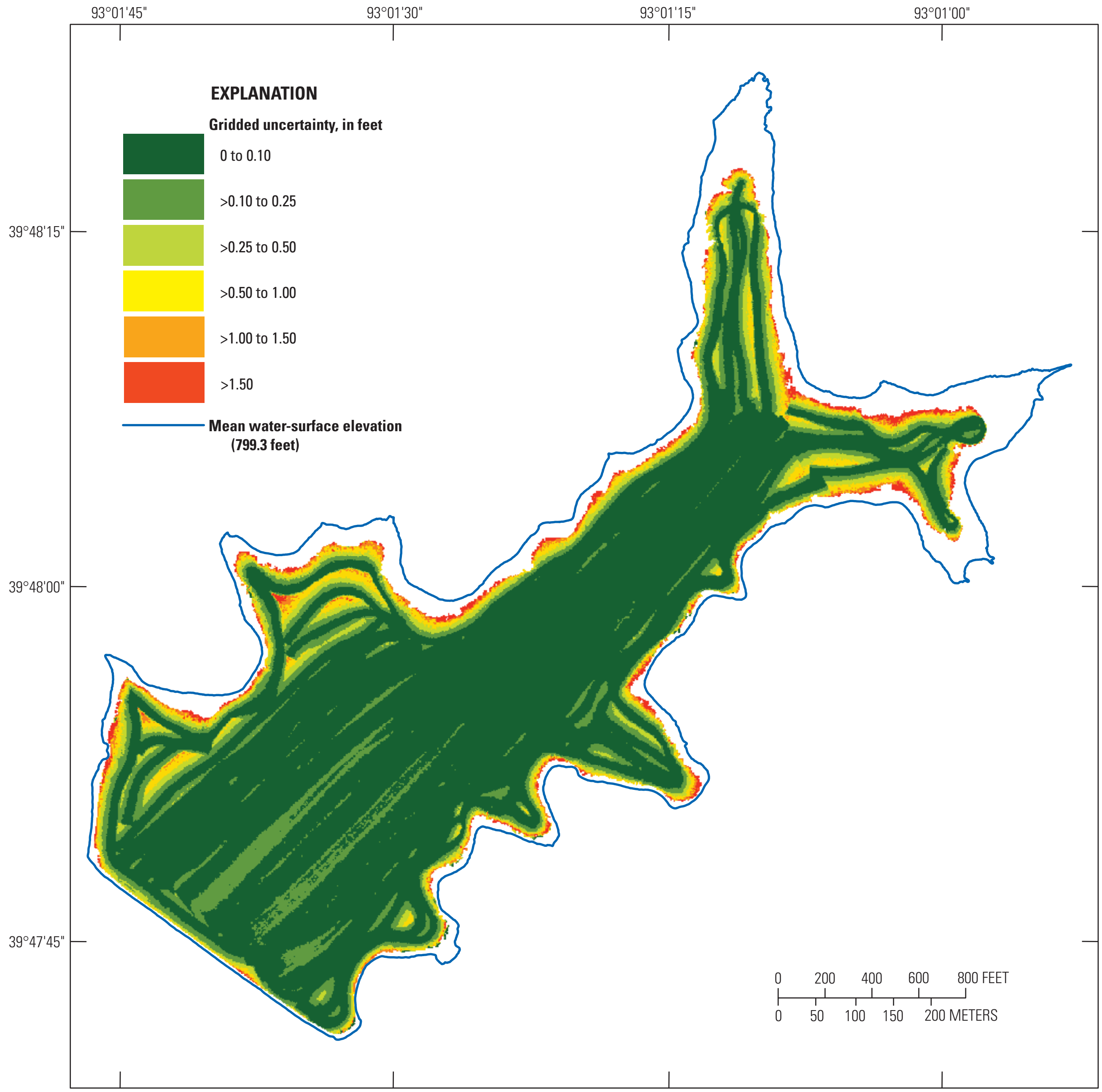


Figure 11. Gridded uncertainty of the bathymetric surface of Brookfield City Lake (lake 23) near Brookfield, Missouri, 2021.

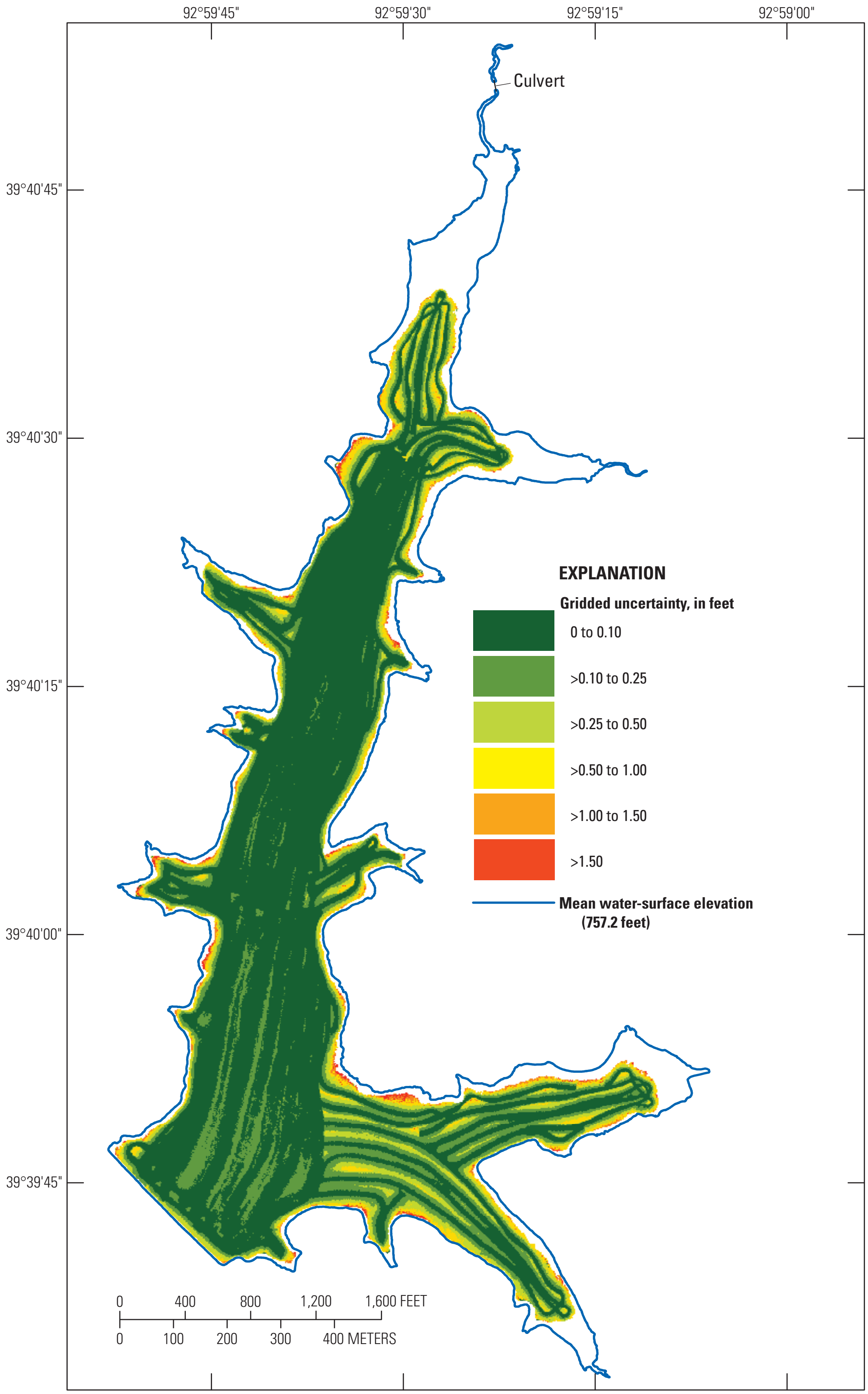


Figure 12. Gridded uncertainty of the bathymetric surface of New Marceline City Lake (lake 24) near Marceline, Missouri, 2021.

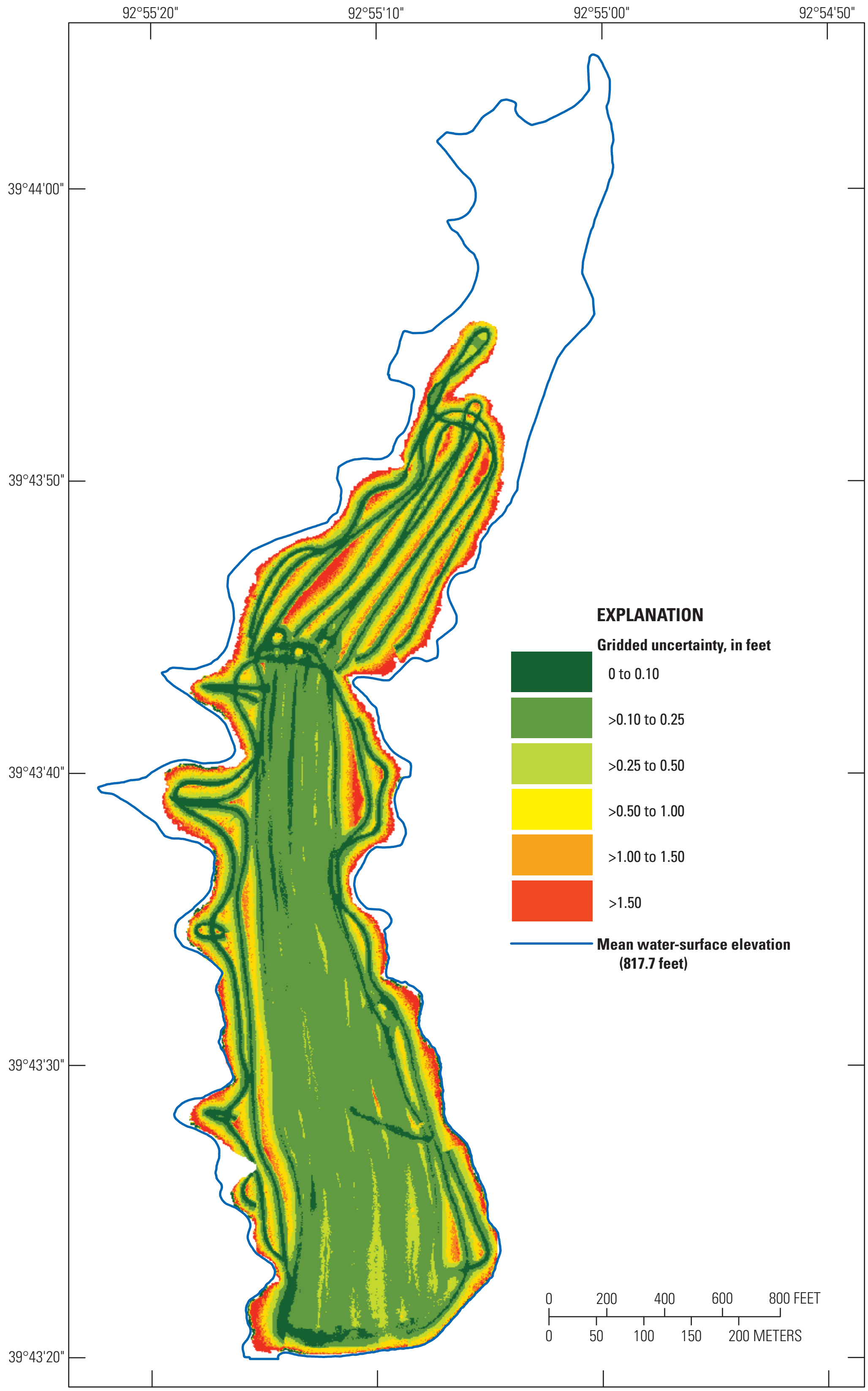


Figure 13. Gridded uncertainty of the bathymetric surface of Marceline Old Reservoir (lake 25) near Marceline, Missouri, 2021.

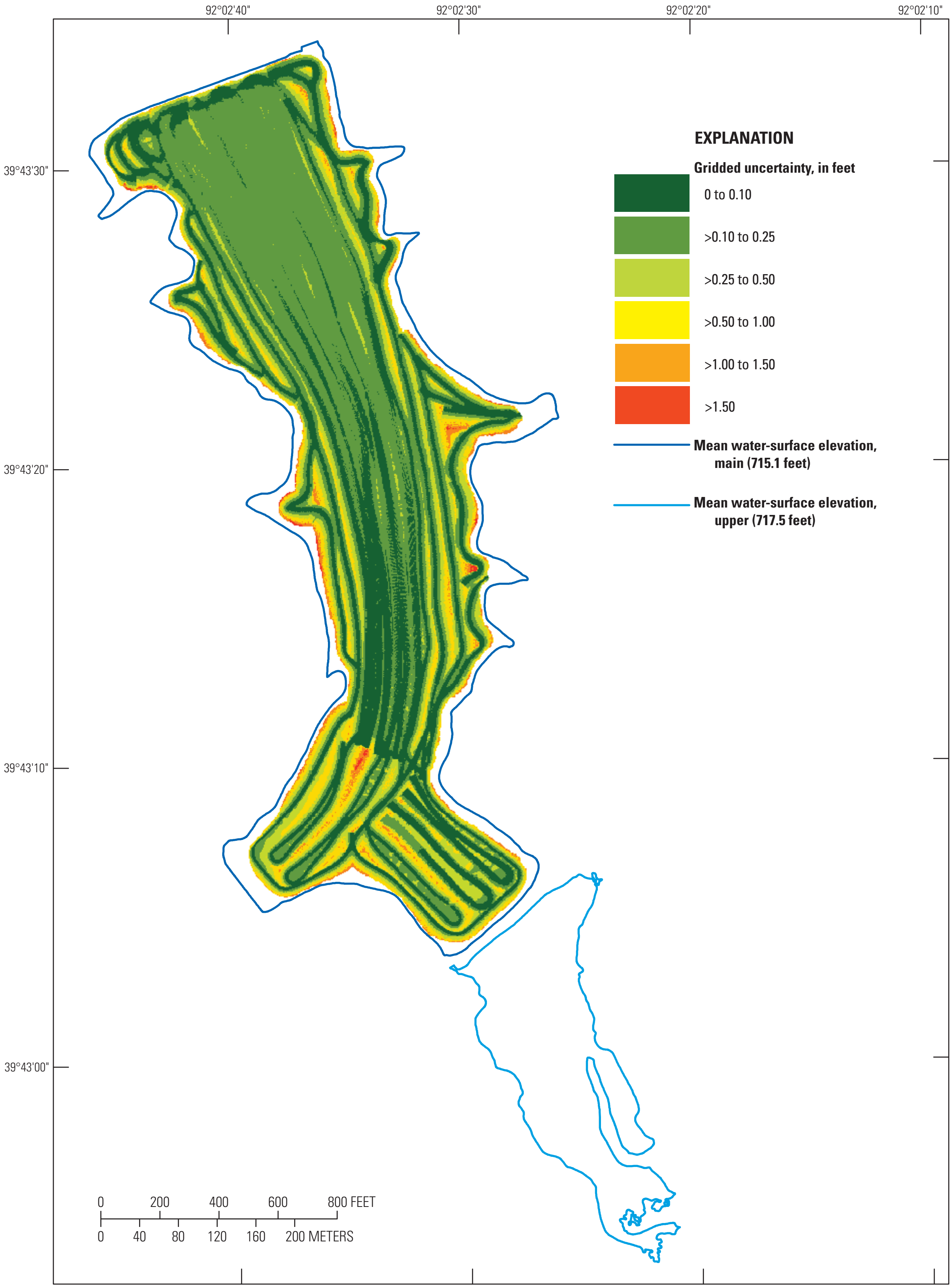


Figure 14. Gridded uncertainty of the bathymetric surface of Shelbina Lake (lake 26) near Shelbina, Missouri, 2021.

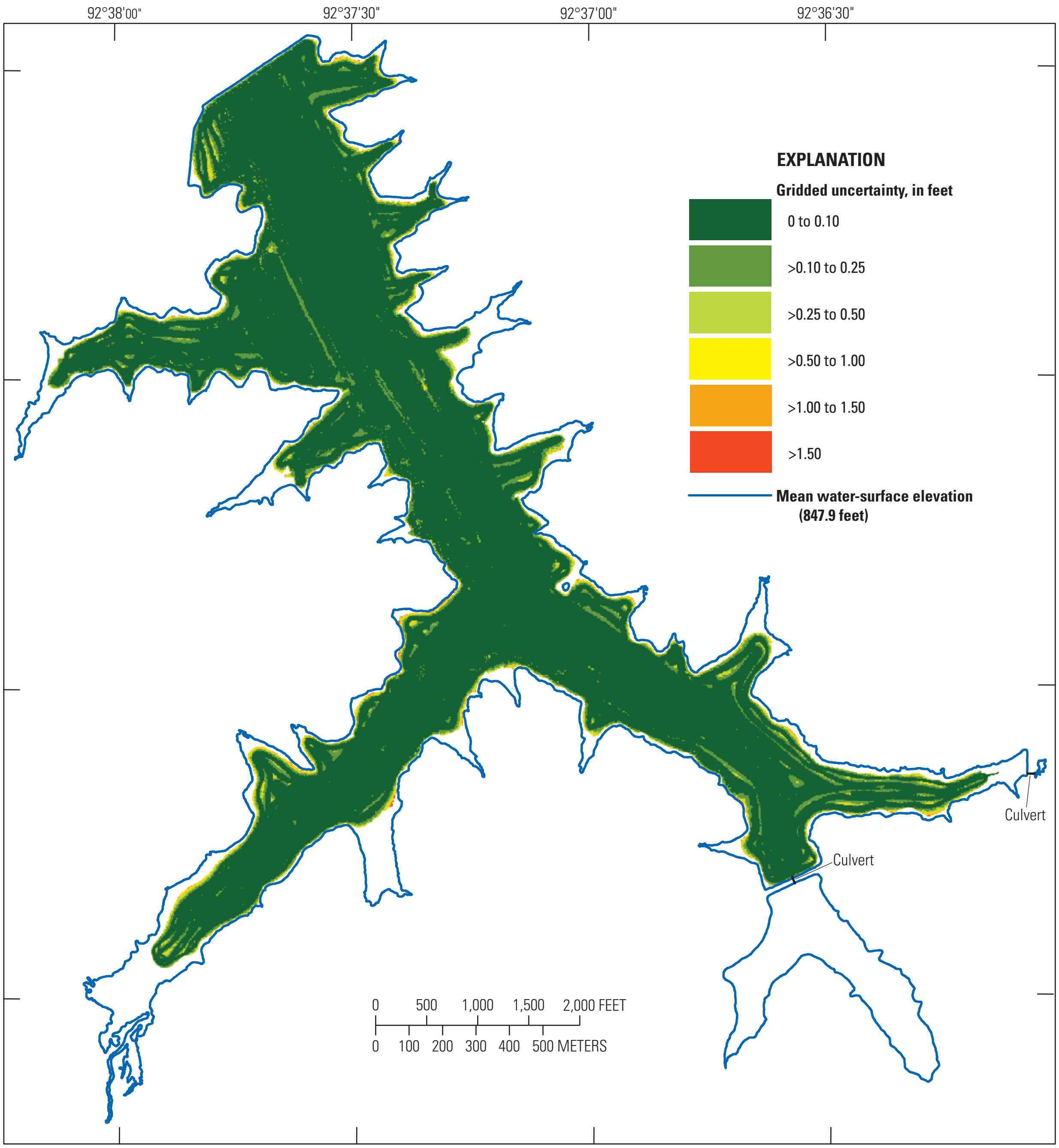


Figure 15. Gridded uncertainty of the bathymetric surface of Hazel Creek Lake (lake 27) near Kirksville, Missouri, 2021.

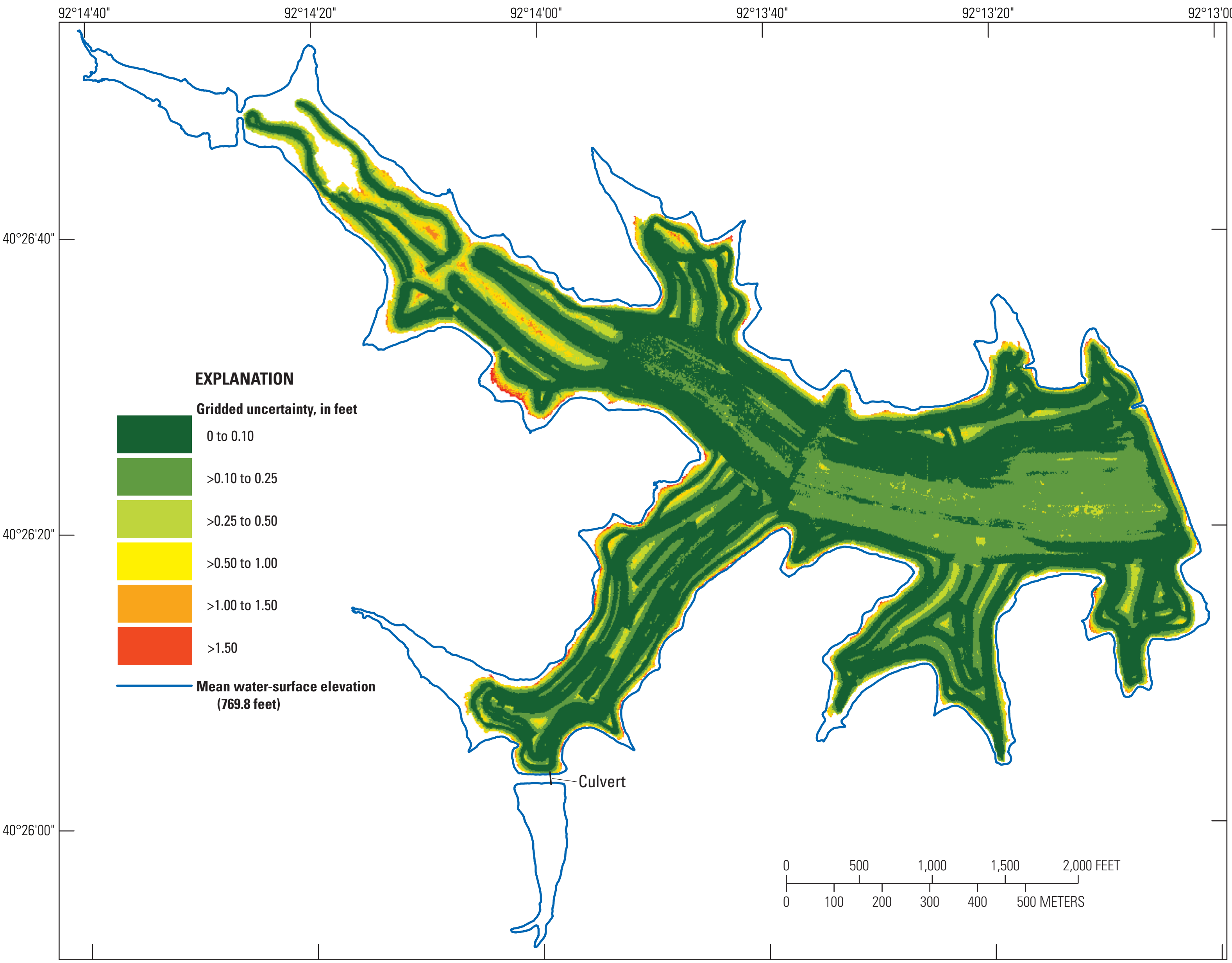


Figure 16. Gridded uncertainty of the bathymetric surface of Memphis Lake (Lake Showme; lake 28) near Memphis, Missouri, 2021.

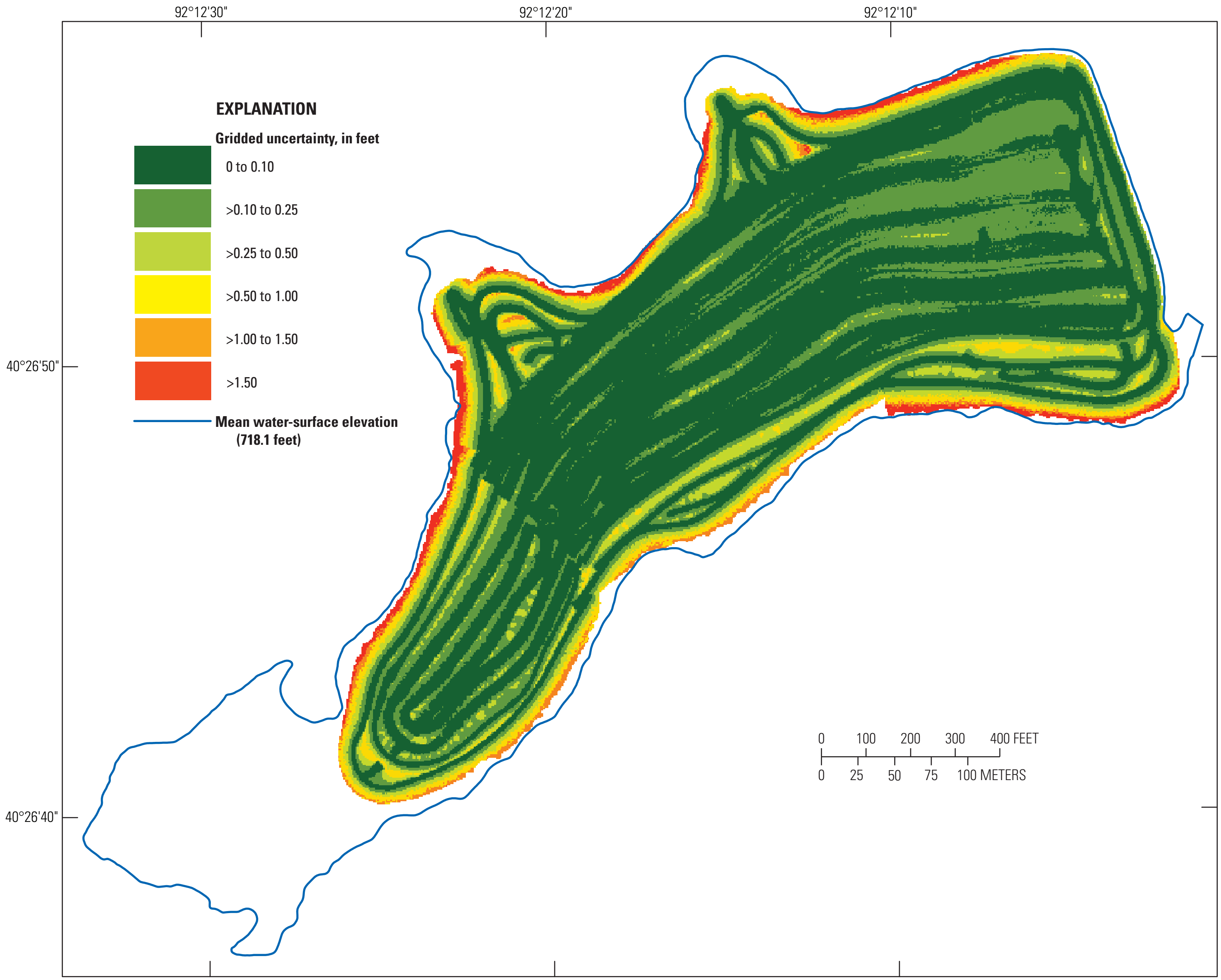


Figure 17. Gridded uncertainty of the bathymetric surface of Memphis Reservoir (lake 29) near Memphis, Missouri, 2021.

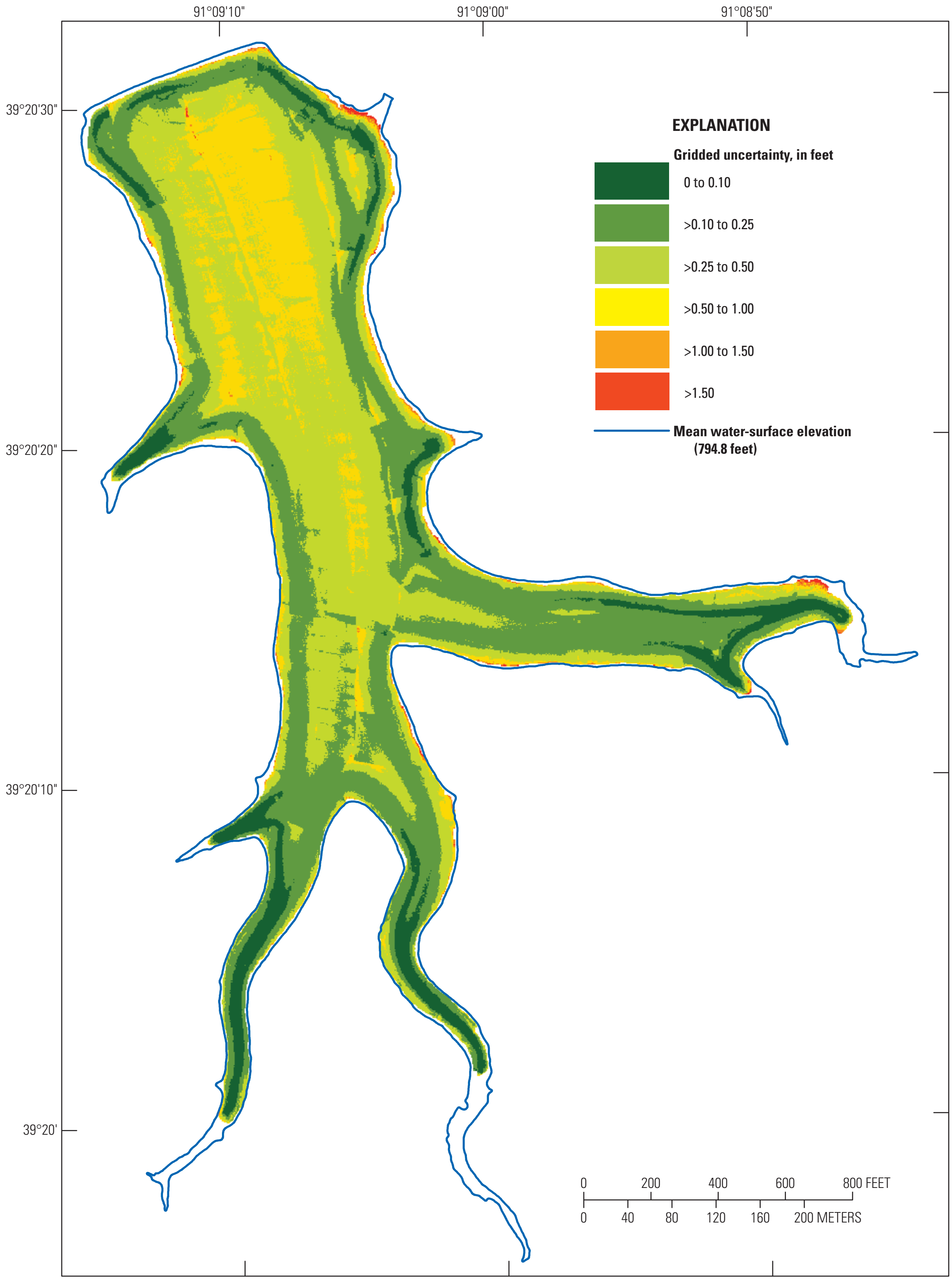


Figure 18. Gridded uncertainty of the bathymetric surface of Bowling Green Reservoir (Jack Floyd Memorial Lake; lake 30) near Bowling Green, Missouri, 2021.

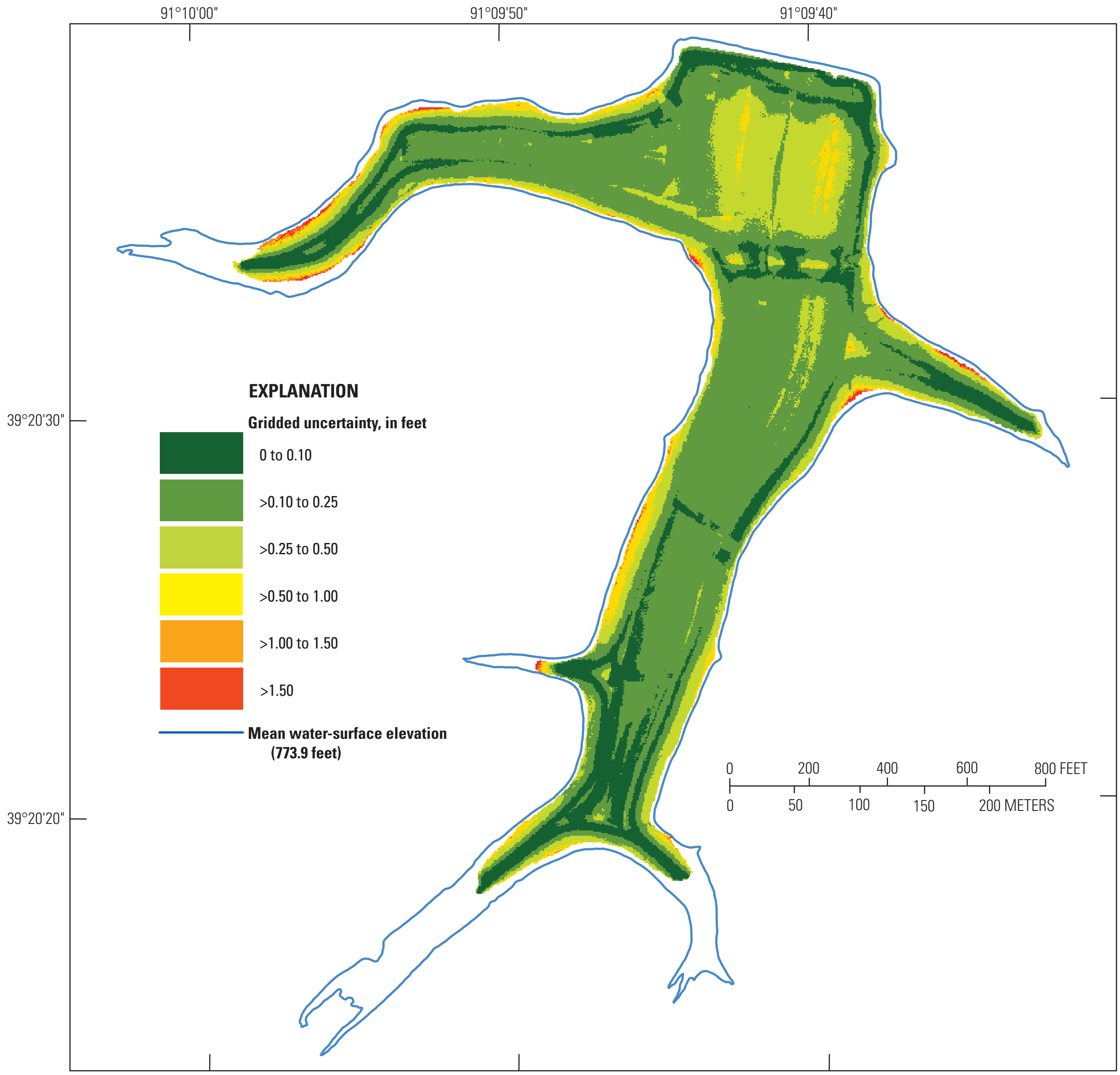


Figure 19. Gridded uncertainty of the bathymetric surface of Old Lake (Bowling Green West; lake 31) near Bowling Green, Missouri, 2021.

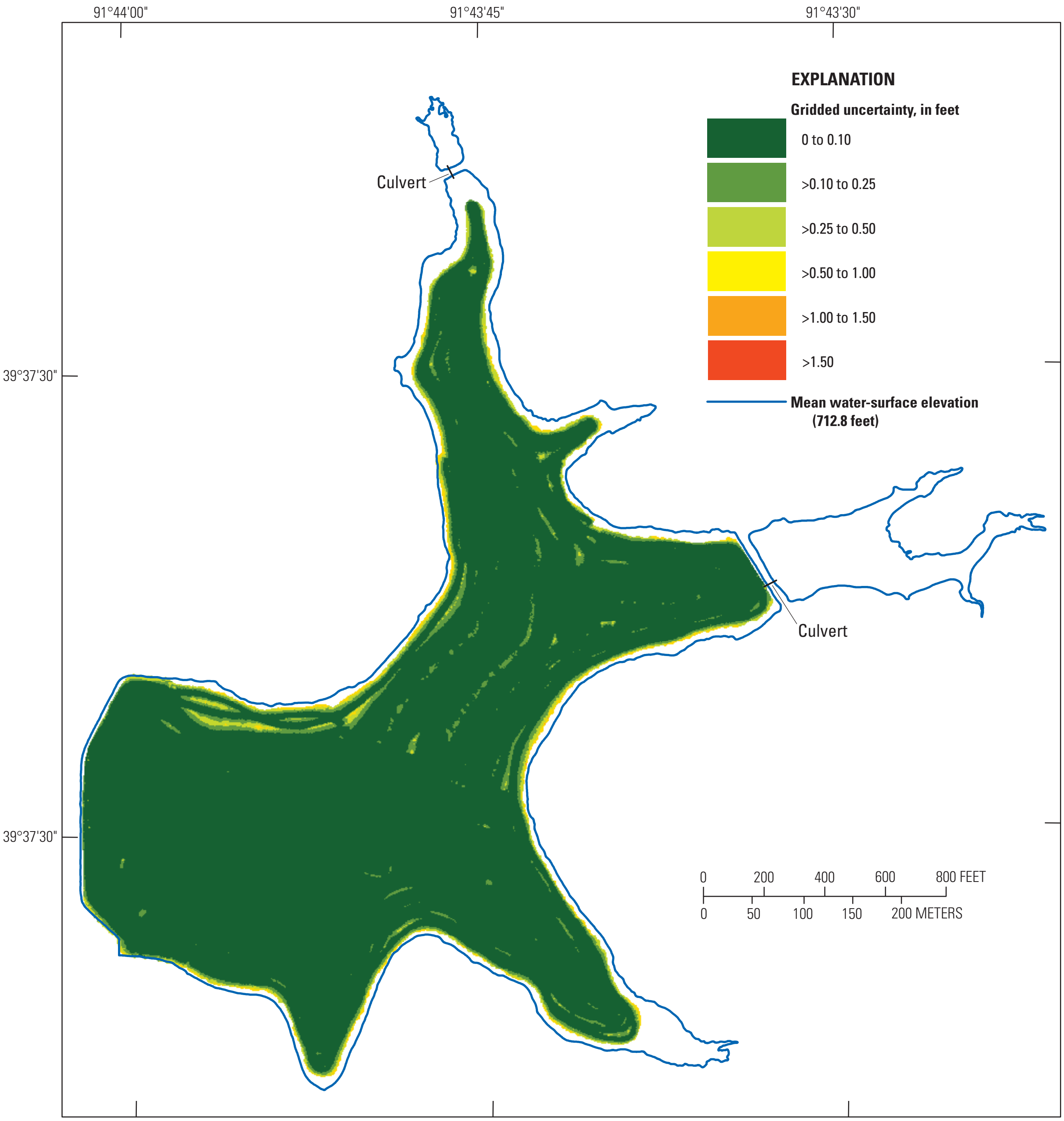


Figure 20. Gridded uncertainty of the bathymetric surface of Monroe Lake B (Monroe City South; lake 32) near Monroe City, Missouri, 2021.

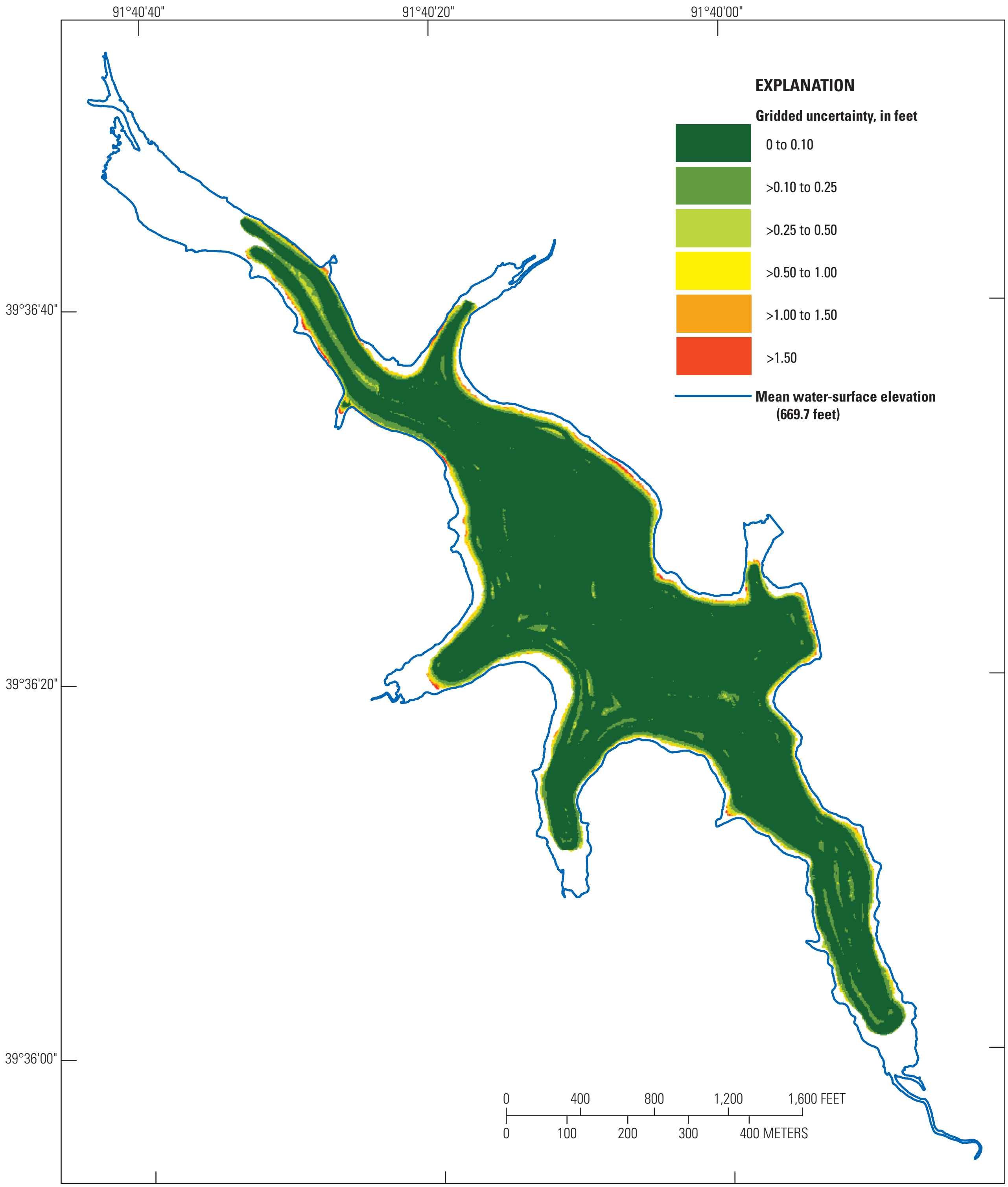


Figure 21. Gridded uncertainty of the bathymetric surface of Monroe City Lake (lake 33) near Monroe City, Missouri, 2021.

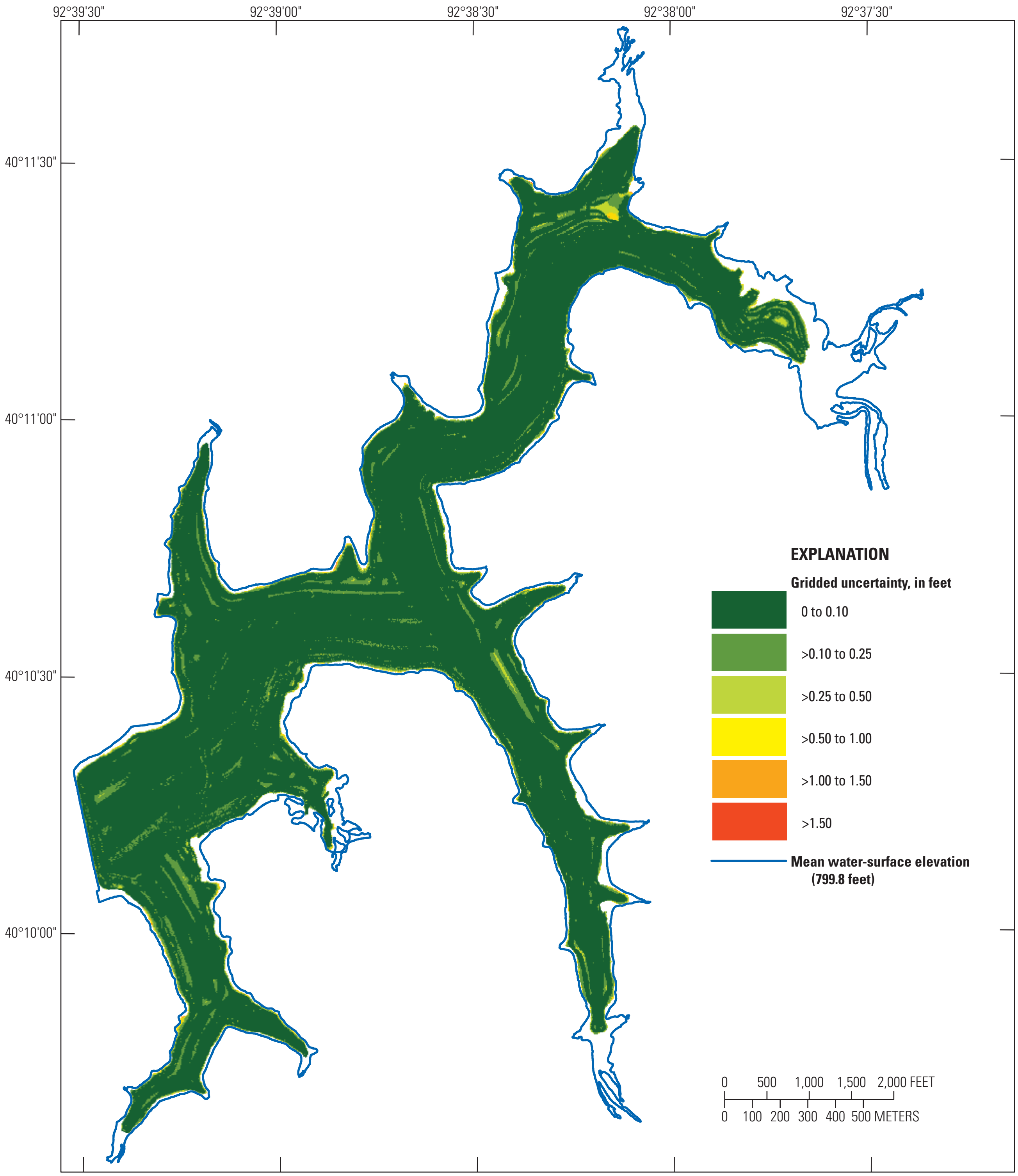


Figure 22. Gridded uncertainty of the bathymetric surface of Forest Lake (lake 34) near Kirksville, Missouri, 2021.

Quality Assurance for Bathymetric Surface, Contour Map, and Bathymetric Change

Accuracy of the bathymetric surface and contours in relation to the survey data is a function of the survey data accuracy, the density of the survey data, and the various processing steps involved in the surface and contour creation. The process of data reduction done to obtain the gridded dataset (at a given grid resolution) from the raw survey data likely degraded the accuracy of the gridded dataset relative to the raw data. At least one area of each lake was resurveyed after the main survey, generally in a direction 45 to 90 degrees to the main survey, to collect a dataset (hereinafter referred to as a “cross-check line”) that could be used to estimate the accuracy of the gridded dataset used to produce the bathymetric surface (table 7). If the survey spanned more than 1 day, at least one cross-check line was collected each day. Raw points in the cross-check lines that were within a horizontal distance of 0.16 ft from a gridded point were selected as cross-check quality-assurance data points, and the elevation values of these cross-check line points were compared to the gridded points. The horizontal distance was chosen to permit a reasonable number of comparison points between the gridded and cross-check data and was loosely based on the interpoint spacing of the raw cross-check line data. The nearest raw cross-check line points were compared to the gridded points, with the data testing at a vertical accuracy shown in table 7 at a 95-percent confidence level; the median absolute vertical error of each survey also is shown in table 7. The mean error is being included because it is shown to be a key metric of volumetric uncertainty (Anderson, 2019).

A mapping quality-assurance dataset was used to evaluate the bathymetric surface and included data points selected at random from the gridded data points at each lake. Points that were used to create the bathymetric surface were not included as bathymetric surface quality-assurance points. The three-dimensional bathymetric surface was tested against the surface quality-assurance dataset from a given lake to determine the vertical accuracy of the surface using methods described in Wilson and Richards (2006). The surface of each lake tested at a vertical accuracy that is shown in table 8 at the 95-percent confidence level; the mean error and median absolute vertical error of each surface also are shown in table 8. The spatial distribution of the vertical accuracy for each lake is shown in figures 23–34. The three-dimensional bathymetric surface of each lake was used as the source for the computation of the surface area and capacity values for the lake and the source for the development of the bathymetric contour map for each lake (plates 1–12).

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 for a given lake were tested with

Table 7. Summary of cross-check line results used for quality assurance of gridded bathymetric data from surveys at water-supply lakes in northeastern Missouri, March 30 to May 4, 2021.

Lake name	Lake number (fig. 1)	Number of raw quality-assurance points in cross-check line dataset	Number of points in comparison dataset	Tested vertical accuracy at a 95-percent confidence level, in feet	Mean vertical error, in feet	Median absolute vertical error, in feet
Brookfield City Lake	23	2,379,655	22,446	0.22	0.03	0.07
New Marceline City Lake	24	1,486,201	13,504	0.40	0.04	0.13
Marceline Old Reservoir	25	918,552	16,038	0.22	0.04	0.07
Shelbina Lake	26	1,111,039	23,733	0.18	0.00	0.07
Hazel Creek Lake	27	2,701,929	8,499	1.69	0.48	0.17
Memphis Lake (Lake Showme)	28	2,113,385	26,365	0.29	0.04	0.10
Memphis Reservoir	29	1,263,622	16,507	0.21	0.03	0.07
Bowling Green Reservoir (Jack Floyd Memorial Lake)	30	1,417,890	105,658	0.31	0.06	0.10
Old Lake (Bowling Green West)	31	1,069,169	54,323	0.24	0.04	0.07
Monroe Lake B (Monroe City South)	32	1,514,944	6,737	0.20	0.00	0.07
Monroe City Lake	33	2,058,140	18,582	0.20	−0.04	0.07
Forest Lake	34	2,730,028	9,737	0.53	0.08	0.16

Table 8. Summary of bathymetric surface quality-assurance results from surveys at water-supply lakes in northeastern Missouri, March 30 to May 4, 2021.

Lake name	Lake number (fig. 1)	Number of points in quality-assurance dataset (table 2)	Tested vertical accuracy at a 95-percent confidence level, in feet	Mean vertical error, in feet	Median absolute vertical error, in feet
Brookfield City Lake	23	47,662	0.18	0.00	0.02
New Marceline City Lake	24	68,763	0.18	0.00	0.02
Marceline Old Reservoir	25	74,797	0.14	0.00	0.02
Shelbina Lake	26	77,137	0.06	0.00	0.02
Hazel Creek Lake	27	52,108	0.27	0.00	0.02
Memphis Lake (Lake Showme)	28	104,976	0.13	0.00	0.02
Memphis Reservoir	29	61,617	0.10	0.00	0.01
Bowling Green Reservoir (Jack Floyd Memorial Lake)	30	86,185	0.24	0.00	0.02
Old Lake (Bowling Green West)	31	51,601	0.28	−0.01	0.02
Monroe Lake B (Monroe City South)	32	27,733	0.14	0.00	0.01
Monroe City Lake	33	40,065	0.17	0.00	0.02
Forest Lake	34	65,281	0.25	0.00	0.02

the dataset used to create the bathymetric surface. A map point was considered a contour elevation evaluation point if it was within a certain horizontal distance of a given contour line (the “contour quality-assurance point search tolerance” in table 9). The contour quality-assurance point search tolerance was chosen such that most of the quality-assurance points could be reasonably considered to be a match to the contour, and generally was less than one-half of the minimum horizontal distance between closely spaced contours. The contours of each lake tested at a vertical accuracy that is shown in table 9 at the 95-percent confidence level; the mean error and median absolute vertical error of the contours for each lake also are shown in table 9.

The quality-assurance statistics provide a measure of the effects of each processing step in the development of the final products for each lake: the results in table 7 summarize the effect of gridding the bathymetry data from the raw data; the results in table 8 summarize the effect of creating a TIN surface from the subsampled gridded data; and the results in table 9 summarize the effects of creating contours from the TIN surface. The contours and area and capacity tables were created from the TIN surface; therefore, the bathymetric TIN surface quality-assurance results presented in table 8 are the best representation of the overall quality of the final products for these lakes.

Quality-assurance data were used to evaluate the bathymetric surface accuracy of Hazel Creek Lake (lake 27), Bowling Green Reservoir (Jack Floyd Memorial Lake; lake 30), Old Lake (Bowling Green West; lake 31), and Forest Lake (lake 34) in the previous surveys at these lakes (Wilson and Richards, 2006). These same data were used as an independent dataset to estimate the accuracy of the bathymetric change raster in the comparisons with the current surveys for these four lakes. The differences between the elevations of the previous survey quality-assurance data points and the 2021 bathymetric mapping points at coincident locations were compared. The bathymetric change surface of each lake tested at a vertical accuracy that is shown in table 10 at the 95-percent confidence level; the mean error and median absolute vertical error of the change surface for each lake also are shown in table 10.

Bathymetry, Capacity, and Bathymetric Change

A bathymetric surface was created from the 2021 surveyed data and used to produce a bathymetric contour map for each lake (plates 1–12). The bathymetric maps are similar to maps produced from the earlier surveys (Wilson and Richards, 2006; appendix of Richards, 2013). The bathymetric surfaces still show aspects of the topography that existed prior to lake impoundment, such as a defined river channels, that formed when the area was dominated by fluvial processes (plates 2, 5, 6, 8, 11, and 12). However, many features have likely been affected by post-impoundment sedimentation and compaction of sediments, which tend to mute the sharp and distinct channel bank features evident in a nonsubmerged channel (for example, upper end of the lake in plates 1, 3, and 9, and the entire lake in plates 4, 7, and 10).

A surface area and capacity table was computed at a 2-ft interval for each lake from the bathymetric surface TIN and is on the respective map plate for each lake (plates 1–12). The surface area and capacity values for each lake at the primary spillway or drop inlet elevation are summarized in table 11.

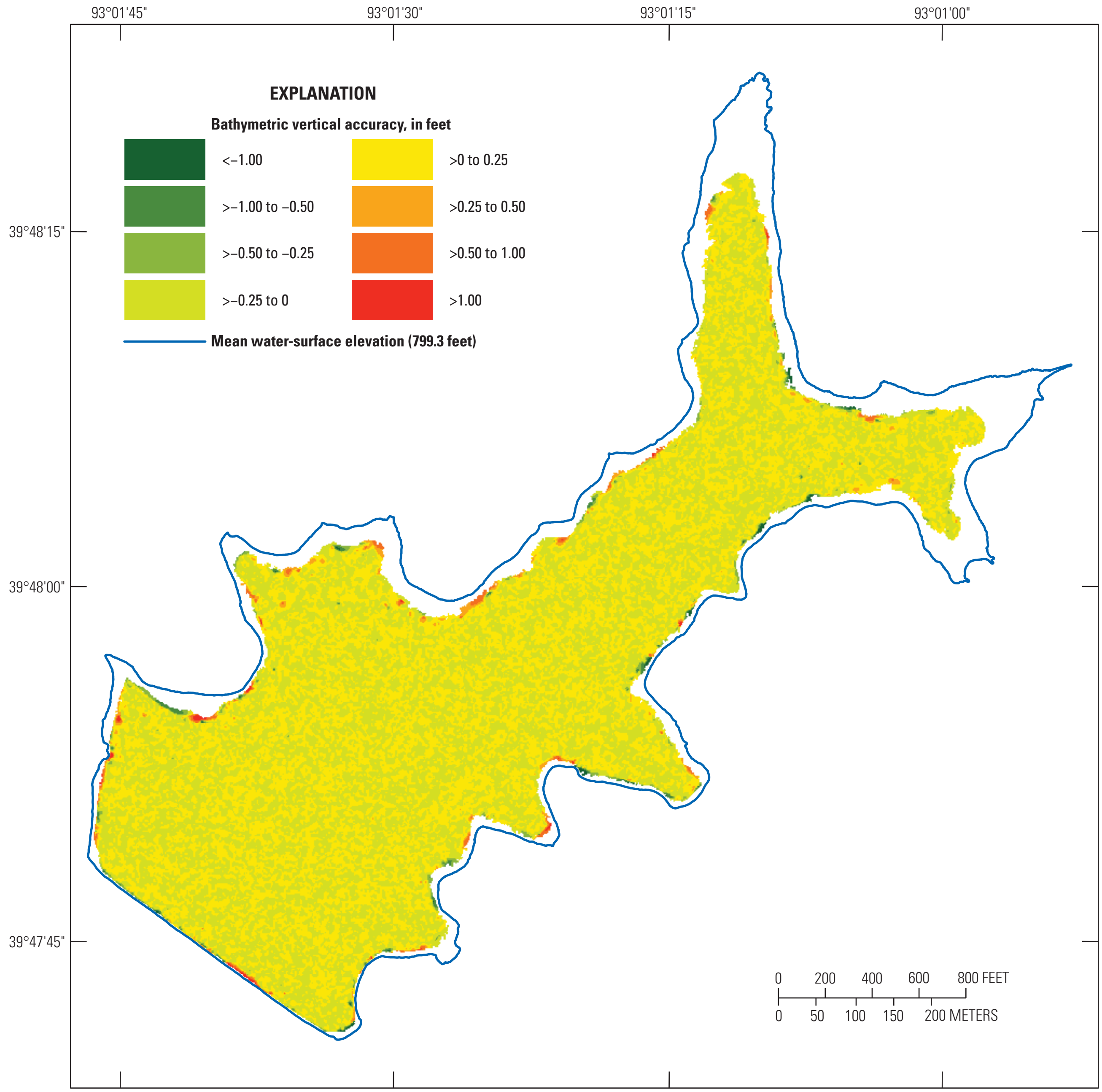


Figure 23. Vertical accuracy of the bathymetric surface of Brookfield City Lake (lake 23) near Brookfield, Missouri, 2021.

When a previous survey existed for a lake (Richards, 2013), the 2021 bathymetric surface was compared to the previous surface to create a bathymetric change map (figs. 35–44). The previous survey capacity at the primary spillway or inlet elevation at each lake for which a previous survey exists is listed in table 12. The capacity value shown for the previous survey has been corrected for any elevation discrepancy between the surveys listed in table 3. The new area and capacity table for each lake is generally similar to the previous survey; however, the capacity generally is less in the 2021 table compared to the previous table at corresponding elevations because of sedimentation.

The bathymetric change maps for the lakes with previous surveys (figs. 35–44) show erosional as well as depositional areas (table 13). Deposition generally appears to be relatively uniform across a given lake area with some localized erosion near the edges of the lake. Notable exceptions to this would include the deposition throughout the old river channel at Memphis Reservoir (lake 29; fig. 40), and the uppermost area of Forest Lake (lake 34; fig. 44). Monroe City Lake (lake 33) had more deposition in the north arm than in the south arm (fig. 43).

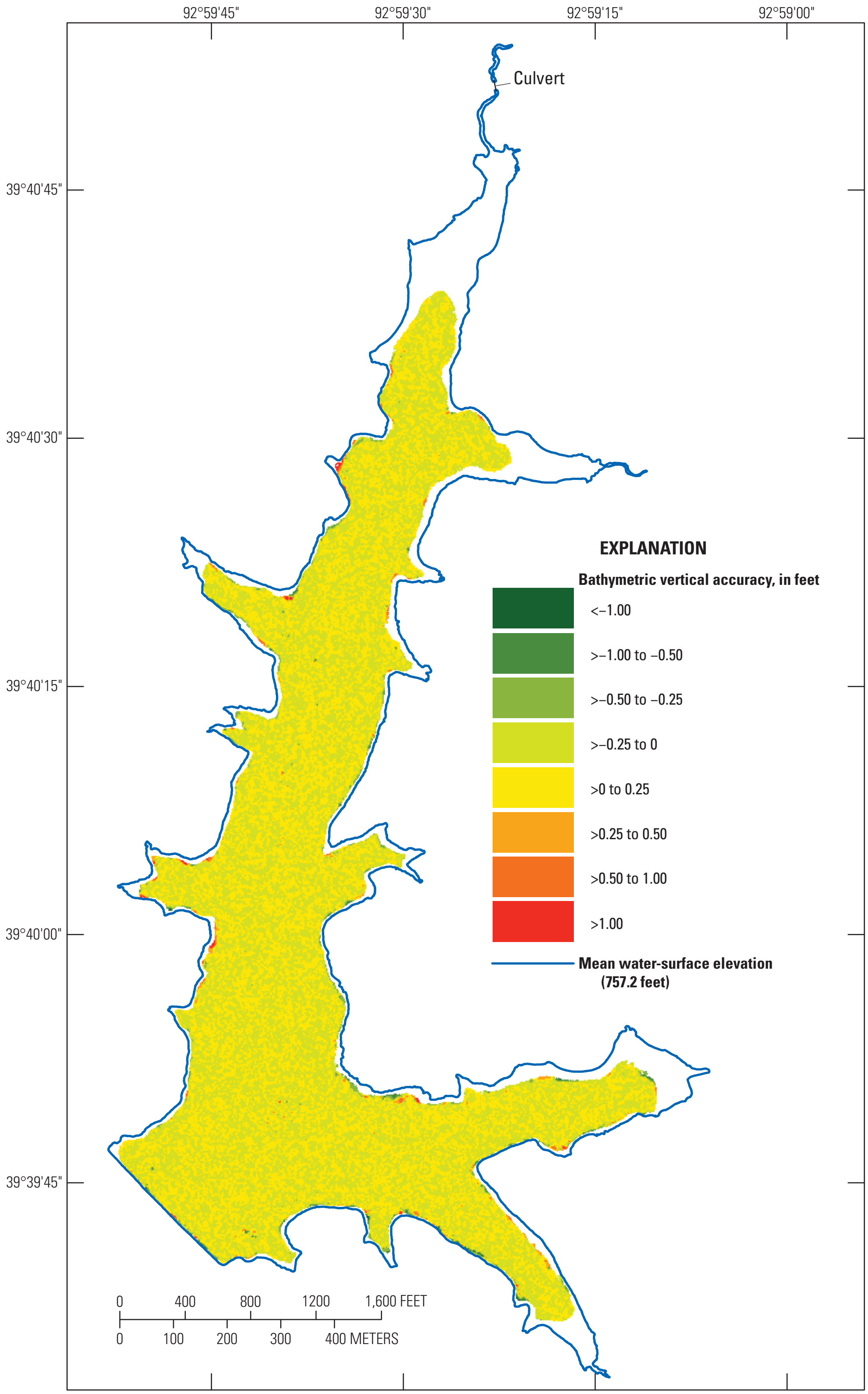


Figure 24. Vertical accuracy of the bathymetric surface of New Marceline City Lake (lake 24) near Marceline, Missouri, 2021.

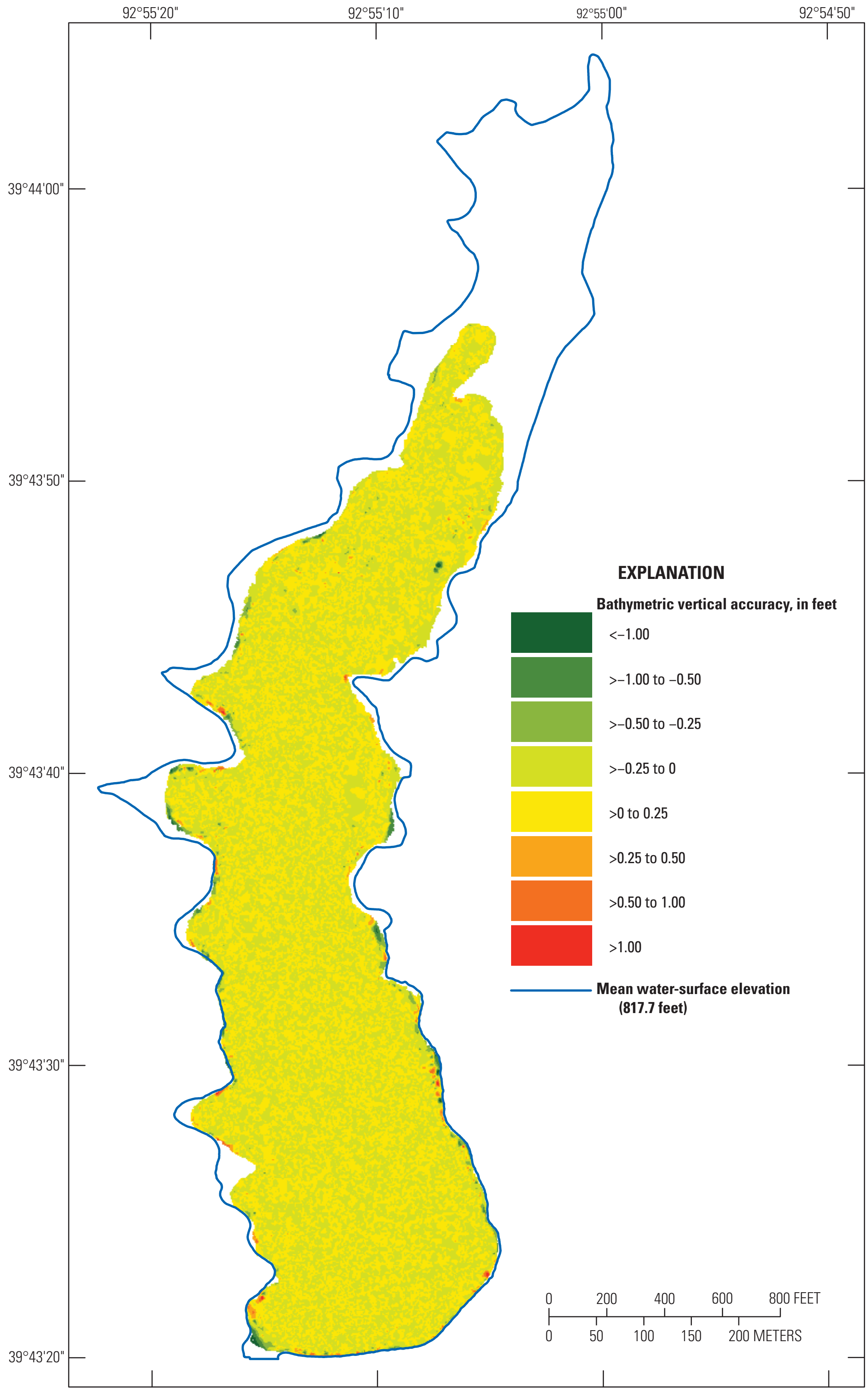


Figure 25. Vertical accuracy of the bathymetric surface of Marceline Old Reservoir (lake 25) near Marceline, Missouri, 2021.

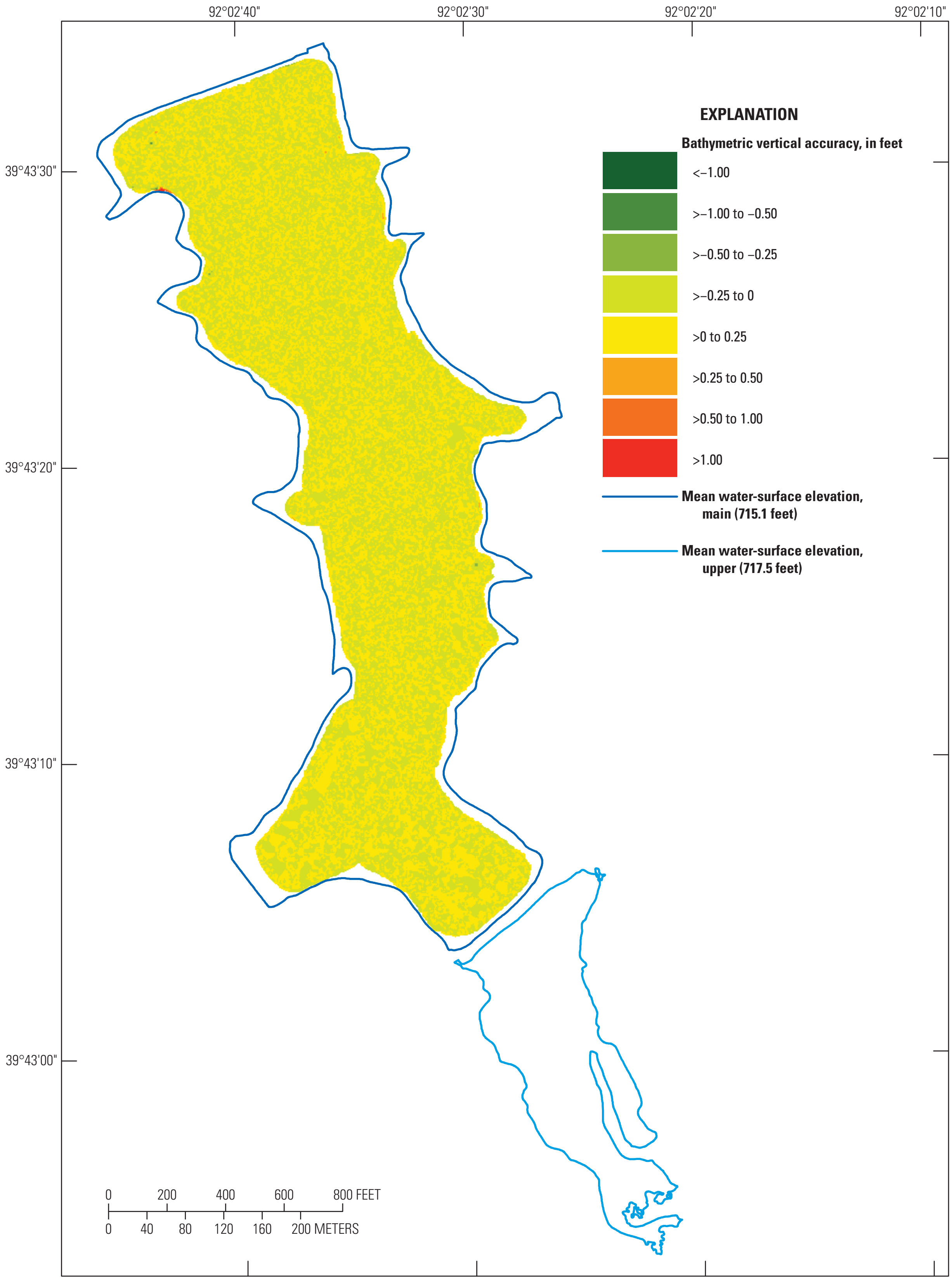


Figure 26. Vertical accuracy of the bathymetric surface of Shelbina Lake (lake 26) near Shelbina, Missouri, 2021.

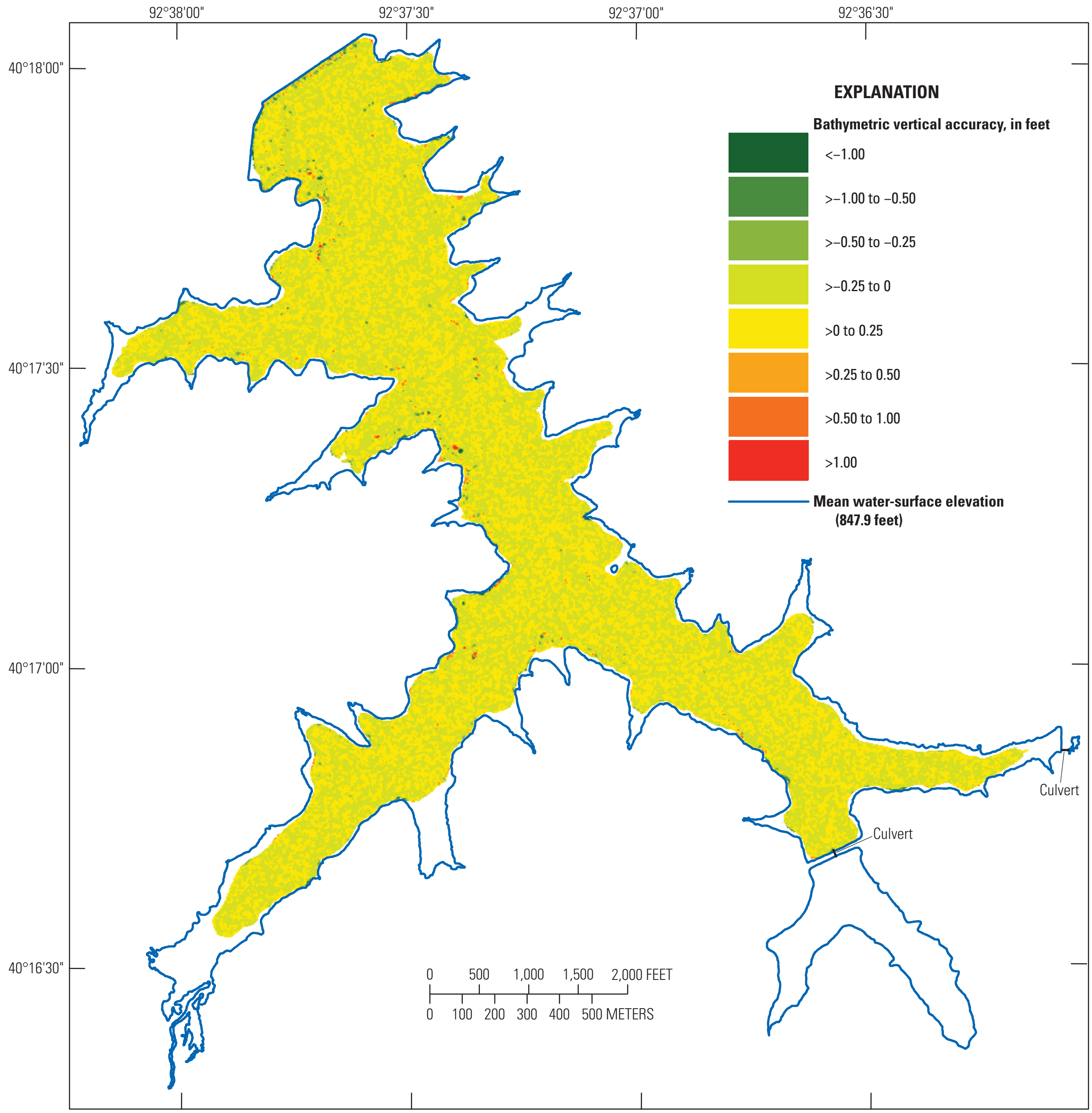


Figure 27. Vertical accuracy of the bathymetric surface of Hazel Creek Lake (lake 27) near Kirksville, Missouri, 2021.

Relative to previous surveys, the change in capacity at the primary spillway elevation ranged from a 7.7-percent decrease at Memphis Reservoir to a 3.9-percent increase at Old Lake (Bowling Green West) (table 12). The mean bathymetric change ranged from 0.03 ft at Hazel Creek and 0.07 ft at Shelbina Lake and bowling Green Reservoir (Jack Floyd Memorial Lake) to 0.63 at Memphis Lake (Lake Showme) and 0.88 at Memphis Reservoir (table 13). The sedimentation rate was determined from the mean bathymetric change times the area of the bathymetric change raster, divided by the duration between the surveys (table 13). The sedimentation rate generally ranged from 0.14 to 1.67 acre-feet per year at Shelbina Lake and Monroe City Lake, respectively; however, Memphis Lake (Lake Showme) had a larger sedimentation rate of 6.80 acre-feet per year, and Forest Lake had a substantially larger sedimentation rate of 17.0 acre-feet per year (table 13). Despite Forest Lake having a small decrease in capacity at the spillway elevation [only 2.4 percent (table 12)], the substantial size of the lake [12,200 acres at the spillway (table 11)] combined with the moderate mean bathymetric change of 0.57 ft (table 13) resulted in a substantial sedimentation rate over the time span between the surveys.

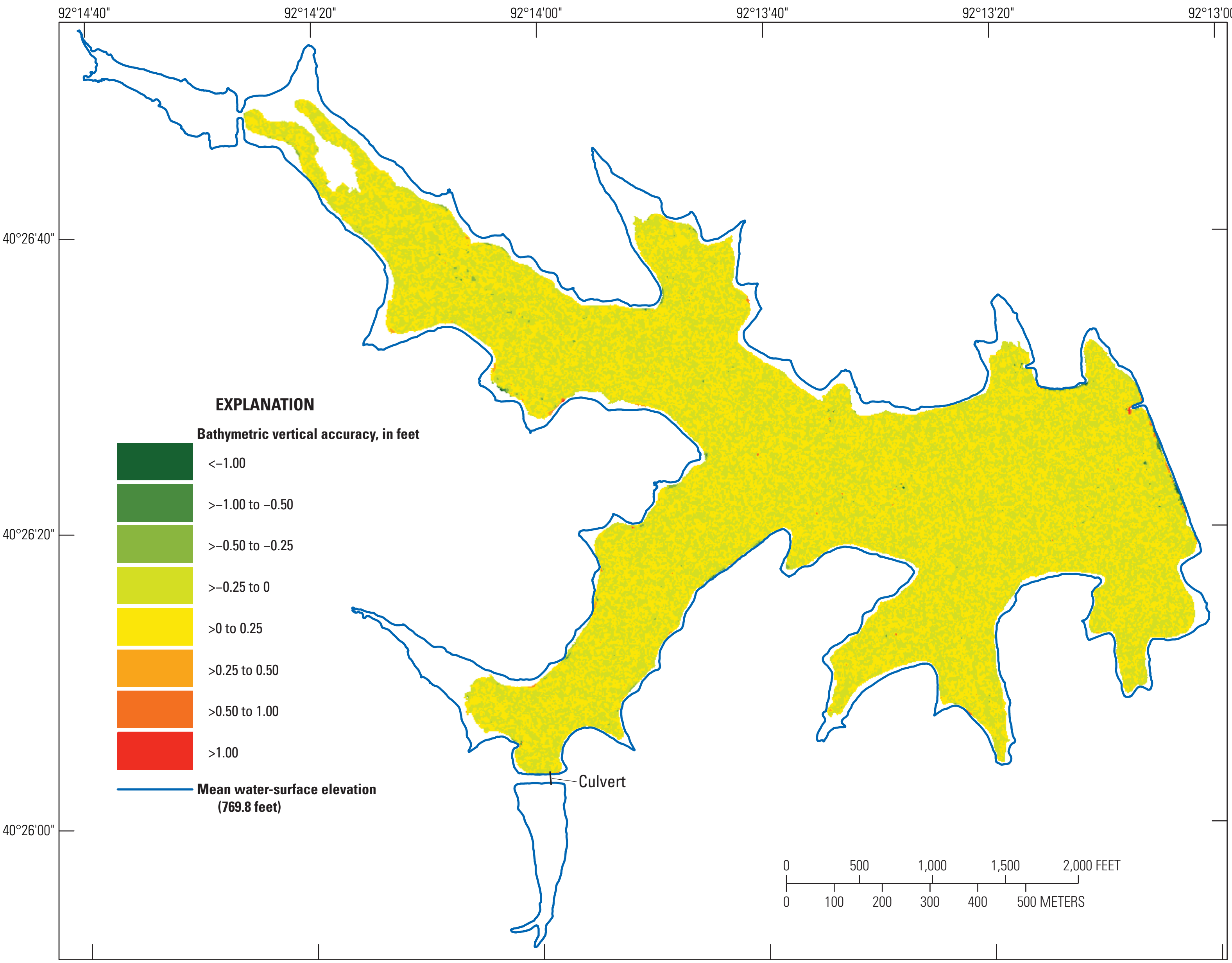


Figure 28. Vertical accuracy of the bathymetric surface of Memphis Lake (Lake Showme; lake 28) near Memphis, Missouri, 2021.

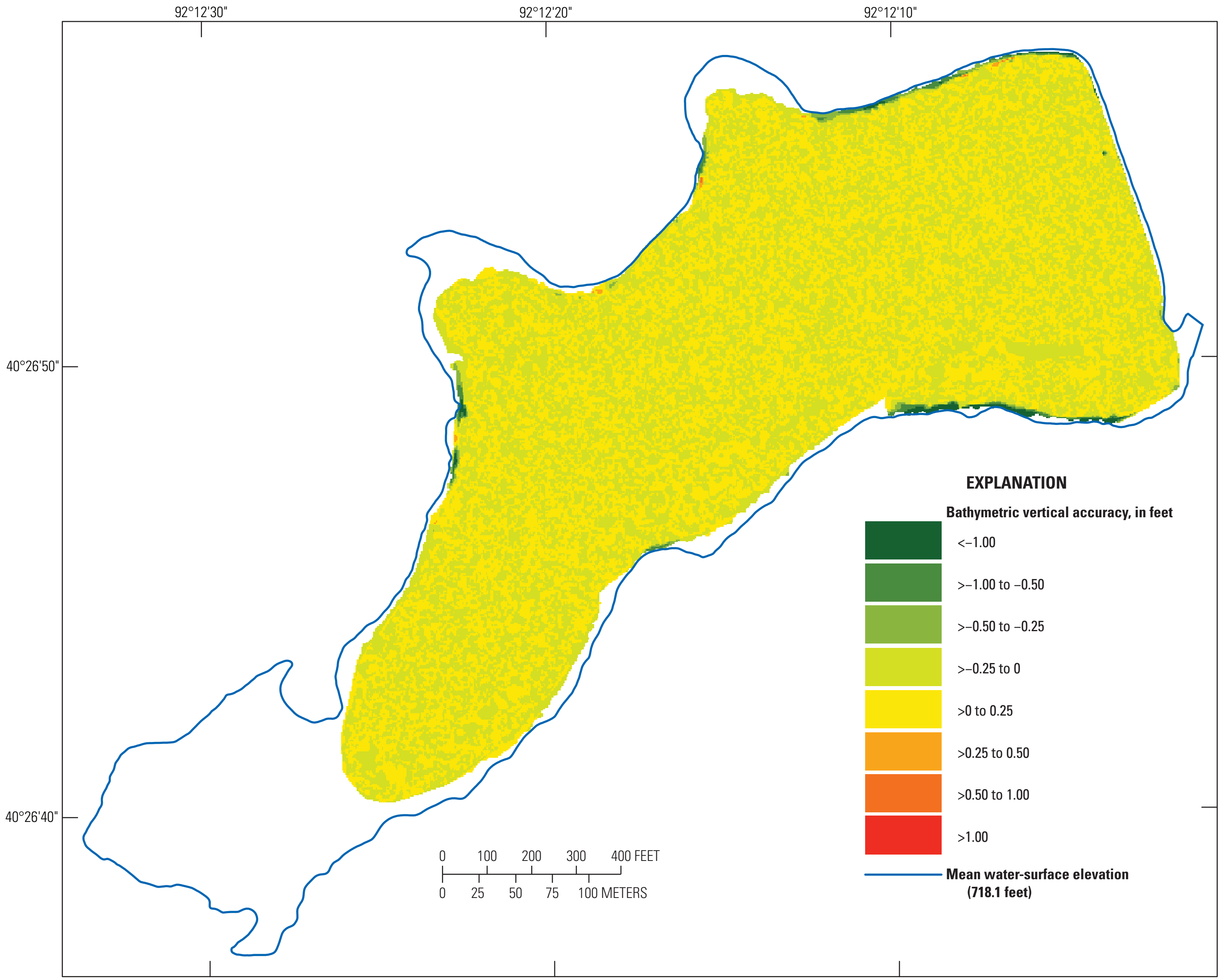


Figure 29. Vertical accuracy of the bathymetric surface of Memphis Reservoir (lake 29) near Memphis, Missouri, 2021.

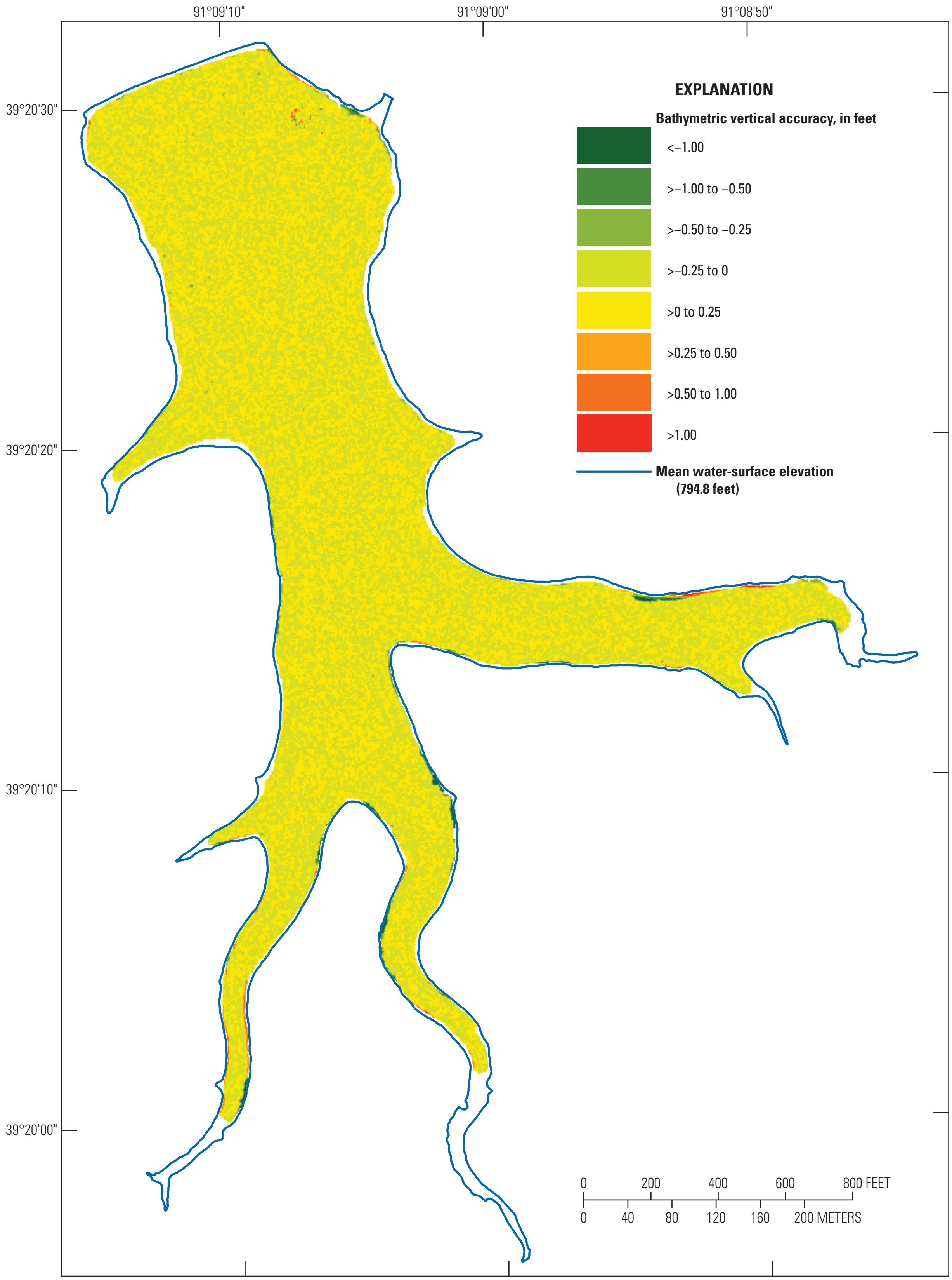


Figure 30. Vertical accuracy of the bathymetric surface of Bowling Green Reservoir (Jack Floyd Memorial Lake; lake 30) near Bowling Green, Missouri, 2021.

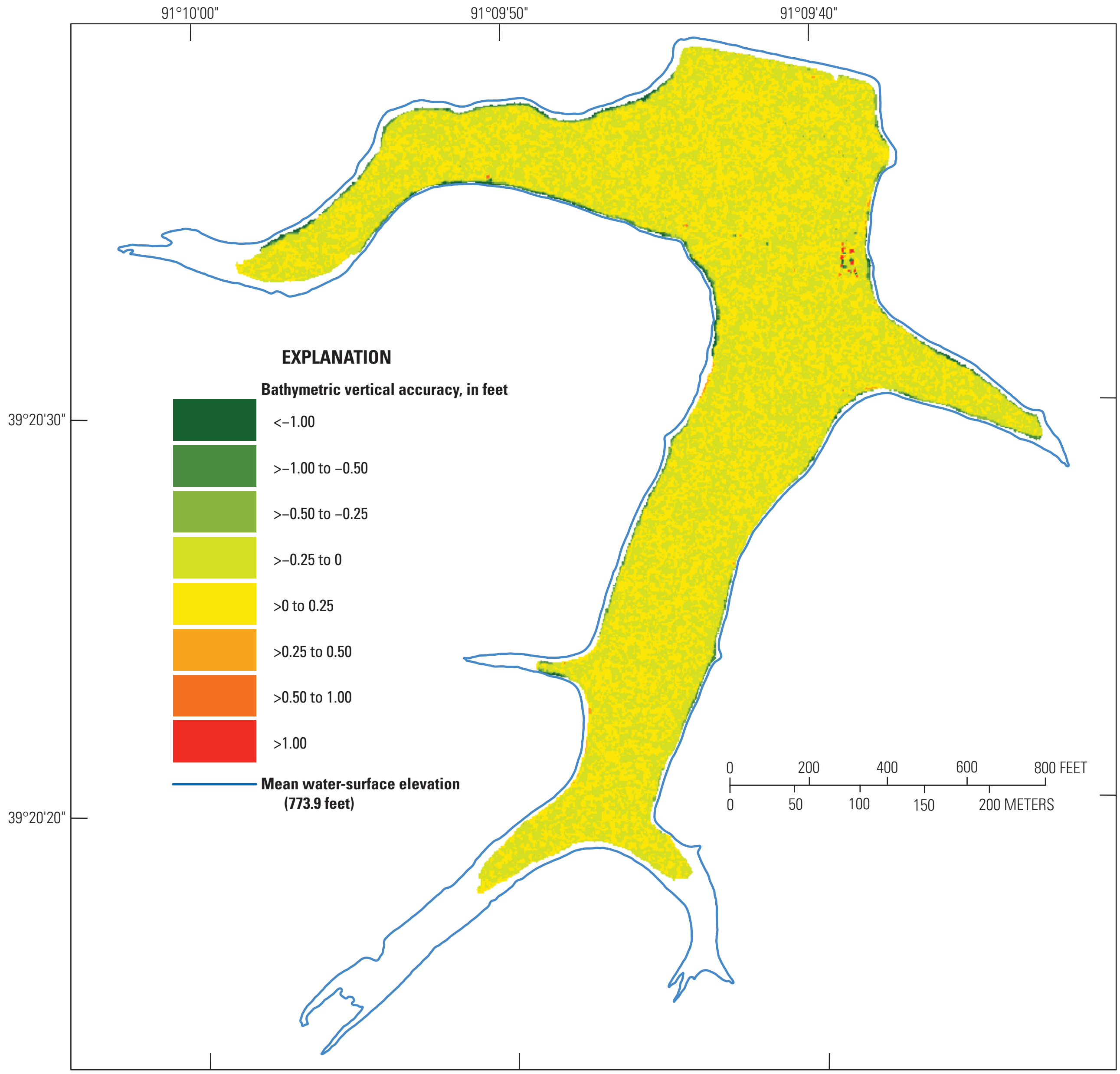


Figure 31. Vertical accuracy of the bathymetric surface of Old Lake (Bowling Green West; lake 31) near Bowling Green, Missouri, 2021.

The ridges of alternating deposition and erosion evident at Brookfield City Lake (fig. 35), New Marceline City Lake (fig. 36), Hazel Creek Lake (fig. 38), Bowling Green Reservoir (fig. 41), and Forest Lake (fig. 44) coincide with the singlebeam transect locations from the previous survey and may be the result of erroneous position or depth readings in the previous surveys. As noted in the 2019 surveys (Huizinga and others, 2022), an MBMS has an INS to record the position and motion of the survey boat with a reasonably high degree of accuracy, whereas data in the previous surveys were collected along transects set laterally across the lake with a singlebeam echosounder system that utilized a DGPS position solution and did not have any correction for pitch and roll movements of the boat (Wilson and Richards, 2006). As indicated in the "Patch Tests" section, errors in position and angular offsets for pitch and roll can make a difference in the depth values obtained by an echosounder system (fig. 10). Although the angular offset for yaw is not an issue for a singlebeam echosounder (no swath width to be skewed as shown in fig. 10*D*) and roll is for a single, nadir point below the echosounder rather than a swath (as shown in fig. 10*B*), angular offsets based on boat movement for pitch and roll (and not recorded by the singlebeam echosounder system) could result in erroneous submerged point placement. Inaccurate DGPS position data results in an offset similar to the latency offset indicated in figure 10*A*. As mentioned in the "Bathymetric Change

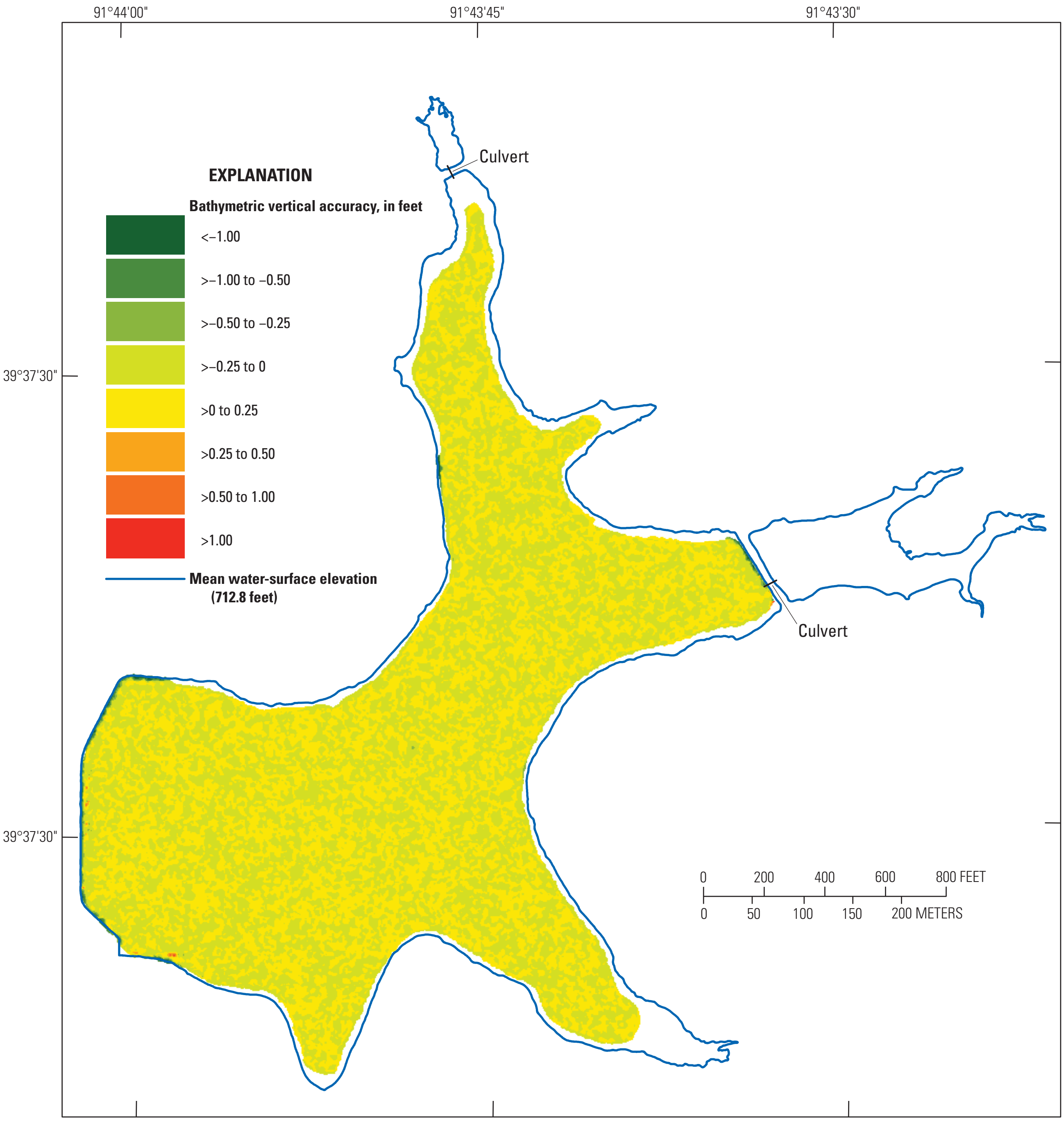


Figure 32. Vertical accuracy of the bathymetric surface of Monroe Lake B (Monroe City South; lake 32) near Monroe City, Missouri, 2021.

Map Creation" section, masking the areas of high slope likely helps limit the areas where minor horizontal positional offsets between coincident points in the two surveys sometimes create erroneous bathymetric change results. Nevertheless, these positional artifacts may persist in other locations of the bathymetric change maps because of roll or pitch offsets.

Areas of apparent erosion in the shallows along the margins of the lakes often coincide with deposition in the deeper parts of the same lake (figs. 35–37, 40, 42, and 43). A similar phenomenon, observed in the 2019 surveys (Huizinga and others, 2022), was attributed to shallow water wave action, possibly affecting sediment deposition with fluctuating lake levels during low-water years. Another possible explanation posited in the 2020 lake survey report (Huizinga and others, 2023) is compaction of sediments deposited in high-water years but exposed to the air in low-water years. However, because the edge erosion phenomenon seems ubiquitous to the 2019 through 2021 surveys, it also may be an indication of

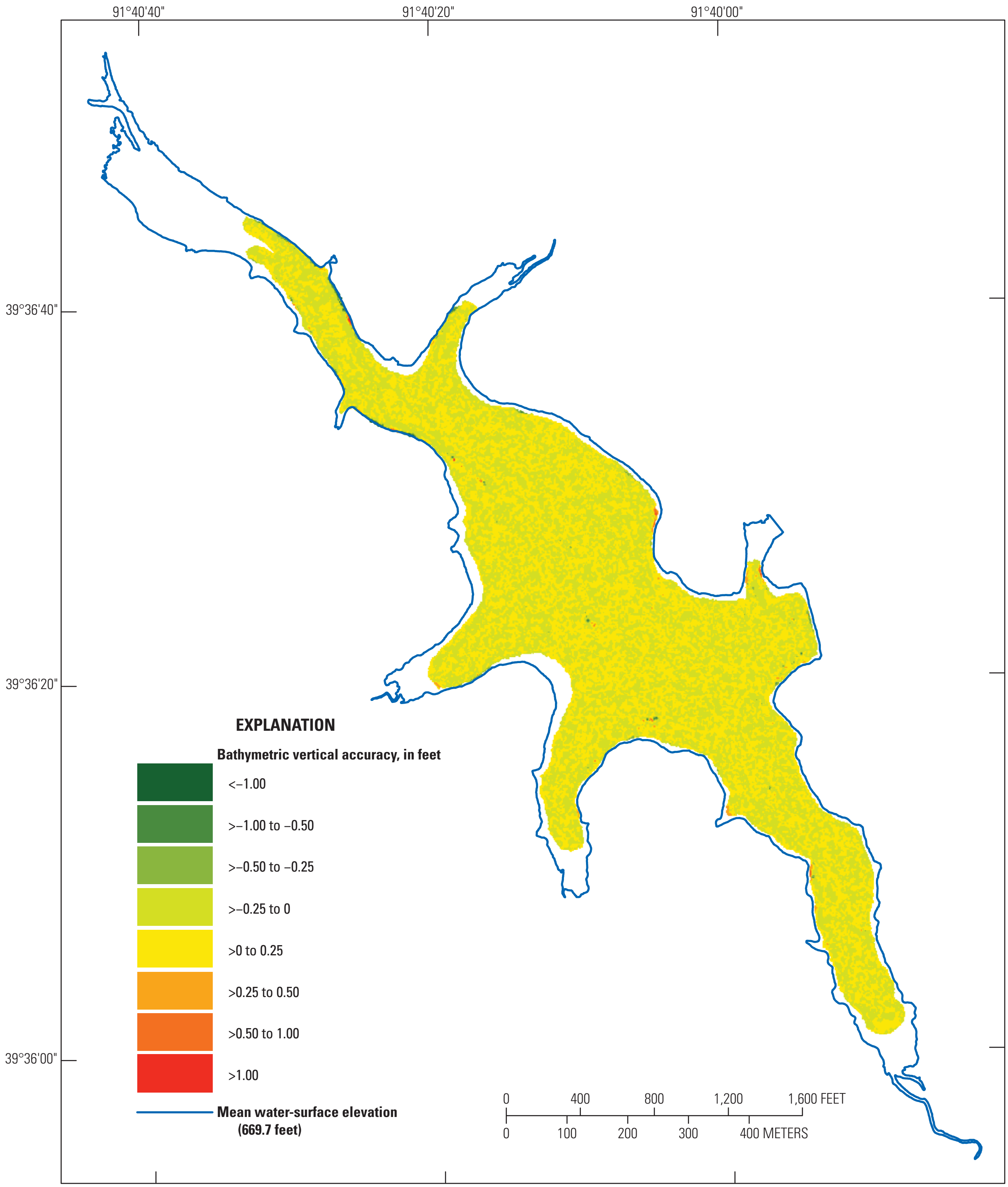


Figure 33. Vertical accuracy of the bathymetric surface of Monroe City Lake (lake 33) near Monroe City, Missouri, 2021.

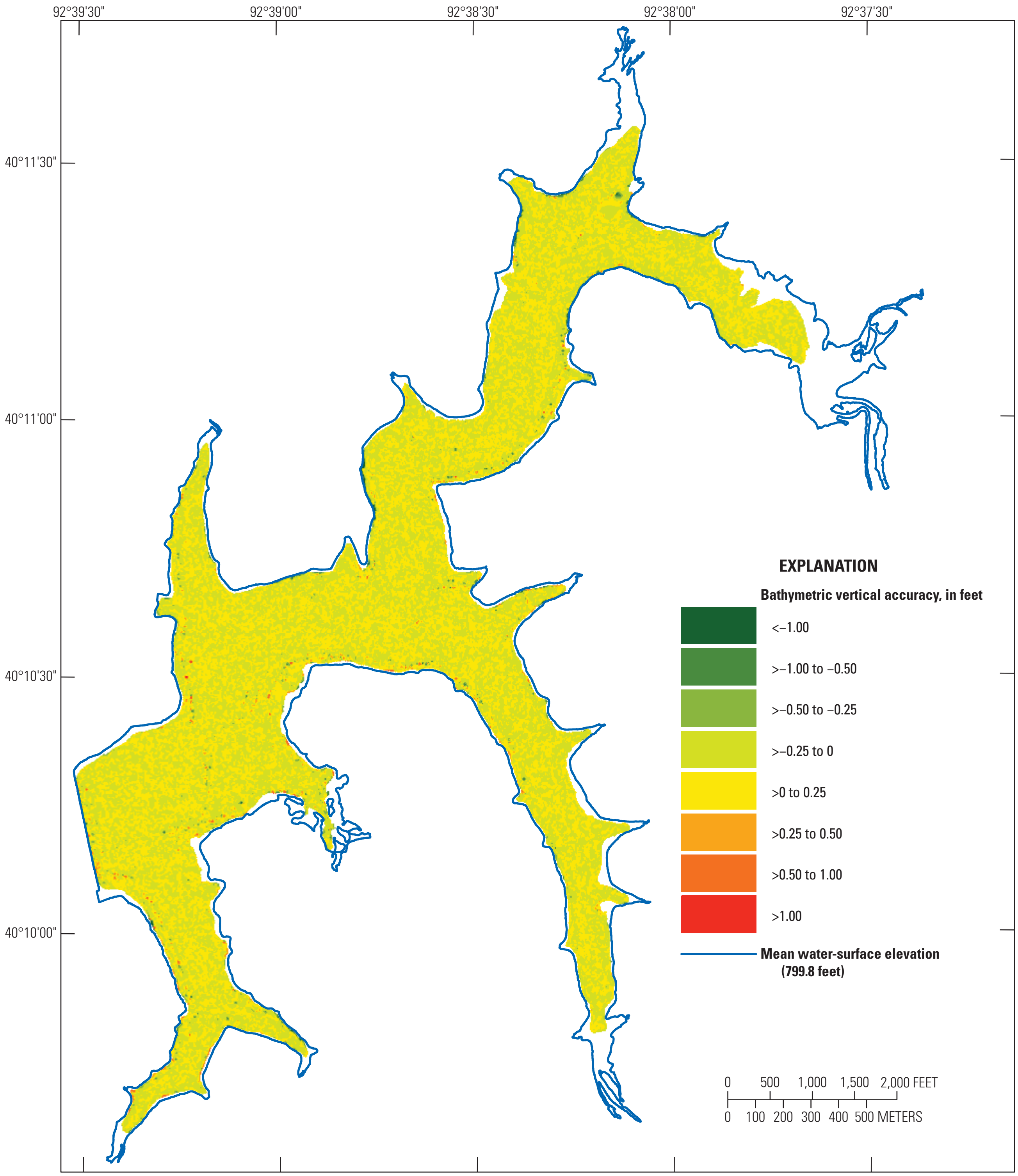


Figure 34. Vertical accuracy of the bathymetric surface of Forest Lake (lake 34) near Kirksville, Missouri, 2021.

Table 9. Summary of bathymetric contour quality-assurance results from surveys at water-supply lakes in northeastern Missouri, March 30 to May 4, 2021.

Lake name	Lake number (fig. 1)	Number of points in quality-assurance dataset (table 2)	Contour quality-assurance point search tolerance, in feet	Number of points in contour-to-point comparison	Tested vertical accuracy at a 95-percent confidence level, in feet	Mean vertical error, in feet	Median absolute vertical error, in feet
Brookfield City Lake	23	47,662	0.66	5,138	0.27	0.00	0.02
New Marceline City Lake	24	68,763	0.66	9,123	0.22	0.00	0.04
Marceline Old Reservoir	25	74,797	0.26	7,253	0.34	0.00	0.04
Shelbina Lake	26	77,137	0.33	4,139	0.15	−0.01	0.03
Hazel Creek Lake	27	52,108	0.33	5,940	0.26	−0.01	0.03
Memphis Lake (Lake Showme)	28	104,976	0.66	31,936	0.23	0.00	0.05
Memphis Reservoir	29	61,617	0.66	4,791	0.19	−0.01	0.03
Bowling Green Reservoir (Jack Floyd Memorial Lake)	30	86,185	0.33	32,103	0.31	−0.01	0.07
Old Lake (Bowling Green West)	31	51,601	0.20	7,008	0.89	−0.02	0.06
Monroe Lake B (Monroe City South)	32	27,733	0.33	1,614	0.18	−0.01	0.01
Monroe City Lake	33	40,065	0.33	6,523	0.21	0.00	0.04
Forest Lake	34	65,281	0.33	8,270	0.38	−0.01	0.05

Table 10. Summary of bathymetric change surface quality-assurance results from selected surveys at water-supply lakes in northeastern Missouri, March 30 to May 4, 2021.

Lake name	Lake number (fig. 1)	Number of points in quality-assurance dataset from previous survey	Number of points in surface comparison	Tested vertical accuracy at a 95-percent confidence level, in feet	Mean vertical error, in feet	Median absolute vertical error, in feet
Hazel Creek Lake	27	22,319	1,855	1.23	0.08	0.30
Bowling Green Reservoir (Jack Floyd Memorial Lake)	30	10,157	2,890	1.38	0.23	0.33
Old Lake (Bowling Green West)	31	7,555	1,904	1.20	−0.06	0.22
Forest Lake	34	38,993	1,675	0.85	−0.02	0.21

some other systemic error in the singlebeam data collected in the previous survey, in addition to shallow water wave action or sediment compaction. Errors caused by motion-induced echosounder attitude changes and issues caused by the lack of a full sound velocity profile were fully discussed in the 2020 lake report (Huizinga and others, 2023).

It is unlikely that a motion-induced pitch angle or elevation change would fully account for the apparent erosion along the shoreline, some of which appears to be 2 ft or more (fig. 37; table 13). Furthermore, motion-induced error likely does not account for the apparent alternation from deposition to erosion as the boat crossed a shallow point or approached the bank while traveling at a more-constant speed in the previous survey. This is observed along the shorelines at Hazel Creek Lake (fig. 38), Bowling Green Reservoir (fig. 41), and Forest Lake (fig. 44).

As explained in the 2020 lake report (Huizinga and others, 2023), the fact that the erosion appears predominantly in the shallower areas of a lake and often coincides with deposition in the deeper part of the same area of the lake may point

Table 11. Summary of surface area and capacity at the listed spillway or inlet elevation from surveys at water-supply lakes in northeastern Missouri, March 30 to May 4, 2021.

[All elevations are referenced to the North American Vertical Datum of 1988]

Lake name	Lake number (fig. 1)	Primary spillway/ inlet elevation, in feet	Surface area, in acres	Capacity, in acre-feet
Brookfield City Lake	23	802.5	125	1,990
New Marceline City Lake	24	757.2	164	2,020
Marceline Old Reservoir	25	817.7	65.4	489
Shelbina Lake	26	715.1	46.6	380
Hazel Creek Lake	27	847.9	493	8,710
Memphis Lake (Lake Showme)	28	769.8	247	3,980
Memphis Reservoir	29	718.1	39.8	203
Bowling Green Reservoir (Jack Floyd Memorial Lake)	30	795.0	44.4	1,240
Old Lake (Bowling Green West)	31	773.9	28.8	478
Monroe Lake B (Monroe City South)	32	712.8	61.9	460
Monroe City Lake	33	669.7	97.4	1,170
Forest Lake	34	799.8	571.9	12,200

to a variable-with-depth phenomenon such as a sound velocity profile issue or another depth-related issue. Sound velocity profiles were not acquired in the previous surveys, and variations with depth were presumed to be minimal (Wilson and Richards, 2006). Instead, the echosounder was calibrated to ensure accurate depth soundings, using a surface water-temperature reading and a bar check at several depths wherein the sound velocity setting of the echosounder was adjusted until the depth reading matched the known distance a plate was held below the echosounder, usually in the deepest part of the lake. A bar check can partially mitigate issues with a sound velocity profile that varies with depth but does not fully address the potential variations with depth provided by a full-depth sound velocity profile and does not account for subtle spatial variations in sound velocity in shallower parts of the lake or coves, which are exposed to predominate wind direction compared to those that are guarded from the wind.

Ultimately, the cause for the apparent erosion in the shallows of the comparisons to date (2019 through 2021) is unknown. Future resurveys using equipment that fully accounts for boat (and echosounder) position and movement would help to draw reasonable conclusions and to mitigate potential motion-induced artifacts. Furthermore, sound velocity profiles in various places throughout the lake are warranted to fully account for subtle variations that might affect echosounder depth readings.

An implied sedimentation rate can be computed from the capacity changes at the primary spillway or intake shown in table 12. For example, at Memphis Lake (Lake Showme), the loss of capacity at the primary spillway elevation is 195 acre-feet (computed as the difference between the “Previous survey capacity” and “Capacity in 2021” at the spillway elevation, table 12) and dividing this value over the 18.9 years between the surveys (table 13) implies a sedimentation rate of about 10.3 acre-feet per year. This implied sedimentation rate at the spillway elevation is substantially different than the volumetric sedimentation rate computed from the bathymetric change raster of 6.8 acre-feet per year for this lake (table 13), and yet still implies substantial sedimentation during the interval. On the other hand, at Hazel Creek Lake, the implied sedimentation rate at the spillway elevation is about −1.86 acre-foot per year (computed from capacity values in table 12 and time between surveys in table 13), whereas the volumetric sedimentation rate computed from the bathymetric change raster is 0.66 acre-feet per year (table 13). As discussed in the 2020 surveys (Huizinga and others, 2023), sediment tends to accumulate more quickly at the upper ends of a lake, where the sediment-laden streamflow initially encounters the slack water of the lake, and the heavier sediment settles out of suspension due to the sudden decrease in water velocity. This dynamic is evident in the bathymetric change maps of Hazel Creek Lake (fig. 38), Old Lake (Bowling Green West; fig. 42), and Forest Lake (fig. 44). These upper ends of the lake often tend to be where multibeam data cannot be acquired owing to the resulting shallow water, and so the sedimentation rate computed from the bathymetric change raster (table 13) may not fully account for deposition or erosion in these areas. Ongoing efforts have been made to mitigate this limitation, including the uses of a remote-controlled boat with ADCP for shallow water data collection and surveying during a time of year when vegetation is at a minimum. Nevertheless, determination of bathymetric change in areas without multibeam data

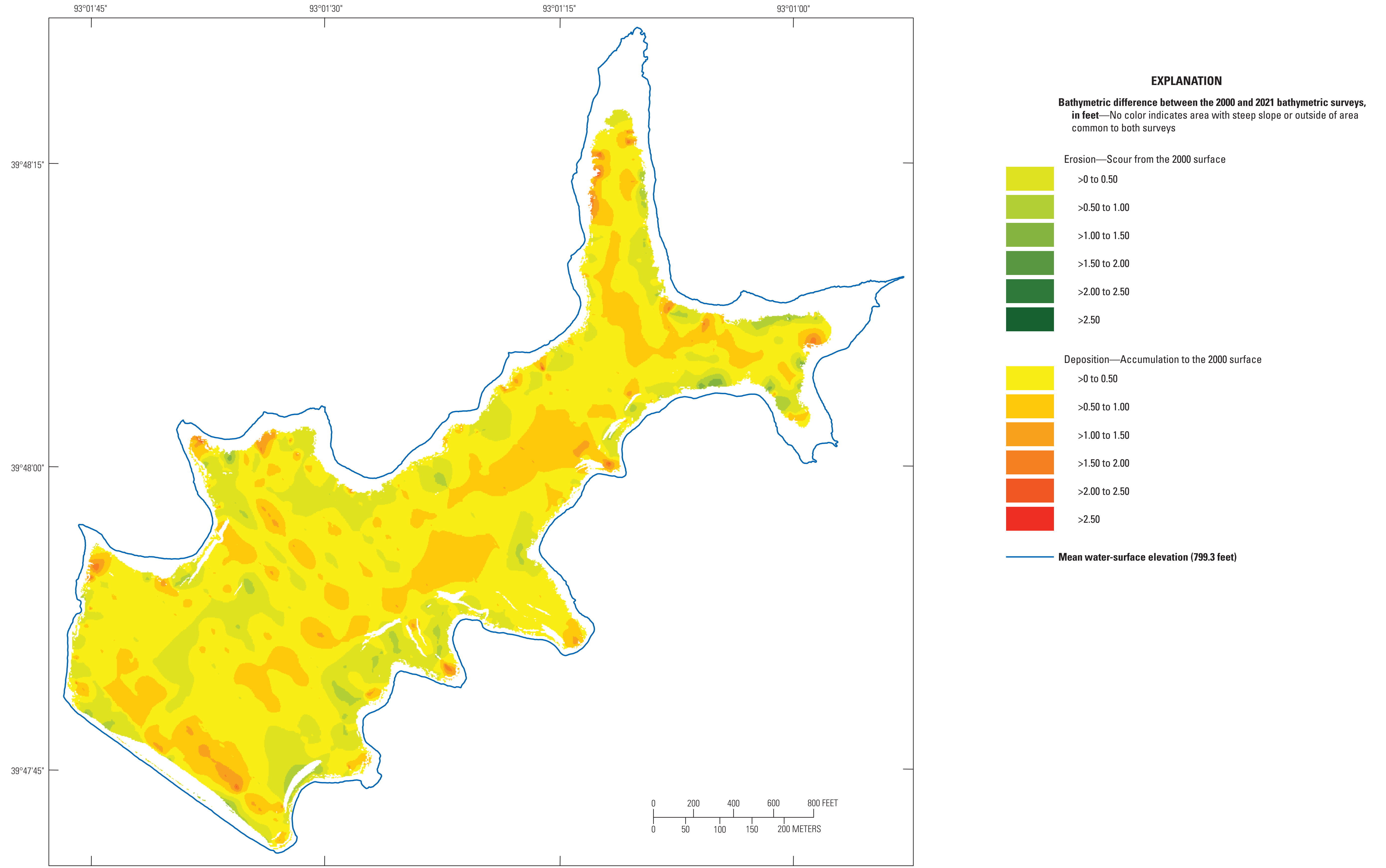


Figure 35. Bathymetric change between the 2000 survey and the 2021 survey of Brookfield City Lake (lake 23) near Brookfield, Missouri.

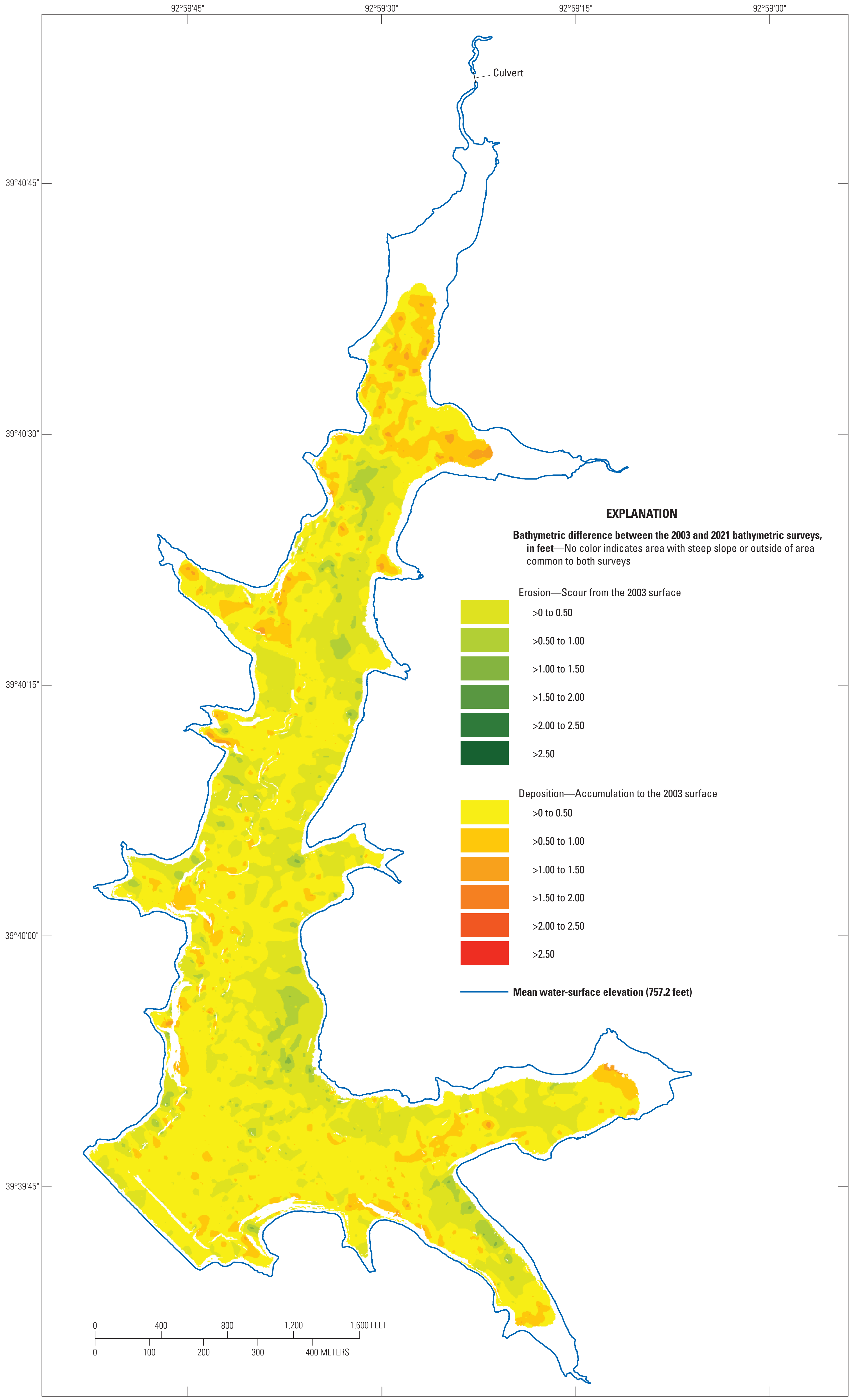


Figure 36. Bathymetric change between the 2003 survey and the 2021 survey of New Marceline City Lake (lake 24) near Marceline, Missouri.

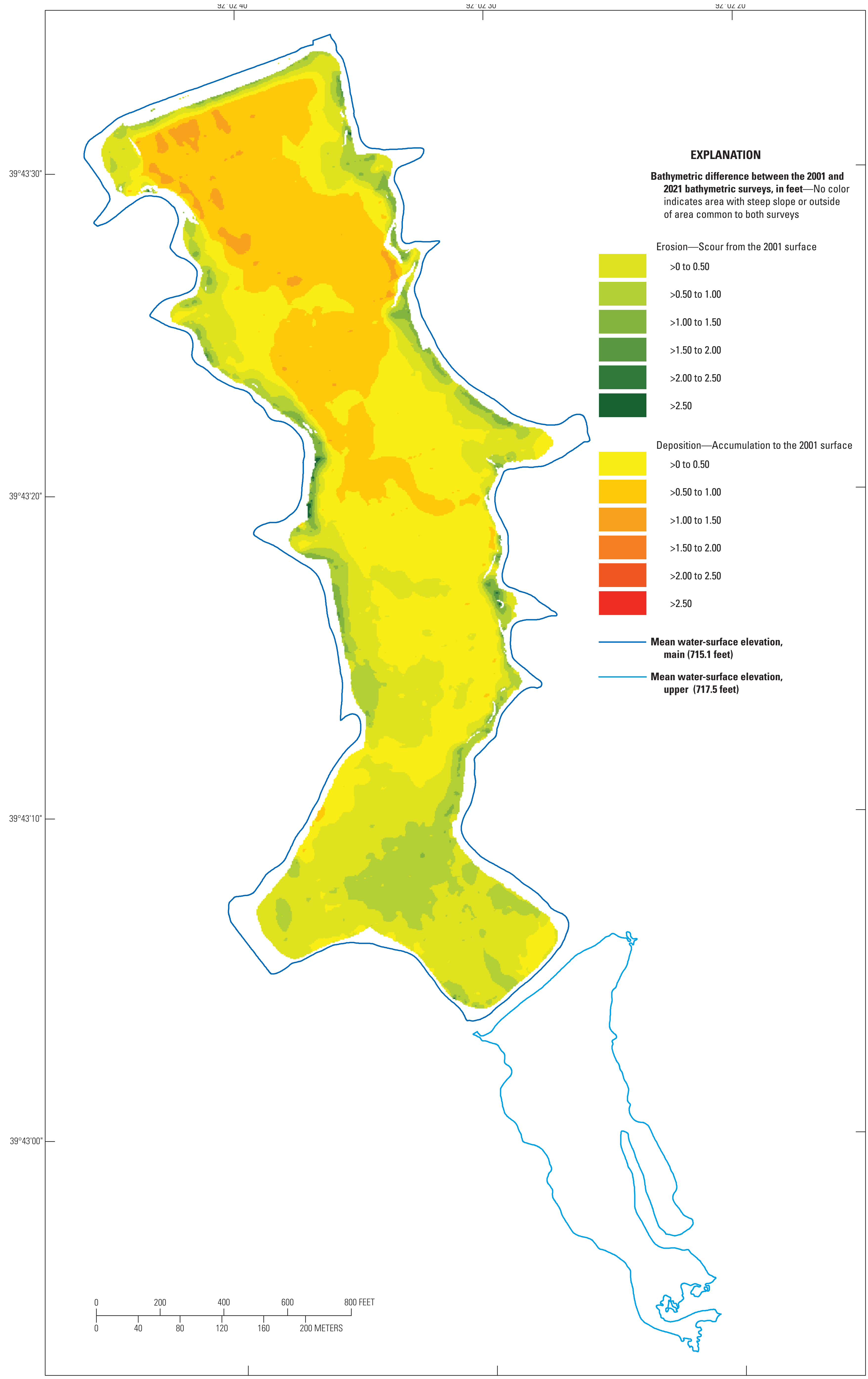


Figure 37. Bathymetric change between the 2001 survey and the 2021 survey of Shelbina Lake (lake 26) near Shelbina, Missouri.

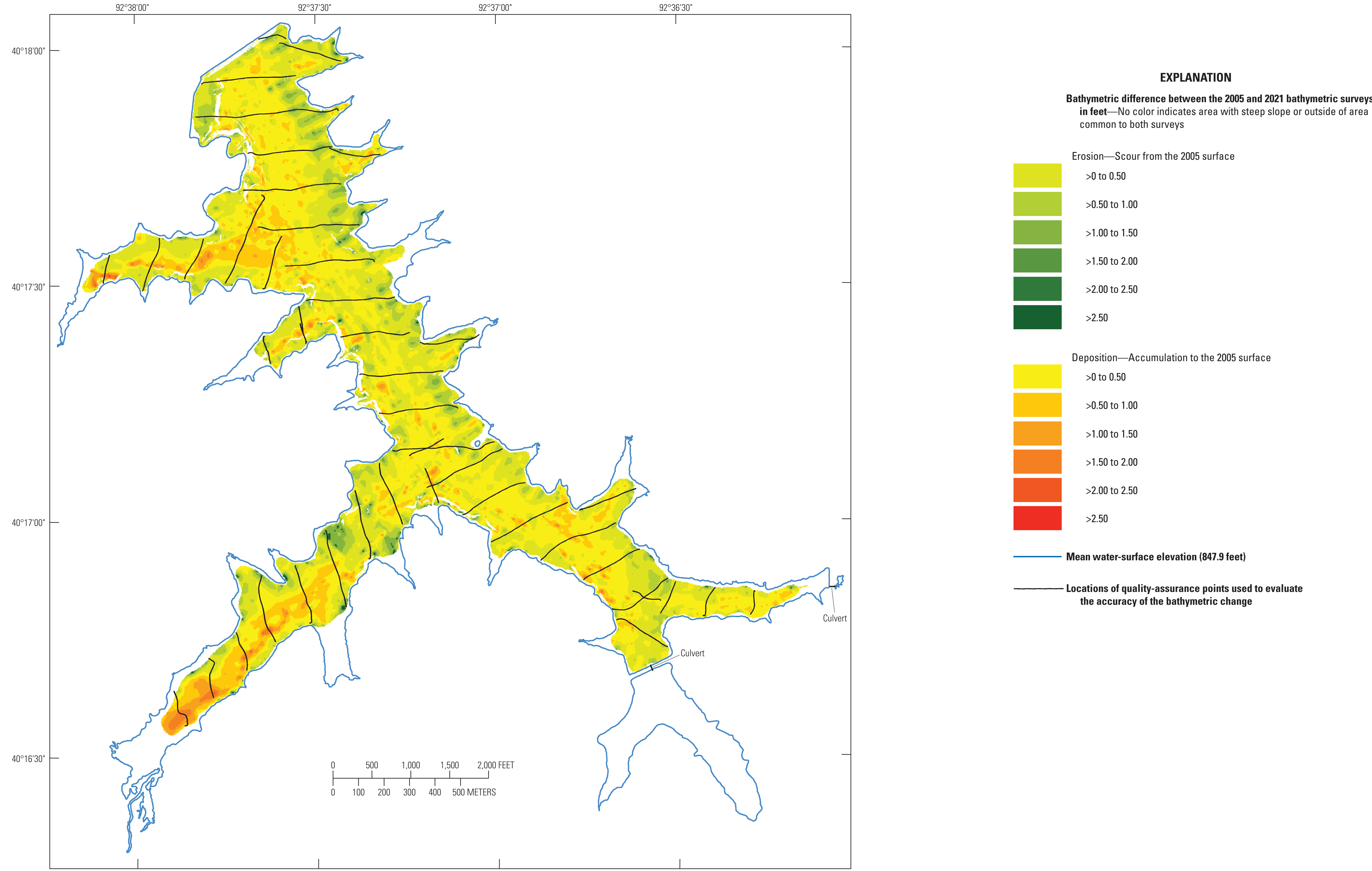


Figure 38. Bathymetric change between the 2005 survey and the 2021 survey of Hazel Creek Lake (lake 27) near Kirksville, Missouri.

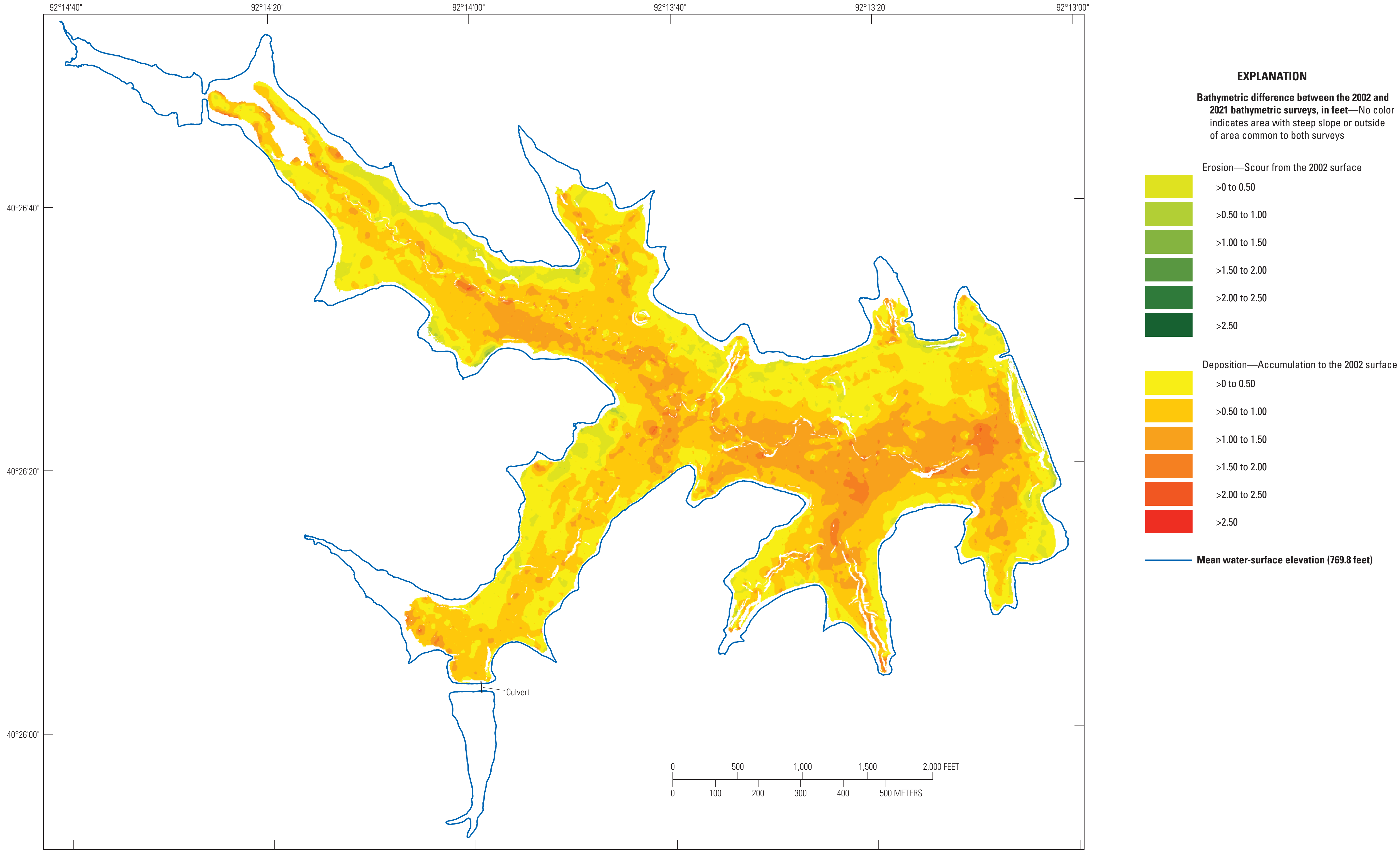


Figure 39. Bathymetric change between the 2002 survey and the 2021 survey of Memphis Lake (Lake Showme; lake 28) near Memphis, Missouri.

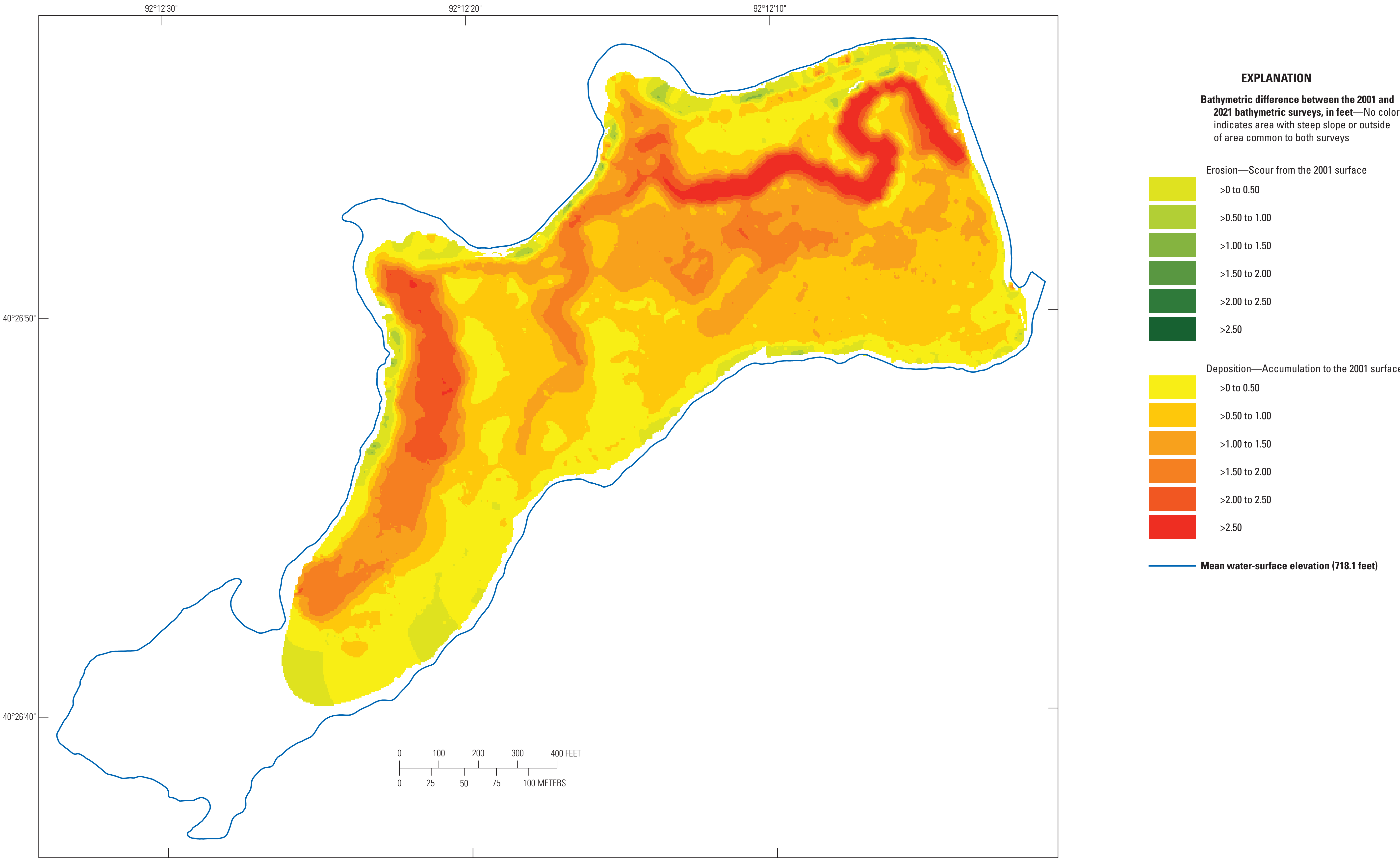


Figure 40. Bathymetric change between the 2001 survey and the 2021 survey of Memphis Reservoir (lake 29) near Memphis, Missouri.

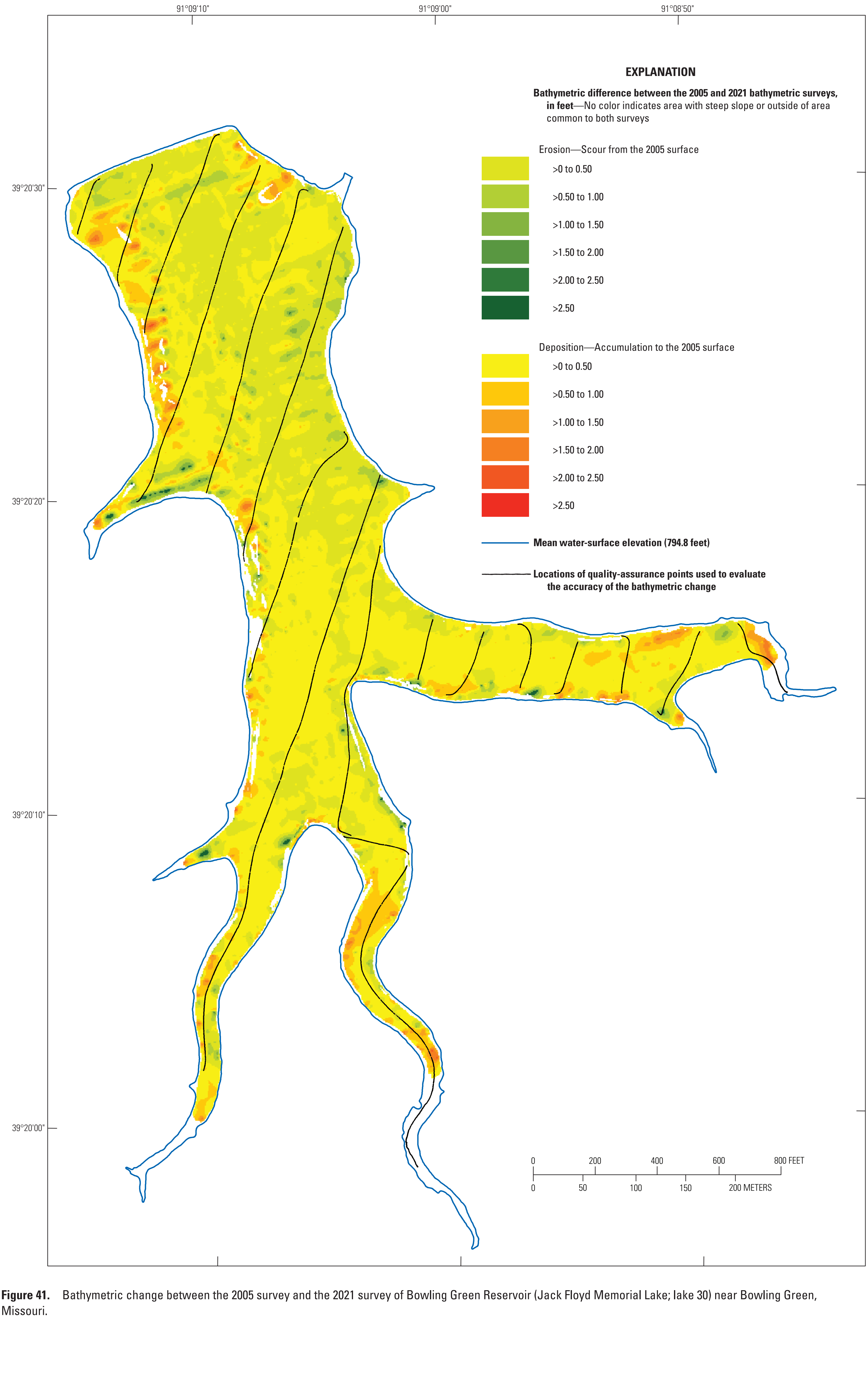


Figure 41. Bathymetric change between the 2005 survey and the 2021 survey of Bowling Green Reservoir (Jack Floyd Memorial Lake; lake 30) near Bowling Green, Missouri.

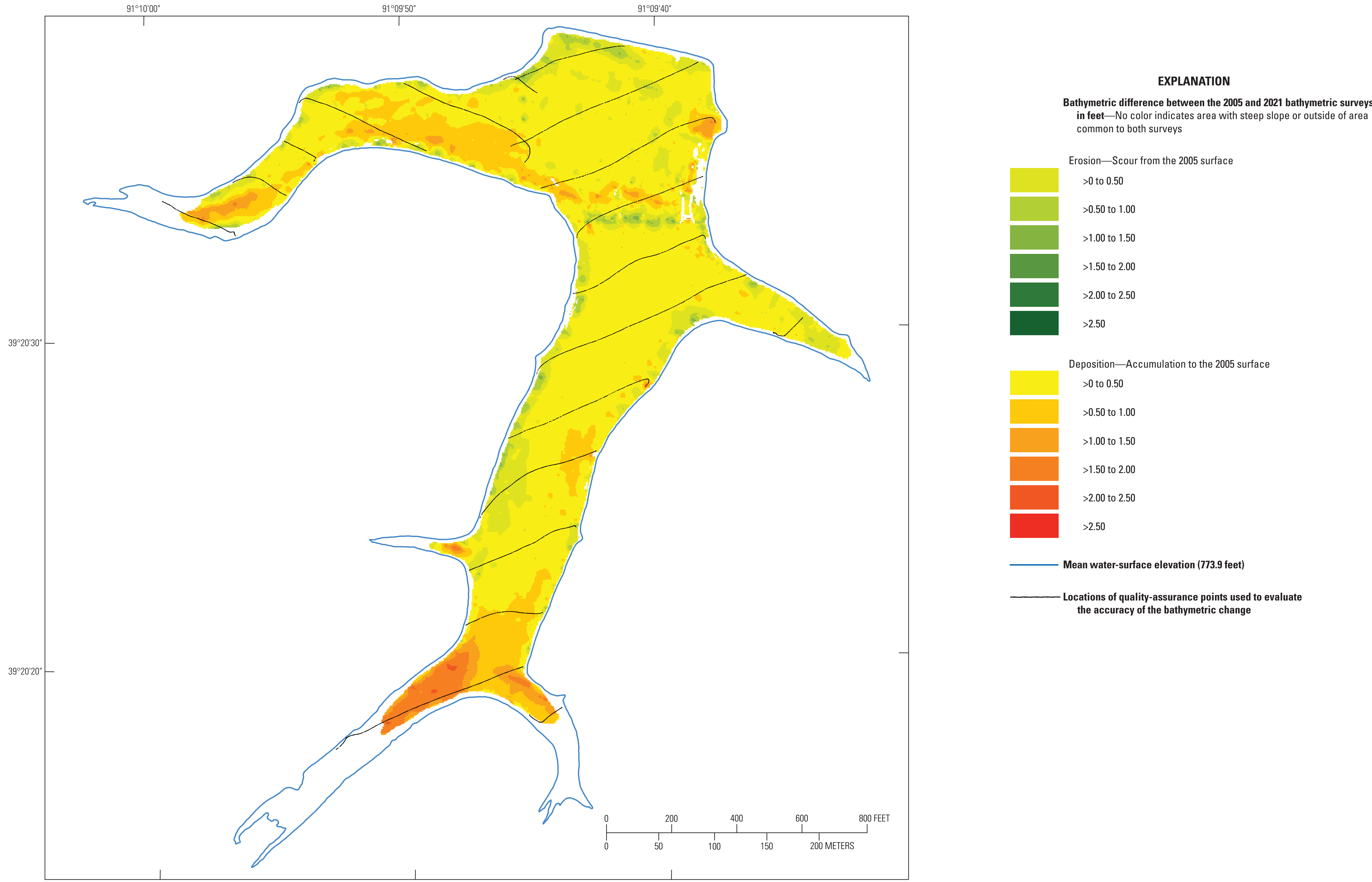
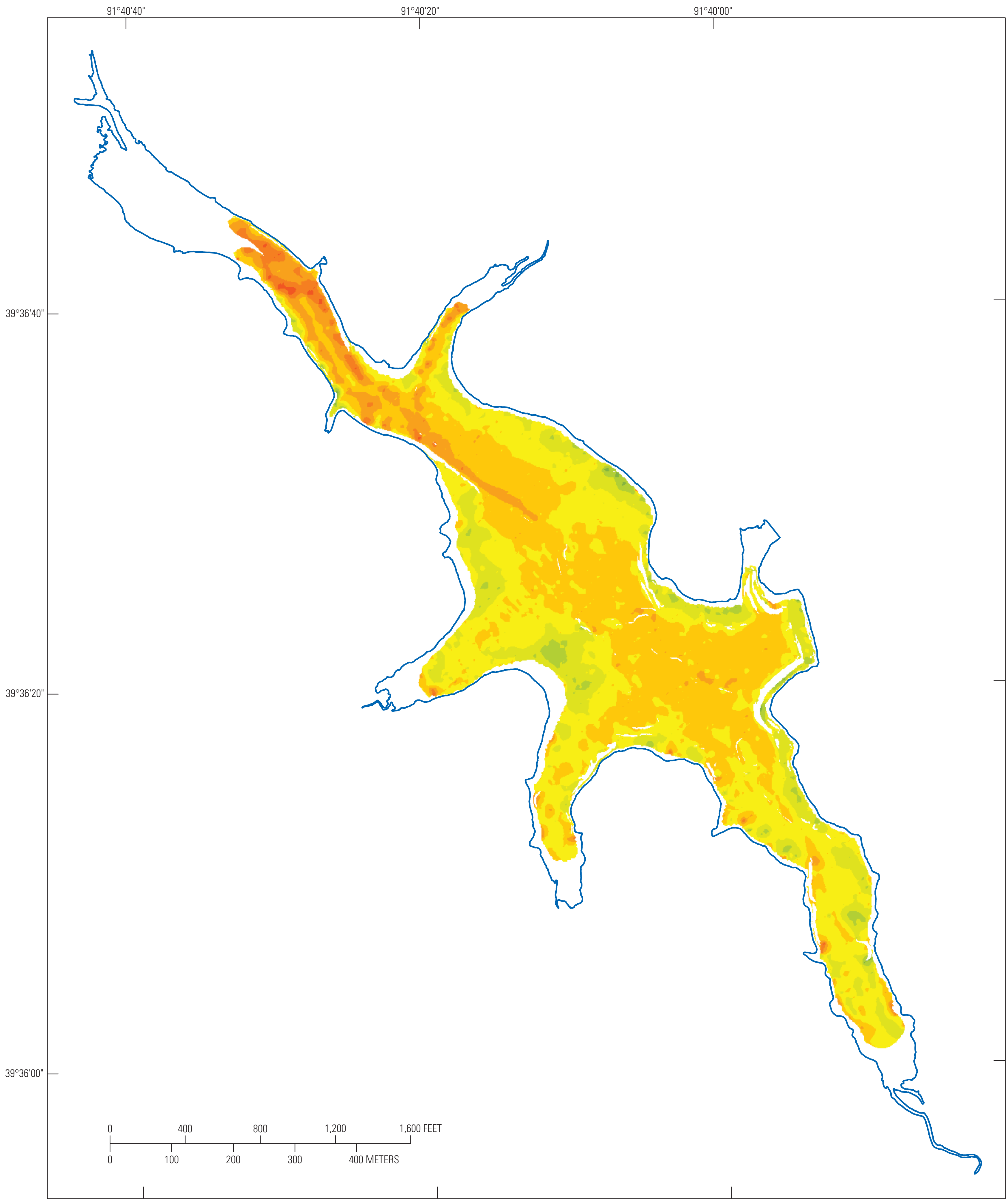


Figure 42. Bathymetric change between the 2005 survey and the 2021 survey of Old Lake (Bowling Green West; lake 31) near Bowling Green, Missouri.



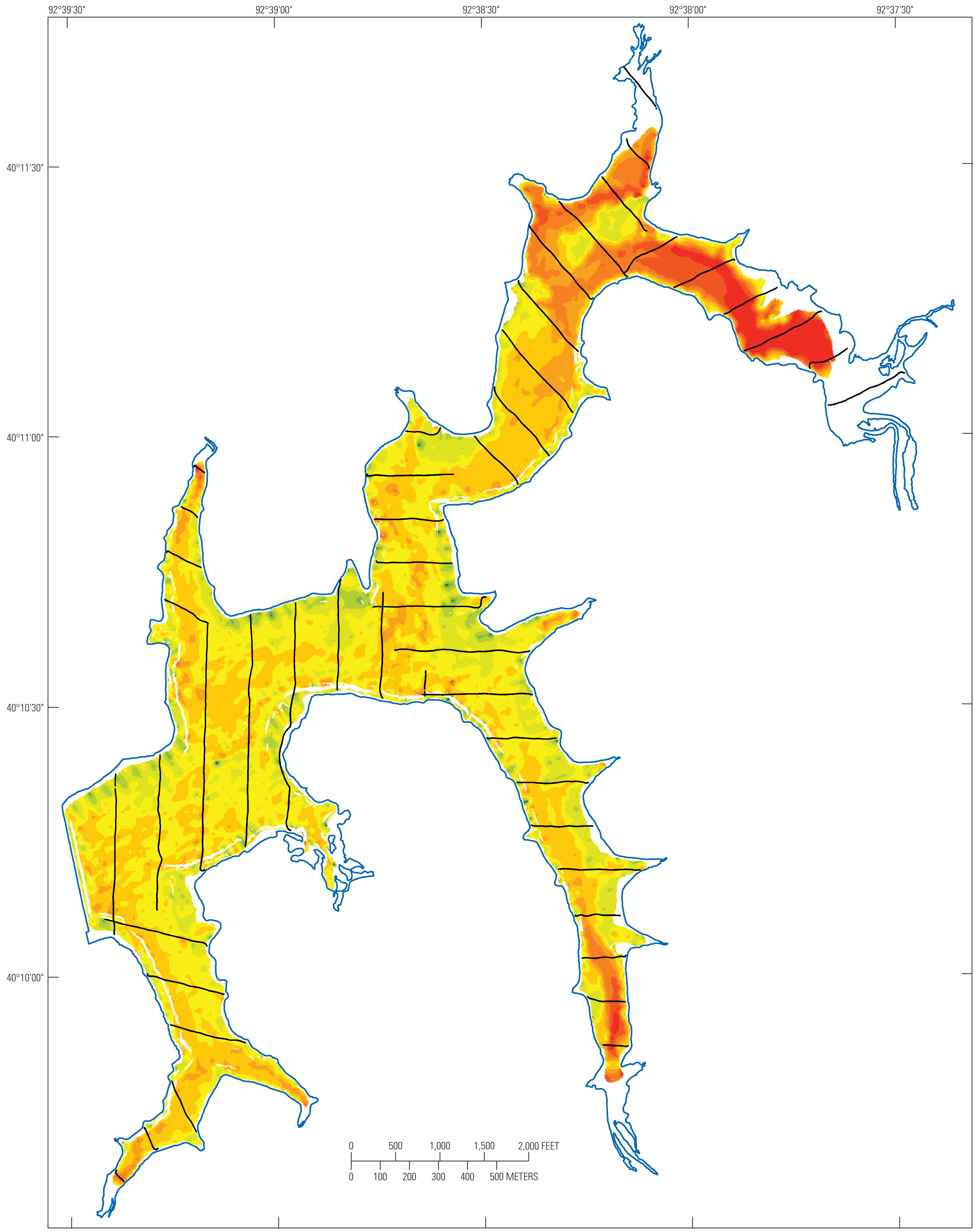
EXPLANATION

Bathymetric difference between the 2002 and 2021 bathymetric surveys, in feet—No color indicates area with steep slope or outside of area common to both surveys

Erosion—Scour from the 2002 surface	Deposition—Accumulation to the 2002 surface
>0 to 0.50	>0 to 0.50
>0.50 to 1.00	>0.50 to 1.00
>1.00 to 1.50	>1.00 to 1.50
>1.50 to 2.00	>1.50 to 2.00
>2.00 to 2.50	>2.00 to 2.50
>2.50	>2.50

Mean water-surface elevation (669.7 feet)

Figure 43. Bathymetric change between the 2002 survey and the 2021 survey of Monroe City Lake (lake 33) near Monroe City, Missouri.



EXPLANATION

Bathymetric difference between the 2005 and 2021 bathymetric surveys, in feet—No color indicates area with steep slope or outside of area common to both surveys

Erosion—Scour from the 2005 surface	Deposition—Accumulation to the 2005 surface
>0 to 0.50	>0 to 0.50
>0.50 to 1.00	>0.50 to 1.00
>1.00 to 1.50	>1.00 to 1.50
>1.50 to 2.00	>1.50 to 2.00
>2.00 to 2.50	>2.00 to 2.50
>2.50	>2.50

Mean water-surface elevation (799.8 feet)

Locations of quality-assurance points used to evaluate the accuracy of the bathymetric change

Figure 44. Bathymetric change between the 2005 survey and the 2021 survey of Forest Lake (lake 34) near Kirksville, Missouri.

Table 12. Summary of surface area and capacity changes at the listed primary spillway elevation from surveys at water-supply lakes in northeastern Missouri, March 30 to May 4, 2021, and previous surveys.

[Dates are shown as month/day/year. All elevations are referenced to the North American Vertical Datum of 1988]

Lake name	Lake number (fig. 1)	Primary spillway/ intake elevation, in feet	Previous survey		2021 Capacity, in acre-feet	Capacity loss, in percent[b]
			Date(s)	Capacity,[a] in acre-feet		
Brookfield City Lake	23	802.5	7/13/2000	2,070	1,990	3.9
New Marceline City Lake	24	757.2	5/19/2003	1,990	2,020	−1.5
Shelbina Lake	26	715.1	6/20/2001	379	380	−0.3
Hazel Creek Lake	27	847.9	3/2/2005–3/4/2005	8,680	8,710	−0.3
Memphis Lake (Lake Showme)	28	769.8	6/3/2002	4,175	3,980	4.7
Memphis Reservoir	29	718.1	6/19/2001	220	203	7.7
Bowling Green Reservoir (Jack Floyd Memorial Lake)	30	795.0	2/23/2005	1,240	1,240	0.0
Old Lake (Bowling Green West)	31	773.9	2/24/2005–2/25/2005	460	478	−3.9
Monroe City Lake	33	669.7	6/5/2002	1,245	1,170	6.0
Forest Lake	34	799.8	3/1/2005–3/2/2005	12,500	12,200	2.4

[a]The capacity values shown for previous surveys are from the area and capacity tables from Richards (2013), with elevations adjusted to account for datum discrepancies found between the previous and current surveys detailed in table 3.

[b]Negative values indicate an increase in capacity.

has not been attempted to date (2023) in this study, because comparing singlebeam data from different sources or surveys typically results in a comparison of interpolated data with interpolated data, which substantially increases the uncertainty. The implied sedimentation rates computed from the spillway capacity values in table 12 may not accurately estimate the overall loss of volume of a given lake throughout the full range of elevations because it only represents loss at the primary spillway or intake elevation. Therefore, the implied sedimentation rates computed from spillway capacity values in table 12 and the computed volumetric sedimentation rates presented in table 13 likely bracket the sedimentation rate of each lake.

Table 13. Summary of bathymetric change statistics computed from the bathymetric change raster at water-supply lakes in northeastern Missouri, March 30 to May 4, 2021.

Lake name	Lake number (fig. 1)	Maximum value of erosion, in feet	Maximum value of deposition, in feet	Mean bathymetric change, in feet	Time between surveys, in years	Yearly mean bathymetric change, in feet per year	Area of bathymetric change raster, in acres	Volume of deposition, in acre-feet	Volume of erosion, in acre-feet	Net volume of sediment, in acre-feet	Volumetric sedimentation rate, in acre-feet per year
Brookfield City Lake	23	−1.48	2.26	0.25	20.7	0.012	90	27.4	4.62	22.8	1.10
New Marceline City Lake	24	−1.26	1.52	0.11	17.9	0.006	130	24.9	10.0	14.9	0.83
Shelbina Lake	26	−2.39	1.27	0.07	19.8	0.003	40	10.5	7.79	2.75	0.14
Hazel Creek Lake	27	−2.27	2.27	0.03	16.1	0.002	374	74.6	63.9	10.6	0.66
Memphis Lake (Lake Showme)	28	−1.24	2.29	0.63	18.9	0.034	203	131	2.50	129	6.80
Memphis Reservoir	29	−1.27	3.23	0.88	19.9	0.044	32	28.4	0.52	27.9	1.41
Bowling Green Reservoir (Jack Floyd Memorial Lake)	30	−2.03	2.22	0.07	16.2	0.004	40	6.66	3.95	2.71	0.17
Old Lake (Bowling Green West)	31	−1.42	2.07	0.29	16.2	0.018	24	8.07	1.03	7.04	0.44
Monroe City Lake	33	−1.41	2.29	0.41	18.9	0.022	76	35.1	3.40	31.7	1.67
Forest Lake	34	−2.04	3.33	0.57	16.2	0.035	485	301	26.4	274	17.0

Summary

In March through May 2021, bathymetric data were collected at 12 water-supply lakes in northeastern Missouri by the U.S. Geological Survey (USGS) in cooperation with the Missouri Department of Natural Resources and in collaboration with various local agencies. These surveys are the third in a 5-year series to establish or update the surface area and capacity tables for the surveyed lakes. Ten of the lakes had been surveyed by the USGS before, and the recent surveys were compared to the earlier surveys to document the changes in the bathymetric surface and capacity of the lake and produce a bathymetric change map.

Bathymetric data were collected using a high-resolution multibeam mapping system (MBMS) mounted on a boat. Two different boats were used for the 2021 surveys: a 24-foot flat-bottom cabin boat and a 16-foot jon boat, which could be more easily launched and retrieved from the bank of a lake. The bathymetric data were collected along transect lines oriented longitudinally in the main lake area, using about 10- to 25-percent overlap of the adjacent survey swaths. Data along the shoreline were collected by navigating the boat parallel to the shore while overlapping the data collected in the main body of the lake. Supplemental depth data were collected in shallow areas with an acoustic Doppler current profiler (ADCP) on a remote-controlled boat at five of the lakes.

Data points from the MBMS, as well as any supplemental ADCP points, were exported at a gridded data resolution appropriate to each lake, either 0.82 foot, 1.64 feet, or 3.28 feet. Geographic information system (GIS) software was used to filter the gridded bathymetric data points to create a dataset that had a minimum point spacing that was about twice that (that is, lower resolution) of the gridded data resolution. Data outside the MBMS survey extent and greater than the surveyed water-surface elevation were obtained from data collected using aerial light detection and ranging (lidar) point cloud data. These upland data points were resampled to a linear distance that matched the map resolution of each lake using GIS software and used to define the upland areas of the lake. A linear enforcement technique was used to add points to the dataset in areas of sparse data (the upper ends of coves where the water was too shallow for the MBMS equipment or aquatic vegetation precluded data acquisition with the MBMS or ADCP) based on surrounding MBMS and upland data values. The various point datasets (MBMS, ADCP, upland data, and linear enforcement) were used to produce a three-dimensional triangulated irregular network (TIN) surface of the lake-bottom elevations for each lake. A surface area and capacity table for each lake was produced from the three-dimensional TIN surface showing surface area and capacity at specified lake water-surface elevations.

If data from a previous bathymetric survey exists for a given lake, a bathymetric change map was generated from the difference between the previous survey and the 2021 bathymetric survey data points where they were coincident. Comparing the results of the previous survey to the 2021 survey required both datasets to be at a common elevation datum, so a point of coincident location and elevation from the previous survey was surveyed again in 2021 (such as the reference mark from the previous survey or the spillway crest) using Global Navigation Satellite System techniques. If a difference existed between the 2021 and the previous elevation, it was assumed that the 2021 elevation was the more accurate value. After applying any vertical elevation changes to the previous survey data to ensure a match to the 2021 survey datum and position, coincident points between the surveys were identified, and a bathymetric change map was generated using the difference in elevation between the coincident point data.

Various quality-assurance tests were conducted to ensure quality data were collected with the MBMS, including beam angle checks and patch tests. Additional quality-assurance tests were conducted on the various datasets from these surveys. The gridded bathymetric data from the MBMS survey were compared to raw data collected along at least one cross-check line at each lake to quantify the vertical accuracy of the gridded data at a 95-percent confidence level. A second quality-assurance dataset was used to evaluate the bathymetric surface and contours and included data points selected at random from the gridded data points at each lake. Points that were used to create the bathymetric surface were not included as bathymetric surface quality-assurance points. The bathymetric surface and contours were tested to quantify the vertical accuracy of each at a 95-percent confidence level.

A change in capacity was observed at all the lakes for which a previous survey existed, and the mean elevation change between the surveys was positive (implying sedimentation) at most of the lakes. Relative to previous surveys, the change in capacity at the primary spillway elevation ranged from a 7.7-percent decrease at Memphis Reservoir to a 3.9-percent increase at Old Lake (Bowling Green West). The mean bathymetric change ranged from 0.03 foot at Hazel Creek and 0.07 foot at Shelbina Lake and bowling Green Reservoir (Jack Floyd Memorial Lake) to 0.63 at Memphis Lake (Lake Showme) and 0.88 at Memphis Reservoir. The time-averaged mean bathymetric change ranged from 0.002 foot per year at Hazel Creek Lake to 0.044 foot per year at Memphis Reservoir. The computed volumetric sedimentation rate generally ranged from 0.14 to 6.80 acre-feet per year at Shelbina Lake and Memphis Lake (Lake Showme), respectively; however, Forest Lake had a substantially larger sedimentation rate of 17.0 acre-feet per year. Changes observed in some bathymetric change maps likely result from the difference in data collection equipment and techniques between the previous and present bathymetric surveys. Certain erosional features around the perimeter of certain lakes may be the result of wave action during low-water years, or may indicate an unidentified but systemic error in the older singlebeam echosounder survey data.

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