Technical Report No. ENV-2020-019

Elephant Butte Reservoir 2017 and 2019 Sedimentation Survey

Rio Grande Project, New Mexico
Upper Colorado Region

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Sedimentation and River Hydraulics Group
Denver, Colorado

December 2019

Mission Statements

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Acknowledgements

Mr. Kent Collins, Civil Engineer (Hydraulics), Technical Service Center, Sedimentation and River Hydraulics Group, planned the 2017 hydrographic survey of Elephant Butte Reservoir and he led efforts to process the bathymetric data. Mr. Collins was assisted in the field by Mr. Ron Hoskins, Welder, Elephant Butte Field Division who piloted the survey boat. Mr. Steven Hollenback, Physical Scientist, Sedimentation and River Hydraulics Group, assisted in the processing of the bathymetric data. Mr. Jack Truax, Physical Scientist, Geographic Applications and Analysis Group, Technical Service Center, developed maps of the Elephant Butte Dam watershed, general location, and data coverage.

Disclaimer

Cover: Elephant Butte Reservoir (Reclamation)

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14. SHORT ABSTRACT **This report documents the 2017 bathymetric survey of Elephant Butte Reservoir, 2019 aerial LiDAR survey of above-water topography, development of a digital surface of the reservoir bottom, and determination of sedimentation volumes. Analysis of this data indicates that at the top of active storage capacity (4407 feet, project vertical datum), the reservoir had a surface area of 35,786 acres and a storage capacity of 2,010,900 acre-feet. Since the original filling in 1915, the reservoir is estimated to have lost 24% of storage capacity (623,900 acre-feet) due to sedimentation. The dead storage pool volume was filled with sediment by the 1960's. The reservoir pool below the invert of the power penstock valve has been reduced to 33 percent of the original penstock storage volume, a loss of 67 percent.**			
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Technical Report No. ENV-2020-019

Elephant Butte Reservoir 2017 and 2019 Sedimentation Survey

TIMOTHY RANDLE
Digitally signed by TIMOTHY RANDLE
Date: 2020.01.17 13:47:49 -07'00'

Prepared by: Timothy J. Randle, PHD, PE, D.WRE., Supervisory Hydraulic Engineer
Manager, Sedimentation and River Hydraulics Group, 86-68240

VINCENT BENOIT
Digitally signed by VINCENT BENOIT
Date: 2020.01.21 06:24:11 -07'00'

Prepared by: Vincent Benoit, Civil Engineering Technician
Sedimentation and River Hydraulics Group, 86-68240

KENT COLLINS
Digitally signed by KENT COLLINS
Date: 2020.01.21 12:19:48 -07'00'

Peer Reviewed by: Kent Collins, MS, PE, Civil Engineer (Hydraulics)
Sedimentation and River Hydraulics Group, 86-68240

Acronyms and Abbreviations

ft^3/s	cubic feet per second (cfs)
DOI	Department of the Interior
ft	foot or feet
GIS	Geographic Information System
GPS	Global Positioning System
HUC	Hydrologic Unit Code
LiDAR	Light Detection and Ranging
mi^2	square miles
NAD 1983	North American Datum, established 1983
NAVD 1988	North American Vertical Datum, established 1988
NGS	National Geodetic Survey
NGVD 1929	National Geodetic Vertical Datum, established 1929
NID	National Inventory of Dams
NRCS	Natural Resources Conservation Service
OPUS	Online Positioning User Service
Reclamation	Bureau of Reclamation
RPVD	Reclamation Project Vertical Datum
RSI	Reservoir Sedimentation Information
RTK	Real-Time Kinematic
SGMC	State Geologic Map Compilation
TSC	Technical Service Center
USGS	U.S. Geological Survey

Executive Summary

Elephant Butte Dam and Reservoir are on the Rio Grande about 150 miles south-southwest along Interstate 25 from Albuquerque, New Mexico; 125 miles northeast along Interstates 10 and 25 from El Paso, Texas; and 4 miles northeast of Truth or Consequences on Highway 51, New Mexico.

A bathymetric survey of Elephant Butte Reservoir was conducted in 2017 with these primary objectives.

1. Estimate reservoir sedimentation volume since the original reservoir filling began in 1915 and since the last survey in 2007.

2. Determine new reservoir surface area and storage capacity tables for the full elevation range of dam and reservoir operations.

The bathymetric survey was conducted from a boat using a multibeam depth sounder that was interfaced with real-time kinematic (RTK) global positioning system (GPS) instruments for horizontal positioning to map the reservoir bottom. The 2017 multibeam bathymetric survey of Elephant Butte Reservoir was combined with data from the 2019 aerial LiDAR survey to produce a combined digital surface of the reservoir bottom.

The reservoir survey was conducted between May 31 and June 8, 2017 when the reservoir water surface elevation ranged between 4340.75 and 4341.45 feet (vertical project datum), nearly 66 feet below the top of normal operations pool elevation of 4407 feet. The above-water topographic data were measured January 2019.

Analysis of the combined data sets indicates the following results:

- At reservoir water surface elevation 4336 feet (project vertical datum), which is 5 feet below water at the time of survey, the reservoir surface area was 12,250 acres with a storage capacity of 427,201 acre-feet.

- At the top of the active storage pool elevation (4407 feet, project vertical datum), the reservoir would have a surface area of 35,786 acres and a storage capacity of 2,010,900 acre-feet.

  Since the original filling of the reservoir in 1915, the reservoir is estimated to have lost 623,900 acre-feet of storage capacity (24 percent) due to sedimentation. Since the last reservoir survey in 2007, the reservoir is estimated to have lost 13,700 acre-feet of storage capacity. This most recent volume loss represents a sediment yield rate of 0.1 acre-feet per square mile per year (acre-feet/mi^2/year), which is considered very low as defined in Reclamation (2006). Between 1915 and 1925, average annual sediment yield

rates were moderate and ranged between 0.8 and 1.0 acre-feet/mi^2/year. The construction of upstream dams has significantly reduced the sediment yield rates.

- Jemez Canyon Dam closed in 1953 with a drainage area of 1,038 mi^2
- Galisteo Dam closed in 1970 with a drainage area of 596 mi^2
- Cochiti Dam closed in 1970 with a drainage area of 11,960 mi^2

- The dead storage pool volume was filled with sediment by the late 1960's. The reservoir pool below the invert of the power penstock valve has been reduced to 33 percent of the original penstock storage volume, a loss of 67 percent. The sedimentation level at the dam is 4236 feet (project vertical datum), which is about 4 feet higher than the invert of the outlet works valve.

- Historic rates of reservoir sedimentation indicate a decreasing trend from 1915 to 1940 and a much lower and more consistent rate since that time. Extrapolation of sedimentation rates suggest that reservoir storage below the power penstock elevation (4287.5 feet, project datum) will be lost to sedimentation within a couple of centuries (by year 2200).

A summary description of the dam, reservoir, and survey results is presented in Table ES-1.

Table ES-1. Reservoir Survey Summary Information

Reservoir Information

Reservoir Name	Elephant Butte	**Region**	**Upper Colorado**
Owner	Bureau of Reclamation	**Area Office**	Albuquerque
Stream	Rio Grande	**Vertical Datum**	Elephant Butte Project Datum1
County	Sierra	**Top of Dam (ft)**	4414
State	New Mexico	**Spillway Crest (ft)**	4407
Lat (deg min sec)	33o 09′ 15″	**Power Penstock Valve Centerline Elevation (ft)**	4290
Long (deg min sec)	107o 11′ 30″	**Low Level Outlet Centerline (ft)**	4234
HUC4	1302	**Total Drainage Area (mi^2)**	25,923
HUC8	13020211	**Date storage began (mm/dd/yyyy)**	01/06/1915
NID ID	NM00129	**Date reservoir nearly filled for first time**	July 1920
Dam Purpose	Water storage for irrigation, flood risk reduction, recreation, and electrical power generation		

HUC = Hydrologic Unit Code; NID = National Inventory of Dams

Original Design

Storage Allocation	Elevation (feet)	Surface area (acres)	Capacity (acre-feet)	Gross Capacity (acre-feet)
Surcharge				
Flood Control				
Multiple Use	4407	40,064	2,631,585	2,634,800
Joint Use				
Conservation				
Inactive or Dead	4231.5	420	3,215	3,215

Survey Summary

Survey Date	Type of Survey	Contributing Sediment Drainage Area (mi²)	Period Sedimentation Volume (ac-ft)	Cumulative Sedimentation (ac-ft)	Lowest Reservoir Bottom Elevation (ft)	Remaining Portion of Dead Storage (%)
1/6/1915	Initial Survey	29,445	2,634,800	-	4,218	100%
2/14/1947	Range line and Contour	26,551	2,197,600	437,200	4,240	63%
2/9/1957	Range line and Contour	26,359	2,206,780	428,020	4,220	52%
10/15/2007	Multibeam and RTK GPS	25,923	2,024,586	610,214	4,244	35%
6/15/2017	Multibeam and RTK GPS	25,923	2,010,900	623,900	4,236	33%

Notes

[1]Elephant Butte Project Datum is 43.3 feet lower than National Geodetic Vertical Datum of 1929 and 45.0 feet lower than North American Vertical Datum of 1988.

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1. Introduction

Elephant Butte Dam and Reservoir are on the Rio Grande (Figure 1). The dam is about 150 road miles (along Interstate 25) south-southwest from Albuquerque, New Mexico; 125 road miles (along Interstates 10 and 25) northwest from El Paso, Texas; and 4 miles northeast from Truth or Consequences, New Mexico. The dam and reservoir are operated by Bureau of Reclamation, Upper Colorado Region, Albuquerque Area Office as part of the Rio Grande Project. The reservoir provides water storage for irrigation, flood risk reduction, recreation, and electrical power generation. Caballo Dam is located 25 road miles downstream from Elephant Butte Dam. Caballo Reservoir reregulates the flows released from Elephant Butte Dam.

All rivers transport sediment particles (e.g., clay, silt, sand, gravel, and cobble) and reservoirs tend to trap sediment, diminishing the reservoir storage capacity over time (Moris and Fan, 1998 and Randle, et al., 2006). Reservoir sedimentation affects all elevations of the reservoir, even above and upstream of the full reservoir pool elevation. Cobble, gravel, and sand particles tend to deposit first forming deltas at the upstream ends of the reservoir while silt and clay particles tend to deposit along the reservoir bottom between the delta and dam.

Periodic reservoir surveys measure the changing reservoir surface area and storage capacity and provide information for forecasting when important dam and reservoir facilities will be impacted by sedimentation.

As part of ongoing operations and sediment monitoring activities, Reclamation's Albuquerque Area Office requested the Technical Service Center's (TSC) Sedimentation and River Hydraulics Group (86-68240) to conduct a bathymetric survey of the underwater portions of the reservoir that were accessible by boat. A complete bathymetric survey was conducted from May 31 to June 8, 2017 with these primary objectives:

1. Estimate reservoir sedimentation volume since the original reservoir filling began in 1915 and since the last survey in 2007.

2. Determine new reservoir surface area and storage capacity tables for the full elevation range of dam and reservoir operations.

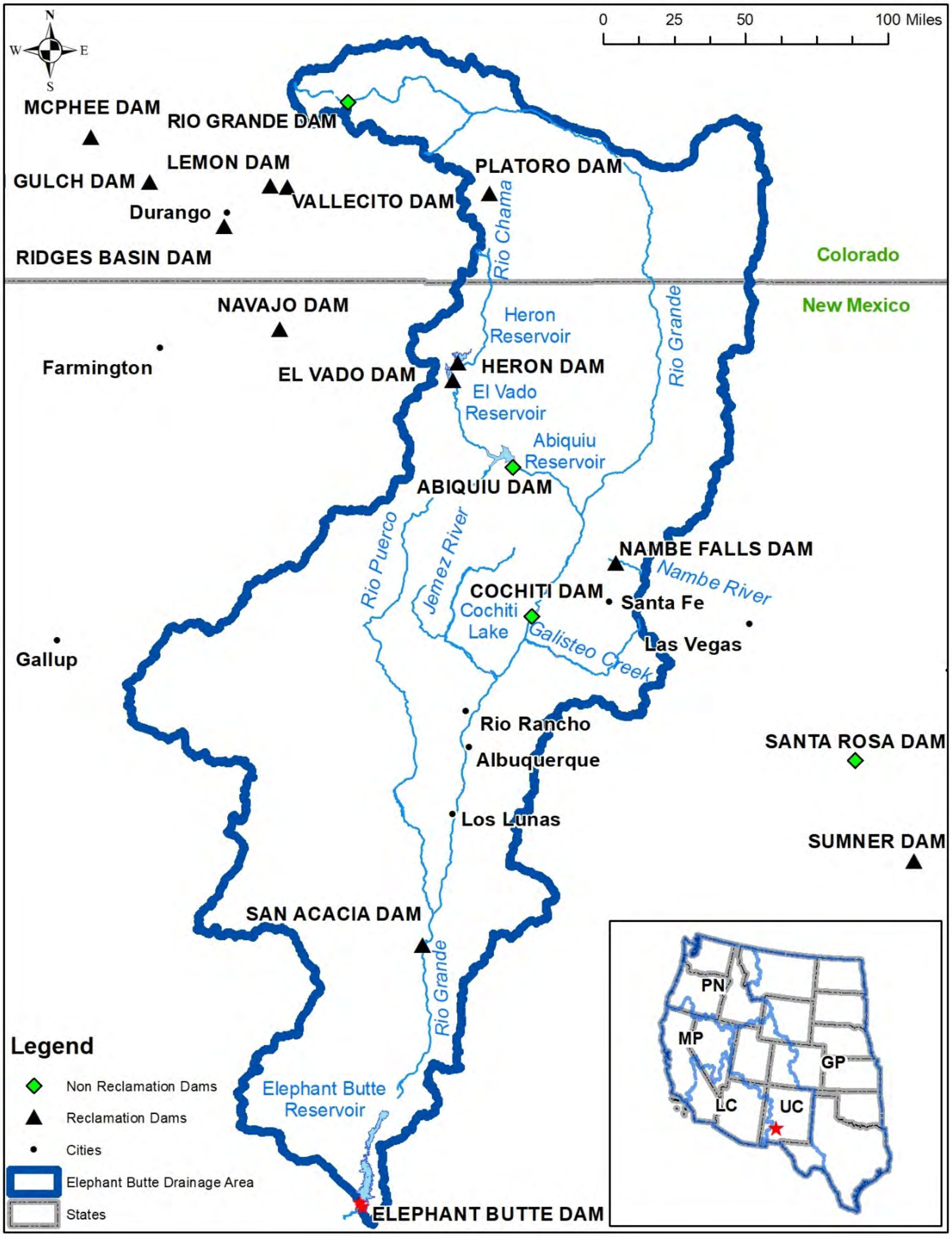

Figure 1. Location map of Elephant Butte Dam, Elephant Butte Reservoir, and upstream watershed. Elephant Butte Dam is 150 highway miles south, southwest of Albuquerque, New Mexico.

2. Watershed Description

The watershed upstream from Elephant Butte Dam has a total drainage area of 29,450 square miles (mi^2), which includes 2,940 mi^2 of closed basin in the northern part of the San Luis Valley in Colorado (https://streamstatsags.cr.usgs.gov/gagepages/html/08361000.htm) (Figure 1). The contributing drainage area is 26,510 mi^2. Because of upstream lakes and reservoirs that trap sediment (Table 1), the net sediment-contributing drainage area to Elephant Butte is 11,970 mi^2 (Ferrari, 2008), 45 percent of the contributing watershed area. The watershed of the sediment contributing drainage area is steep, mostly arid, dissected by numerous arroyos, and has cities, towns, and pueblos along the Rio Grande valley.

Table 1. Selected USGS gaging stations below dams of the Rio Grande Watershed and their drainage areas (USGS Stream Stats, https://streamstats.usgs.gov/ss/).

USGS Gage Name	USGS Gage Number	Year Dam Closed	Contributing Drainage Area (mi^2)
Rio Grande below Elephant Butte Dam, NM	08361000	1916	26,510
Rio Grande Floodway at San Marcial, NM	08358400	N/A	24,760
Jemez River below Jemez Canyon Dam, NM	08329000	1953	1,038
Galisteo Creek below Galisteo Dam, NM	08317950	1970	596
Rio Grande below Cochiti Dam, NM	08317400	1970	11,960
Elephant Butte sediment-contributing drainage	N/A	1970	11,970

2.1. Geology

The most dominant surficial geologic types in the sediment-contributing drainage area are clastic sedimentary rock, undifferentiated unconsolidated sediments, sedimentary rock, and some igneous rocks (Table 2). The unconsolidated sediments (40 percent of drainage area) are much more erodible than the rock.

Table 2. Summary of geologic categories within the sediment-contributing drainage area.

Surficial Geology	**Drainage Area** Portion
Sedimentary, clastic[1]	31.4%
Unconsolidated[2], undifferentiated[3]	22.1%
Unconsolidated and Sedimentary, undifferentiated	17.5%
Igneous, volcanic	15.2%
Sedimentary, undifferentiated	7.5%
Igneous, intrusive	1.8%
Sedimentary, carbonate	1.6%
Igneous and Metamorphic, undifferentiated	0.9%

Surficial Geology	**Drainage Area** Portion
Metamorphic, undifferentiated	0.7%
Igneous and Sedimentary, undifferentiated	0.7%
Metamorphic, sedimentary clastic	0.1%
Metamorphic, schist	0.1%
Water	0.3%

[1]Clastic sedimentary material consists of clast of pre-existing rocks cemented together to form sedimentary rock.
[2]Unconsolidated material consists of loosely arranged, or unstratified or whose particles are not cemented together through diagenesis as defined by the USGS.
[3]Undifferentiated material are sediments where it is not possible to specify finer age divisions.

Reclamation (1960) provides a description of the sediment-contributing watershed geology from the Otowi Bridge (20 miles upstream and northeast from Cochiti Dam) downstream to Elephant Butte Reservoir:

> *The unconsolidated sediments of the Santa Fe formation (Miocene and Pliocene continental deposits) have been eroded to form the valley of the Rio Grande from the lower end of White Rock Canyon near Cochiti Dam, to near San Acacia, NM. The flood plains and terraces of the valley are composed of alluvium which is available for transport and which contributes large quantities of sediment to the Rio Grande.*
>
> *From the mouth of Rio Salado, just upstream from San Acacia, to the headwaters of Elephant Butte Reservoir, the Palomas formation of the Quaternary Period has been eroded to form the river valley. The major geologic formations of the Rio Grande Valley are of the Cenozoic Era.*

The soils of the sediment-contributing drainage area consist primarily of Hydrologic Soil Groups B and D (Figure 2). Description of the soil groups are listed below from the Natural Resource Conservation Service (2007).

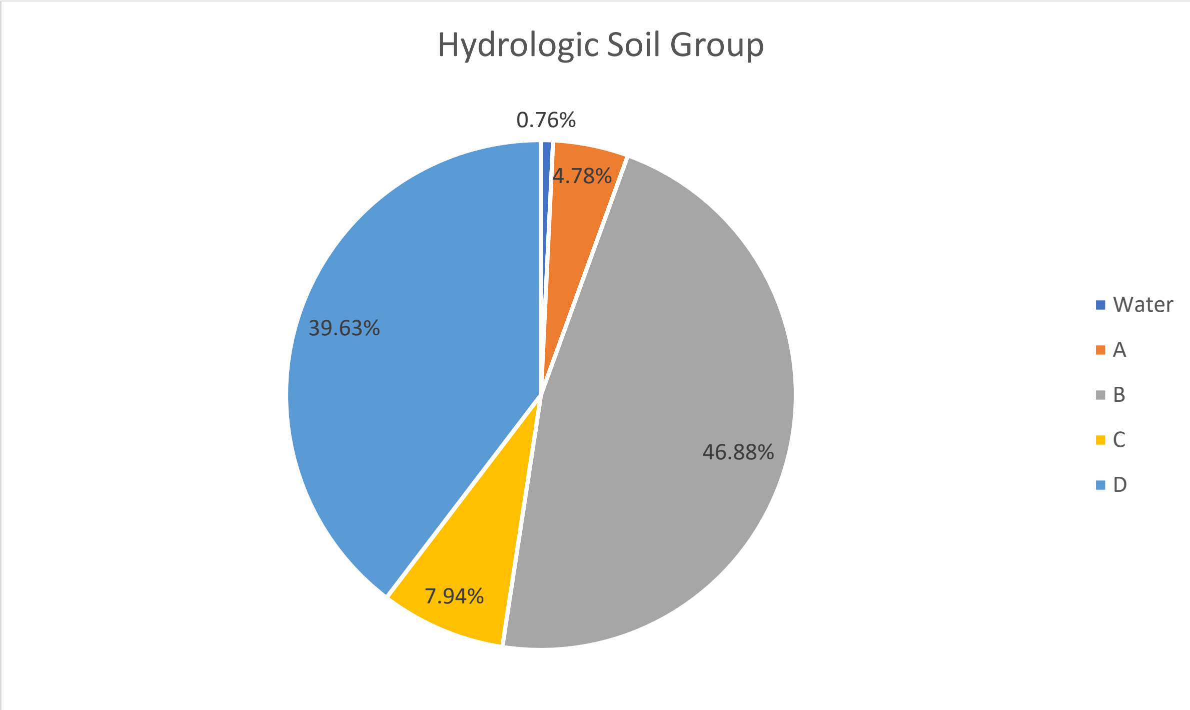

Figure 2. Portions of different soil types within the sediment-contributing watershed.

- Group A soils "have low runoff potential when thoroughly wet. Water is transmitted freely through the soil." "Soils typically have less than 10 percent clay and more than 90 percent sand or gravel and have gravel or sand textures. Some soils having loamy sand, sandy loam, loam or silt loam textures may be placed in this group if they are well aggregated, of low bulk density, or contain greater than 35 percent rock fragments."

- Group B soils "have moderately low runoff potential when thoroughly wet. Water transmission through the soil is unimpeded." "Soils typically have between 10 percent and 20 percent clay and 50 percent to 90 percent sand and have loamy sand or sandy loam textures. Some soils having loam, silt loam, silt, or sandy clay loam textures may be placed in this group if they are well aggregated, of low bulk density, or contain greater than 35 percent rock fragments."

- Group C soils "have moderately high runoff potential when thoroughly wet. Water transmission through the soil is somewhat restricted." "Soils typically have between 20 percent and 40 percent clay and less than 50 percent sand and have loam, silt loam, sandy clay loam, clay loam, and silty clay loam textures. Some soils having clay, silty clay, or sandy clay textures may be placed in this group if they are well aggregated, of low bulk density, or contain greater than 35 percent rock fragments."

- Group D soils "have high runoff potential when thoroughly wet. Water movement through the soil is restricted or very restricted." "Soils typically have greater than 40

> percent clay, less than 50 percent sand, and have clayey textures. In some areas, they also have high shrink-swell potential. All soils with a depth to a water impermeable layer less than 20 inches and all soils with a water table within 24 inches of the surface are in this group, although some may have a dual classification . . . if they can be adequately drained."

Vegetation types within the watershed primarily consist of conifers in the higher elevations and desert shrubs in the lower elevations. Within the river corridor there are riparian vegetation types. Land use activities within the watershed primarily consist of farming, ranching and urban areas. These types of land use tend to increase sediment yields and runoff throughout the watershed.

2.2. Climate and Runoff

Reservoir inflows are primarily from the Rio Grande. The USGS stream gage on the Rio Grande Floodway at San Marcial, NM measured stream flow for 93 percent of the total contributing drainage area into Elephant Butte Reservoir (Table 1). Based on San Marcial stream flow records from water years 1964 through 2016, the mean-annual runoff is 506,310 acre-feet per year (699 cubic feet per second, ft^3/s). The average annual runoff from the contributing arid watershed is 0.36 in/yr. This runoff is primarily from snowmelt in the upper portions of the watershed and infrequent monsoon storms in the lower portions of the watershed. The ratio of reservoir storage capacity to the mean annual runoff is nearly 4. This means that a full reservoir stores a water volume equivalent to 4 years of mean-annual stream flow.

Stream flows are highly variable both seasonally and from year to year. During water years 1964 through 2016, the highest annual stream-flow volume (during water year 1987) was 1,768 times greater than the lowest annual stream-flow volume (during water year 1971) (Figure 3). The largest annual peak discharge (during water year 1985) was 16 times greater than the smallest annual peak discharge (during water year 1971) (Figure 4). Annual flow volumes were greater than 1,000,000 acre-ft/year during water years 1979, 1980, 1983, 1985, 1986, 1987, 1993, and 1995. Annual flow volumes were less than 100,000 acre-ft/year during water years 1964, 1966, 1967, 1970, 1971, 1972, and 1974.

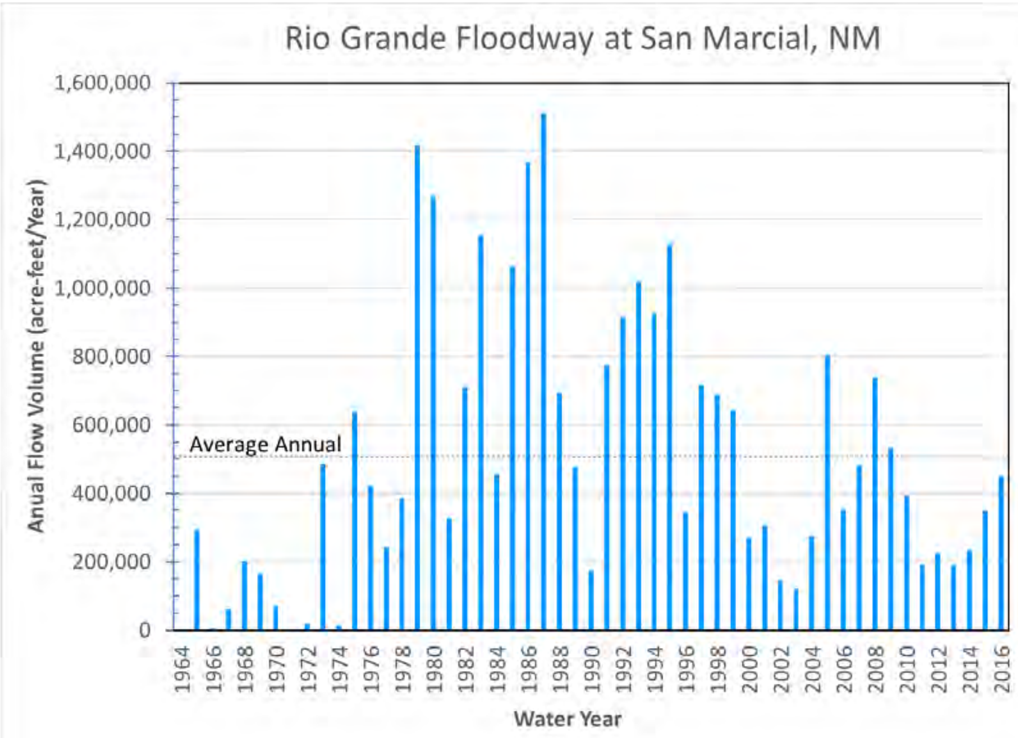

Figure 3. Annual Rio Grande stream flow volumes past the USGS gage at San Marcial, New Mexico are highly variable (https://waterdata.usgs.gov/nm/nwis/uv?site_no=08358400).

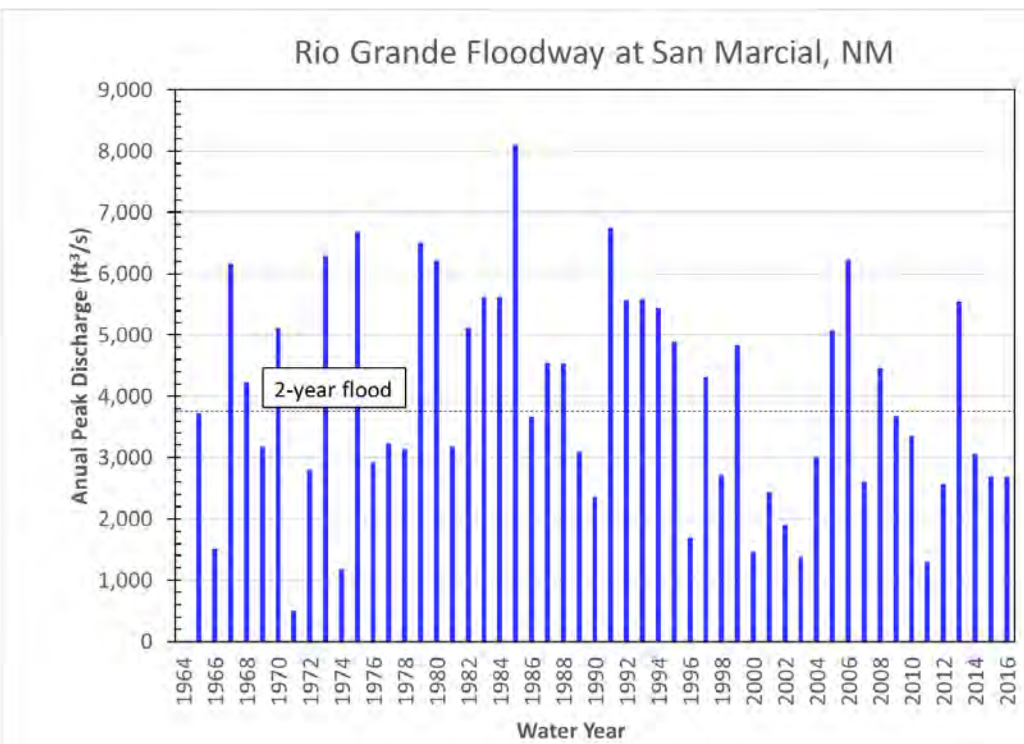

Figure 4. Annual Rio Grande peak discharges past the USGS gage at San Marcial, New Mexico are highly variable (https://nwis.waterdata.usgs.gov/nm/nwis/peak/?site_no=08358400&agency_cd=USGS).

2.3. Dam Operations and Reservoir Characteristics

Elephant Butte Dam (a concrete gravity structure) was completed in 1916, but began storing water in January 1915. The dam has a hydraulic height 197 feet and was constructed to store water for irrigation and provide year-round power generation (https://www.usbr.gov/projects/index.php?id=94). The historic reservoir water surface elevations (Reclamation Project Vertical Datum, RPVD) are presented in Figure 5. Reservoir water surface elevations fluctuate from year to year in response to varying inflow volumes and the annual releases for irrigation water and requirements of the Rio Grande Compact. Within the water year, the reservoir water surface may fluctuate 5 to 50 feet.

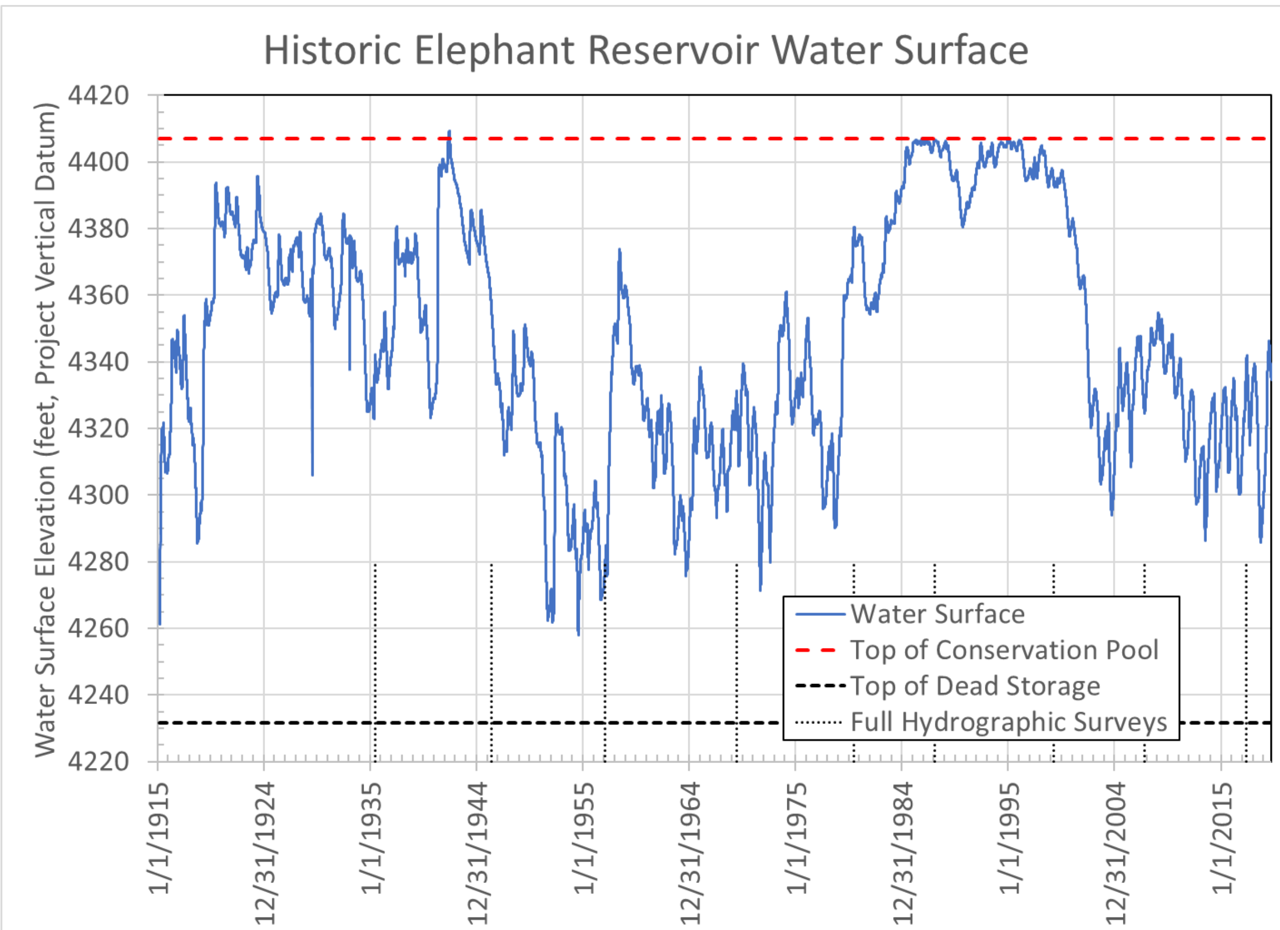

Figure 5. Historic Elephant Butte water surface elevations (RPVD) and dates of full hydrographic surveys. Data web source: https://www.usbr.gov/rsvrWater/HistoricalApp.html.

Elephant Butte Reservoir had an original length of 40 miles at full pool with an average width of 1.9 miles. There are no major tributaries. The reservoir is quite narrow (700 to 1,400 feet) along the "narrows" which is 15 to 19 miles upstream from the dam. The widest portion of the reservoir (3.7 miles wide) coincides with a tributary arroyo arm (Monticello Canyon), 11 miles upstream from the dam.

The reservoir filled during water year 1985 and remained full through the middle of water year 1989. The reservoir lowered about 20 feet during water year 1990 and was full again during water years1992 through 1998. A large delta deposited at the upstream end of the reservoir during this period. Over 100 feet of reservoir drawdown occurred during water years 2000 through 2004 and allowed the Rio Grande to incise the delta and redeposit the eroding sediments all the way downstream to Kettle Butte, which is about 6.5 miles upstream from the dam.

Sediment management activities for Elephant Butte consist of using the sluice gates to remove sediment from the face of the dam. The sluice gate air vents were undersized during construction, so sediment sluicing can only take place when the reservoir head is not too great. There are no other active sediment management efforts taking place in the reservoir (B. Kalminson, personal communication, December 16, 2019).

3. Previous Reservoir Surveys

Prior to dam closure and initial reservoir filling, a survey was conducted in 1903-1904 and 1907-1908 to measure the original surface areas and corresponding storage capacities. Although the documentation summarizing the original survey methods has not been located for this analysis, plane-table survey would have been the most likely method for this time period. A 10-foot contour interval map was produced from this original survey.

Range lines with monuments were surveyed along the reservoir prior to the initial storage in 1915. These range lines have been surveyed multiple times since 1915 (Table 3). Range line 90 is near the dam and range line 9 is upstream from the reservoir and under the influence of the reservoir delta (Ferrari, 2008).

Table 3. Previous Bathymetric Reservoir Surveys of Elephant Butte Reservoir.

Survey Year	Extent of Survey	Survey Method	Depth Sounder	Above water survey
1915	Full	Contour		Plane table assumed
1925	Partial	Range line		
1935	Full	Range line		
1940	Partial	Range line		
1946	Full	Range line		
1951	Partial	Range line		
1957	Full	Range line	Single beam	No change assumed
1969	Full	Range line	Single beam	No change assumed
1980	Full	Range line	Single beam	No change assumed
1988	Full	Range line	Single beam	No change assumed
1999	Full	Range line	Single beam	1980 photo revised U.S. Geological Survey 7.5 minute quadrangle map

For more details on these previous surveys are described in these reservoir sedimentation survey reports:

- 1957 sedimentation survey (Reclamation, 1960).
- 1969 sedimentation survey (Lara, 1972)
- 1980 sedimentation survey (Lara, 1983)
- 1988 sedimentation survey (Orvis, 1989)
- 1999 sedimentation survey (Collins and Ferrari, 2000)
- 2007 sedimentation survey (Ferrari, 2008)

Hydrographic surveys from 1925 to 1999 (Table 3), used the range line survey method described below by Ferrari and Collins (2006):

> "Range line surveys and analysis methods involve determining cross-sectional changes along range lines and applying the changes to the reservoir surface areas enclosed by the range lines." "The range line method consists of laying out a system of representative ranges and determining the present sediment depths along those lines." "Ranges subdivide the main body of the reservoir and its principal tributary arms so that sediment deposits in each subdivision or segment are represented by the average of conditions measured at the ranges."
>
> The "new contour area . . . between any two ranges is computed by applying an adjustment factor to the original contour area . . . between the same two ranges. This adjustment factor is defined as the ratio of the new average width to the original average width for both upstream and downstream ranges at the specified contour. The revised segmented surface areas for each contour are then summed for the whole reservoir. The summarized segmented surface area versus elevation becomes the basic input for volume computations.

The 2007 hydrographic survey used a multibeam depth sounder and RTK-GPS to provide near continuous data coverage below the water surface elevation 4327 (Ferrari, 2008). The 2007 multibeam bathymetric survey was comprehensive, but these data were combined with above water data from USGS quadrangle map contours for the downstream 4 miles of reservoir (range lines 90 to 78), 2004 LiDAR survey for the next 30 miles (range lines 78 to 23), and 2007 LiDAR survey for the remaining 8 miles of upstream reservoir (range lines 23 to 9).

4. Survey Control and Datum

For the 2017 survey, all bathymetry and GPS control measurements were collected in North American Datum 1983 (NAD 1983) State Plane (horizontal) coordinates, New Mexico Central Zone WKID 2258, US survey feet and North American Vertical Datum 1988 (NAVD 1988, Geoid 12A, US survey feet elevations. During processing, all bathymetry and GPS measurements were converted to Reclamation Project Vertical Datum (RPVD) for Elephant Butte Dam. The RPVD was determined to be 45.0 feet lower than NAVD 1988 (Geoid 12A).

GPS base-station receivers were set up over temporary monuments located along the reservoir shoreline. State plane and elevation coordinates for the GPS base station were computed using the Online Positioning User Service (OPUS) developed by the National Geodetic Survey (NGS) (www.ngs.noaa.gov/OPUS/).

The RPVD at Elephant Butte Reservoir was determined from comparison of RTK GPS water surface elevation measurements in the downstream end of the reservoir to water surface elevation records from the dam gage at the corresponding time of the GPS measurements.

The difference between NGVD 1929 and NAVD 1988 at Elephant Butte Dam was computed using the US Army Corps of Engineers conversion program Corpscon v6.0.1. Corpscon uses NGS data and algorithms to convert between various horizontal projections and vertical datums (www.agc.army.mil/Missions/Corpscon.aspx). The Corpscon calculations confirmed that NGVD 1929 is 2.1 feet lower than NAVD 1988.

5. Methods Summary

A complete bathymetric survey of Elephant Butte Reservoir was conducted during June 2017 from a boat using a multibeam depth sounder to continuously measure water depths and produce a surface map. Water surface elevations during the bathymetric survey were between 4340.75 and 4341.45 feet (RPVD). The horizontal position of the moving boat was continually tracked using RTK GPS. A map of the data points collected, including the GPS base stations is presented in Figure 6. These bathymetric data were then combined with data from the January 2019 LiDAR survey (Atlantic, 2019) when the reservoir water surface elevation was below 4300 feet (RPVD). Data from these two surveys were combined to produce a complete and continuous digital surface of the reservoir bottom.

Appendix A provides more details of the hydrographic survey methods. Appendix B provides more details above the-water survey data. Surface areas at 2-foot contour intervals were computed using GIS software and the ACAP-85 computer program the was used to produce the reservoir surface area and capacity tables at 0.01-foot increments. Appendix C provides more details about the methods used to generate surface area and storage capacity tables.

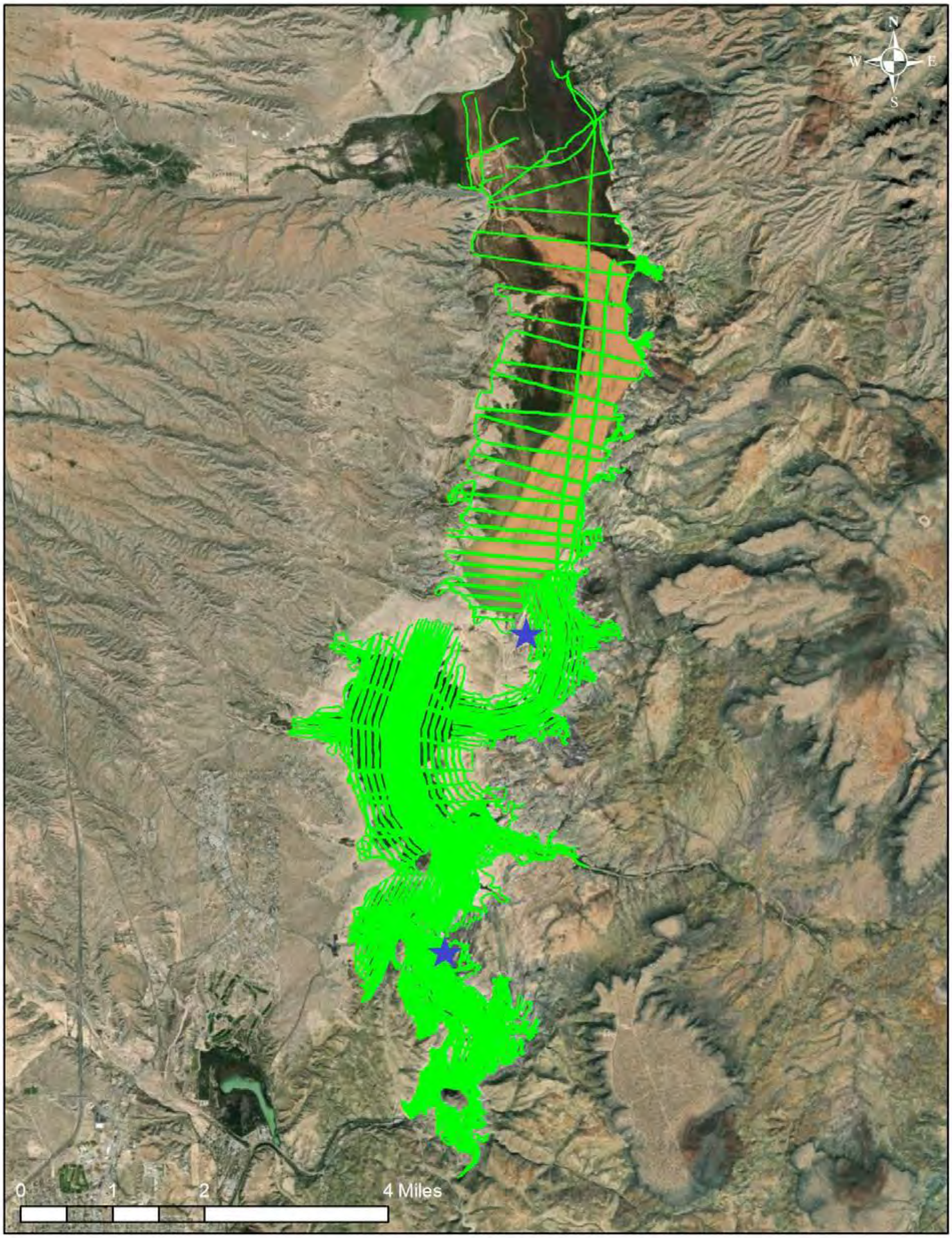

Figure 6. Coverage map of bathymetric survey data points measured in Elephant Butte Reservoir, and the GPS base station positions (blue stars), during the period May 31 to June 8, 2017.

6. Reservoir Surface Area and Storage Capacity

Bathymetric and topographic contour maps (5- and 10-foot contour intervals) of the reservoir bottom are presented in Maps section of this report. Tables of reservoir surface area and storage capacity were produced for the full range of reservoir elevations (Reclamation, 2019). Plots of the 2017 area and capacity curves are presented in Figure 7 along with curves from the 1915 and 2007 surveys. These data are also summarized in Table 4. For the 2017 survey, area and capacity curves are based on the bathymetric (below-water) survey up to 4336 feet elevation (RPVD), while curves above this elevation are based on 2019 aerial LiDAR survey.

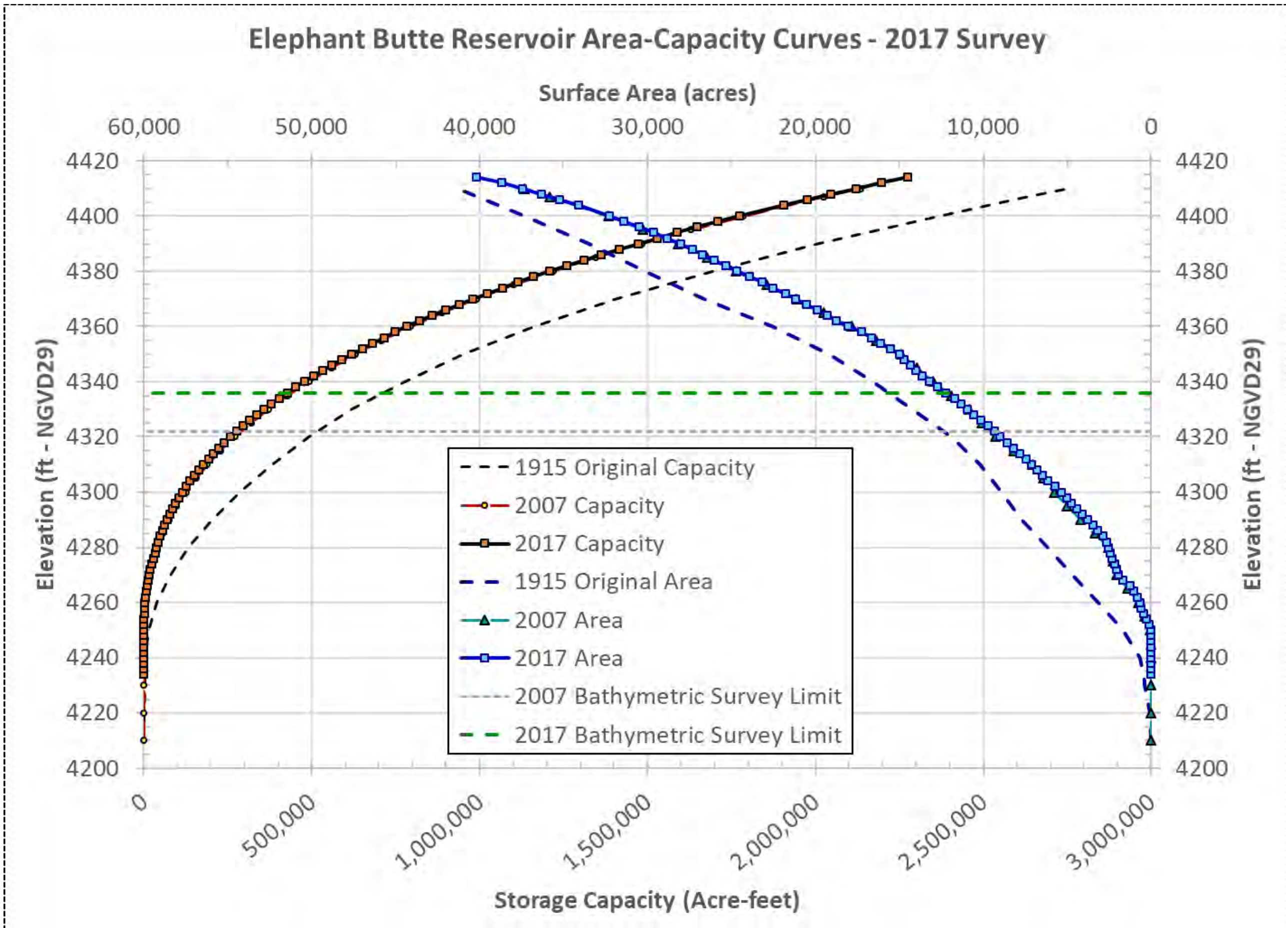

Figure 7. Plot of Elephant Butte Reservoir surface area and storage capacity versus elevation (RPVD).

Table 4. Summary comparison of historic reservoir storage capacity data.

	Reservoir Surface Area (acres)			Reservoir Storage Capacity (acre-ft)			Sedimentation Volume (acre-ft)
Elevation (ft)	1915	2007	2017	1915	2007	2017	1915 to 2017
4407	40,060	35,826	35,786	2,634,800	2,024,586	2,010,900	623,900
4400	37,328	32,335	32,276	2,363,900	1,786,026	1,773,281	590,619
4390	33,451	28,179	28,042	2,010,300	1,483,458	1,472,367	537,933
4380	30,191	24,727	24,658	1,692,800	1,218,927	1,208,841	483,959
4370	26,620	21,131	21,156	1,408,000	989,638	980,238	427,762
4360	22,563	17,868	18,085	1,162,100	794,642	783,977	378,123
4350	19,194	14,899	15,013	954,400	630,803	619,806	334,594
4340	16,595	12,997	13,219	775,600	491,323	478,161	297,439
4330	14,240	10,863	10,972	621,400	372,028	357,875	263,525
4320	11,894	9,283	8,996	490,800	271,301	258,333	232,467
4310	10,202	7,098	7,146	380,800	189,399	177,939	202,861
4300	8,923	5,786	5,371	285,400	124,978	115,092	170,308
4290	7,715	4,217	3,786	202,100	74,961	69,230	132,870
4280	6,145	2,540	2,545	132,800	41,179	38,495	94,305
4270	4,691	2,058	1,964	78,600	18,194	15,881	62,719
4260	3,157	748	683	39,700	4,165	3,647	36,053
4250	1,684	57	16	15,800	141	54	15,746
4240	671	0	2	4,660	0	2	4,658
4230	376	0	0	2,960	0	0	2,960
4220	98	0	0	490	0	0	490
4210	0			0			0

A comparison of the 1915 and 2017 surface area curves indicates that largest reduction in surface area occurs between elevations 4370 and 4390 feet (RPVD). The 2019 LiDAR survey is considered more accurate than the 1915 survey methods. However, the surface area and storage loss due to reservoir sedimentation is likely greater than any differences due to survey methods. Between 2007 and 2017, the surface area increased between elevations 4330 and 4370 feet (RPVD) and generally decreased between elevations 4290 and 4320 feet (RPVD). These changes could be explained by channel incision of the exposed delta surface and redeposition of eroded delta sediments in the receded reservoir. Elephant Butte Reservoir was drawn down to elevation 4285 in September 2018 (prior to the 2019 LiDAR survey). This was the lowest reservoir elevation since 1971.

7. Reservoir Sedimentation Volume Spatial Distribution

Elephant Butte Reservoir would be expected to trap more than 90 percent of inflowing sediments based on the Brune trap efficiency curve (Brune, 1953; Strand and Pemberton, 1982; Morris and Fan, 1998; and Randle et al., 2006). These sediments have deposited along the Rio Grande, upstream of the reservoir pool, and along the reservoir bottom all the way to Elephant Butte Dam. The coarsest particles (primarily sand and gravel) settle at the upstream end of the reservoir where the Rio Grande and smaller tributary channels meet the reservoir pool. The backwater effects of the reservoir pool and delta cause some sediment to deposit upstream of the reservoir pool. Finer particles (silt and clay) settle along the reservoir bottom. A small portion of reservoir sediments are likely released through the dam when water is released through the outlet works. Because reservoir pool elevations have varied as much as 140 feet since 1915, the location where the Rio Grande meets the reservoir pool can vary 30 miles. Therefore, the deposition layers of coarse and fine sediment can be quite complex.

A longitudinal profile and representative cross sections of the 2017 and 2019 reservoir bottom were developed in GIS. The longitudinal profile (Figure 8) indicates a break in slope at about 12 miles upstream from Elephant Butte Dam (near Monticello Canyon). This is also where the sediment deposition profile is thickest. A break in profile slope is common where the delta topset slope may be about one-half the upstream river slope and the downstream foreset slope may be about six times the river slope (Stand and Pemberton, 1982; Morris and Fan, 1998; and Randle et al., 2006). The 2017 and 2019 longitudinal profiles were digitized along the thalweg which meanders along the reservoir alignment for a total length of 50 miles. For comparison with previous reservoir sediment profiles, the longitudinal stationing of the 2017 and 2019 profile was adjusted to the stationing of straight-line segments between established range lines for a total length of 42 miles (Figure 9).

Reservoir cross section plots (Figure 10, Figure 11, Figure 12, and Figure 13) show the lateral distribution of sediment deposits. In general, reservoir sedimentation tends to be flat across the reservoir. However, the delivery of sediment from tributary arroyos can produce a cross slope where tributary deltas intersect the main delta (Figure 10 and Figure 11). Along most of the exposed delta, the Rio Grande flows through a single channel with levees on both sides (Figure 10, Figure 11). Distributary delta channels are evident where the Rio Grande intersects the drawn down reservoir pool.

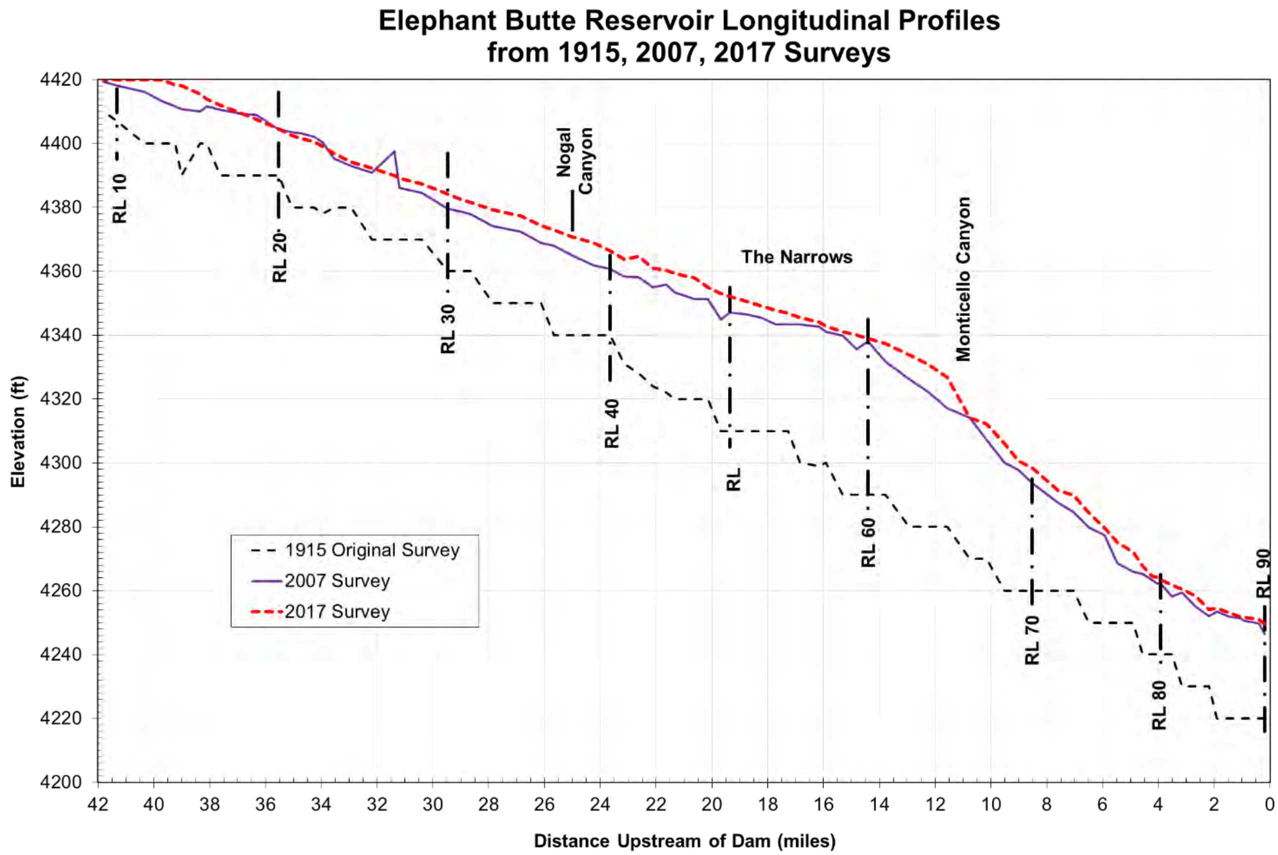

Figure 8. Longitudinal profiles of the Elephant Butte Reservoir bottom between upstream river range line 9 and Elephant Butte Dam (near range line 90).

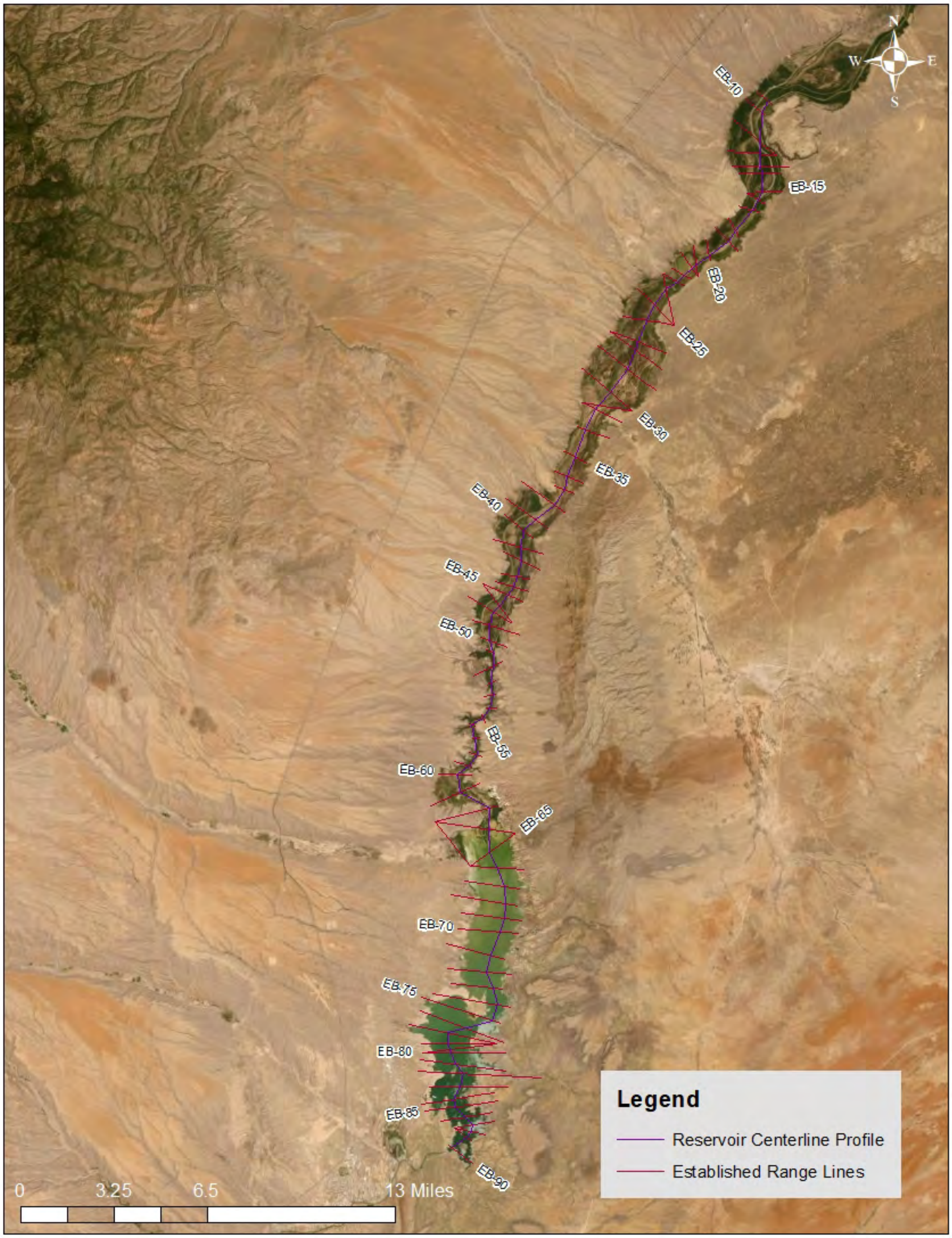

Figure 9. Profile and established range lines

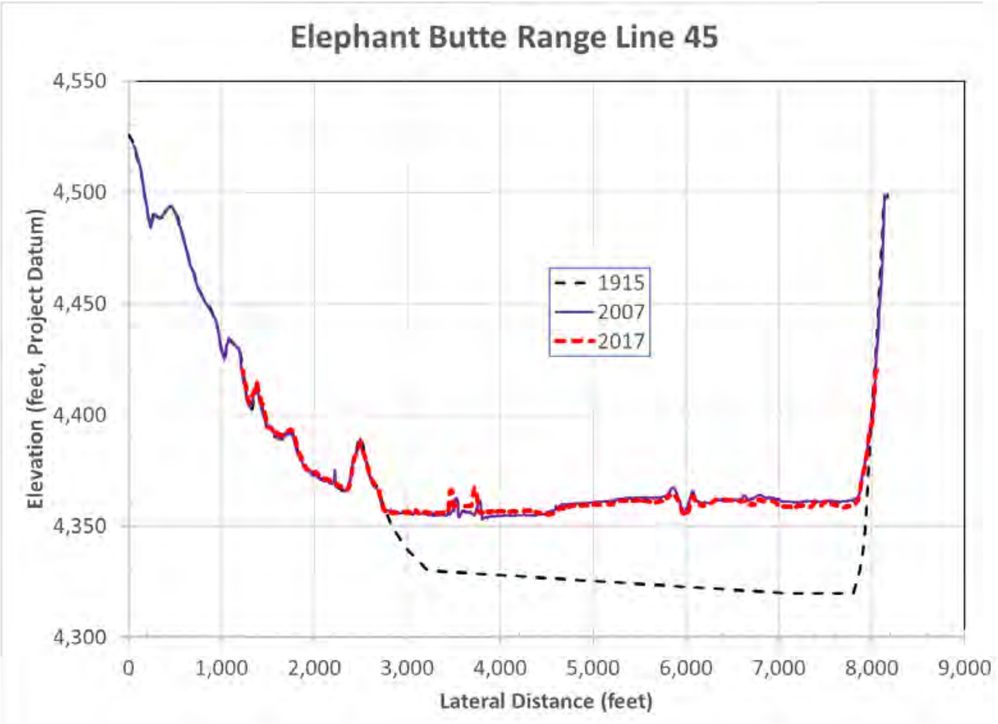

Figure 10. Cross section of the reservoir delta at range line 45 (looking upstream), 21.3 miles upstream from the Elephant Butte Dam.

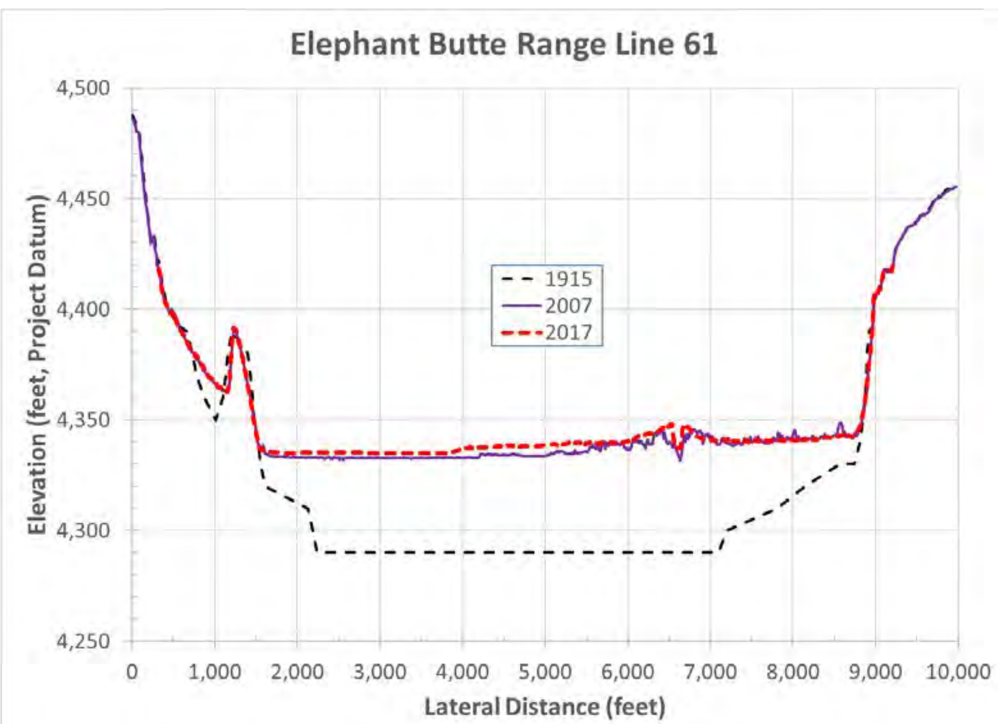

Figure 11. Cross section of the reservoir delta at range line 61 (looking upstream), 13.8 miles upstream from the Elephant Butte Dam. Sediment contributions from Monticello Canyon from the right (west) side are likely responsible for the cross slope between lateral stations 5,200 and 8,800 feet.

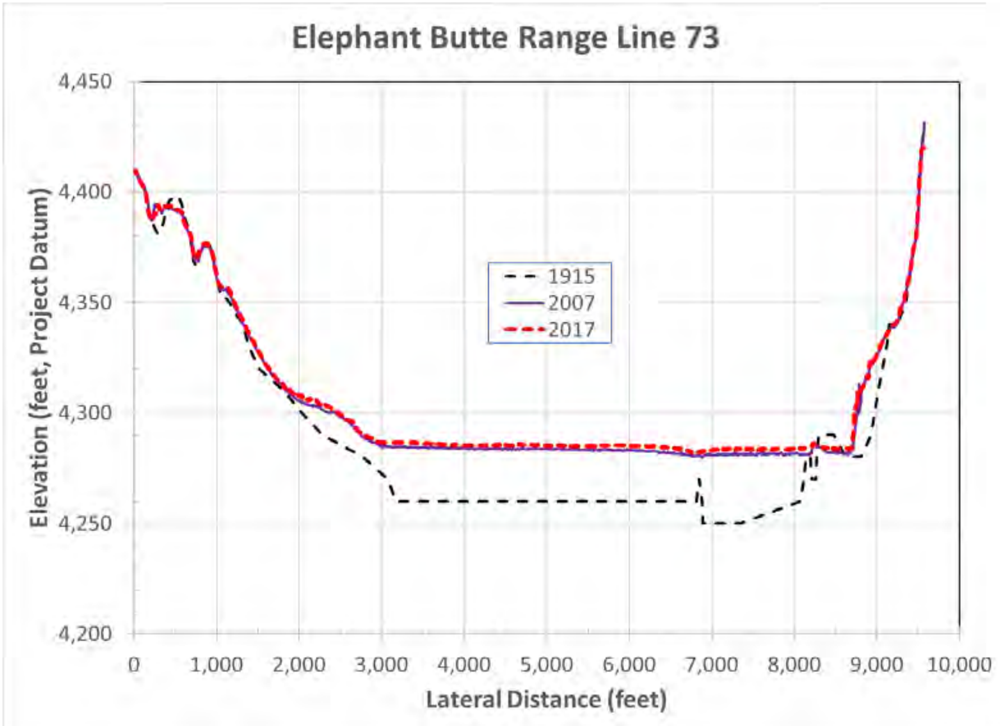

Figure 12. Cross section of the reservoir delta at range line 73 (looking upstream), 6.5 miles upstream from the Elephant Butte Dam.

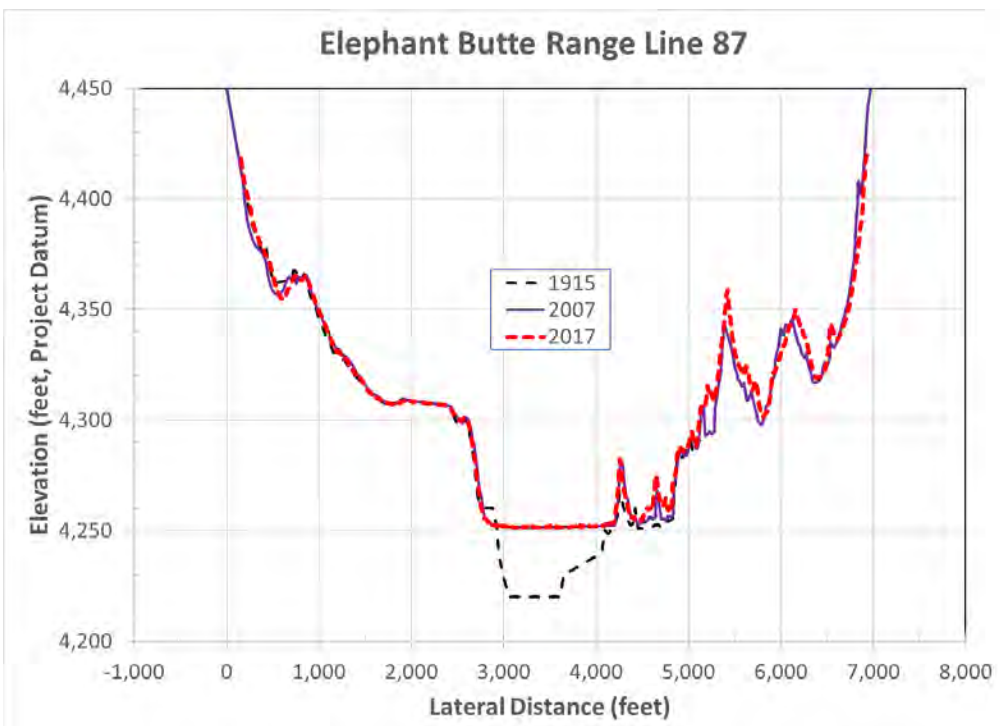

Figure 13. Cross section of the reservoir delta at range line 87 (looking upstream), 1.0 mile upstream from the Elephant Butte Dam.

8. Sedimentation Trends

Graphs of the historic reservoir sedimentation rates over time (Figure 14) and cumulative reservoir sedimentation volume over time (Figure 15) indicate initially high sedimentation rates that decreased from 1915 through the mid 1950's. Sedimentation rates were more consistent between 1957 and 1999. Sedimentation rates could not be determined when there was a change in the range line survey method in 1957 and when multibeam survey was introduced in 2007. Sedimentation rates have been low (1,400 acre-feet/year) between 2007 and 2017, which is likely due to below average water years from 2010 through 2016 (Figure 3). The low reservoir sedimentation rate corresponds to a very low sediment yield rate of 0.1 acre-feet/mi^2/year from the upstream watershed. Future sedimentation rates are expected to increase during periods of above average Rio Grande flows.

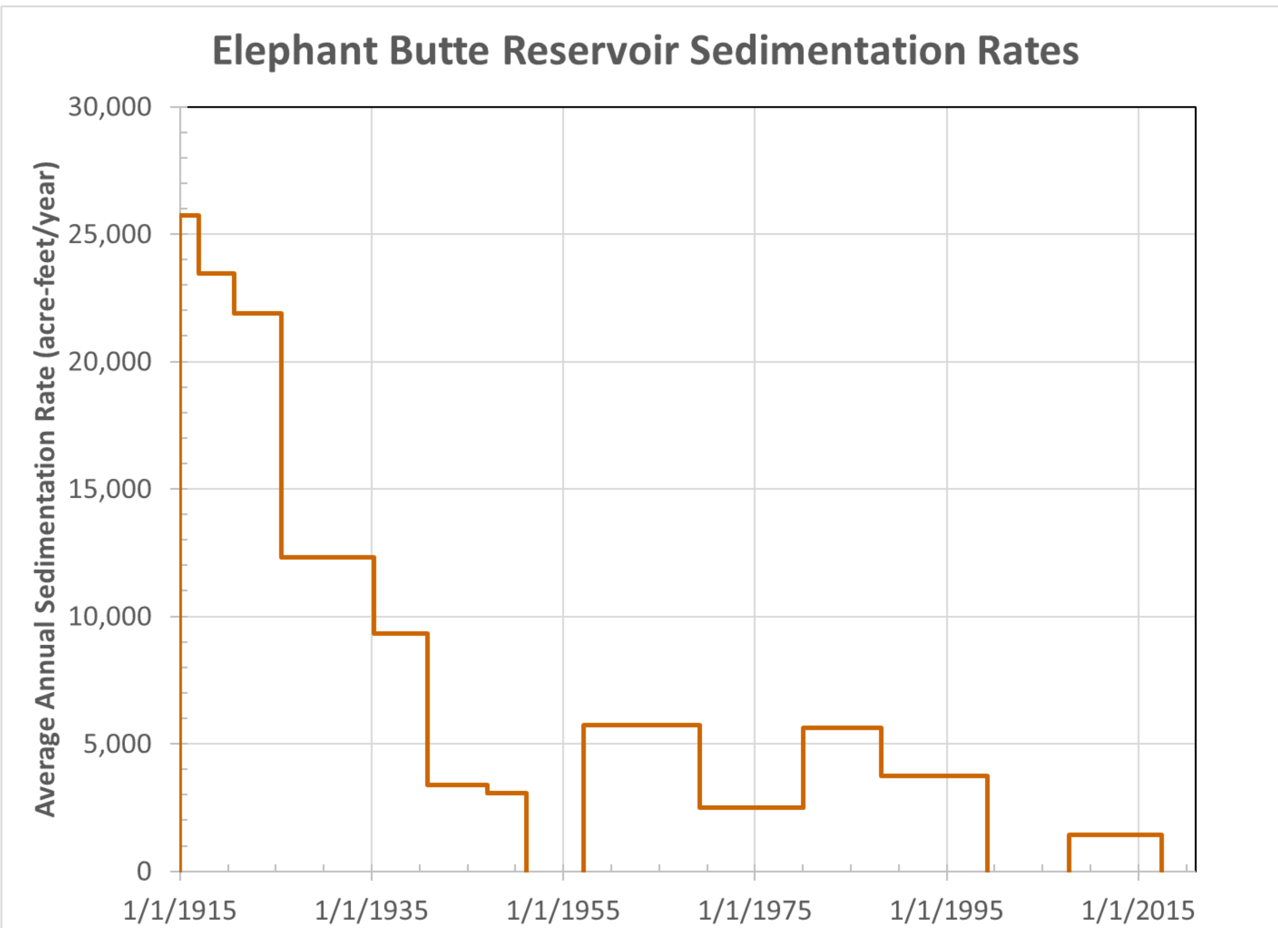

Figure 14. Average Elephant Butte Reservoir sedimentation rates over time. Data are based on Reclamation (1960) and Ferrari (2008).

As of the 2017 and 2019 survey, the total sedimentation in Elephant Butte Reservoir was 624,000 acre-feet (1.0 billion yd^3), which is 24 percent of the original storage capacity. This sedimentation volume is more than six times the storage capacity of a median-sized Reclamation reservoir (100,000 acre-feet).

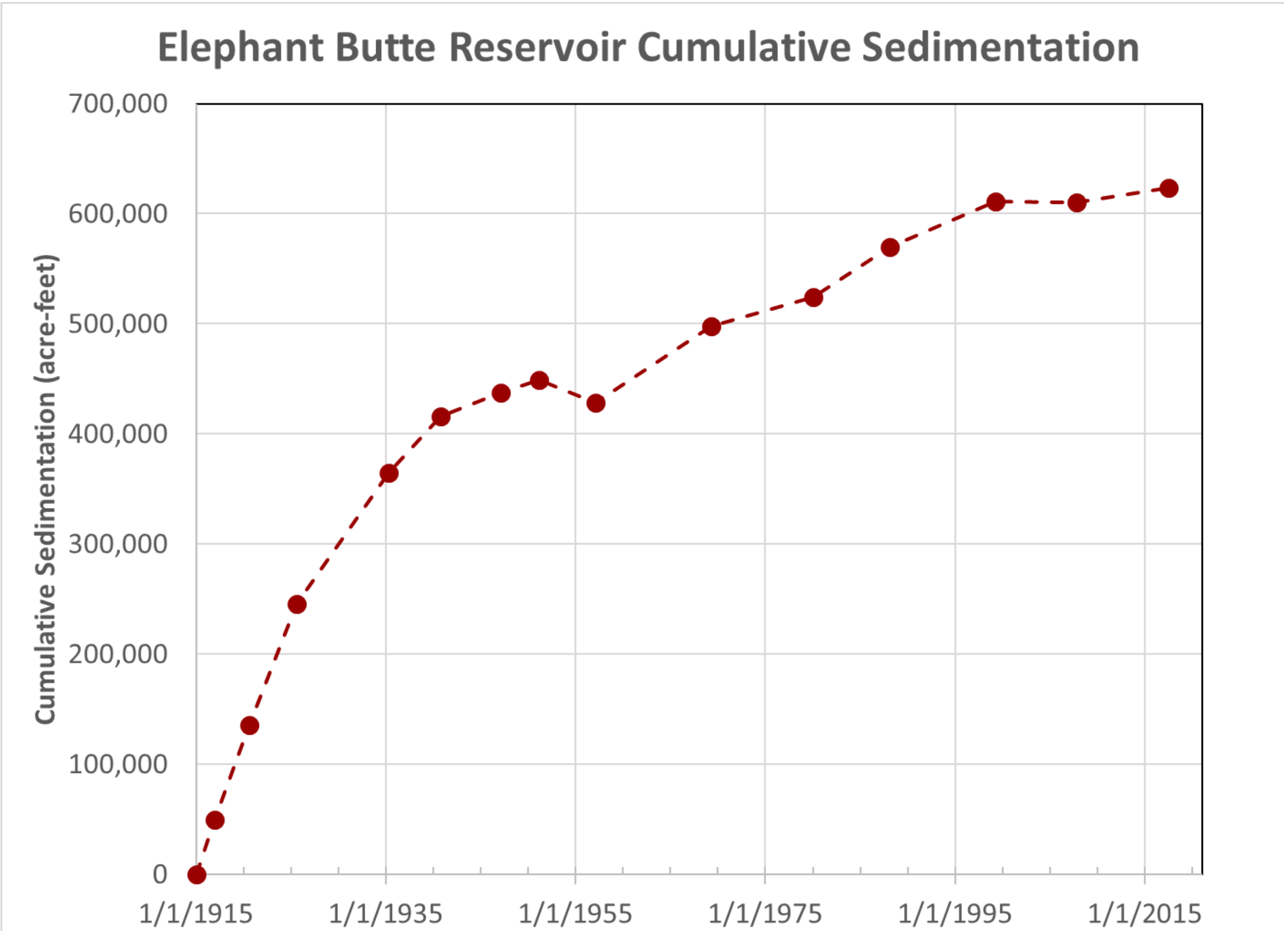

Figure 15. Cumulative sedimentation in Elephant Butte Reservoir over time.

Sedimentation accumulates along the entire reservoir length, at all reservoir elevations, and against Elephant Butte Dam (Figure 8). The early range-line surveys showed about 12 feet of variation in the lowest reservoir elevation (Figure 16). By the 1969 survey, sedimentation near the dam significantly increased the lowest reservoir bottom elevation and effectively eliminated the dead storage. The reservoir storage capacity below the power penstock invert has been decreasing over time (Figure 17). In the absence of reservoir sediment management, non-linear extrapolation of the trend line suggests that the storage capacity below the power penstock will be eliminated within the next two centuries. The reservoir dead storage has already been filled with sediment, so future sedimentation may reduce the reliability of the outlet works as large wood and sediment accumulate around the trash rack. This occurred at Paonia Reservoir near Paonia, CO (Collins and Kimbrel, 2015). Once sedimentation has reached the invert of the power penstock, additional sedimentation and large wood may reduce the reliability of the penstocks.

The National Reservoir Sedimentation and Sustainability Team (Randle, et al., 2019) has described methods to manage reservoir sedimentation. Even though the costs of sediment management may seem large, the cost of eventually losing the reservoir and all its benefits to sedimentation and the cost of constructing new reservoirs elsewhere may be much larger.

At the Cochiti Reservoir upstream of Elephant Butte, the delta may very well reach Cochiti Dam within the next century (Davis, et al., 2015 and Ramous-Villanueva, et al., 2019). As this happens, some of the Rio Grande sediment loads may pass through Cochiti Reservoir and subsequently increase the sediment loads to Elephant Butte Reservoir.

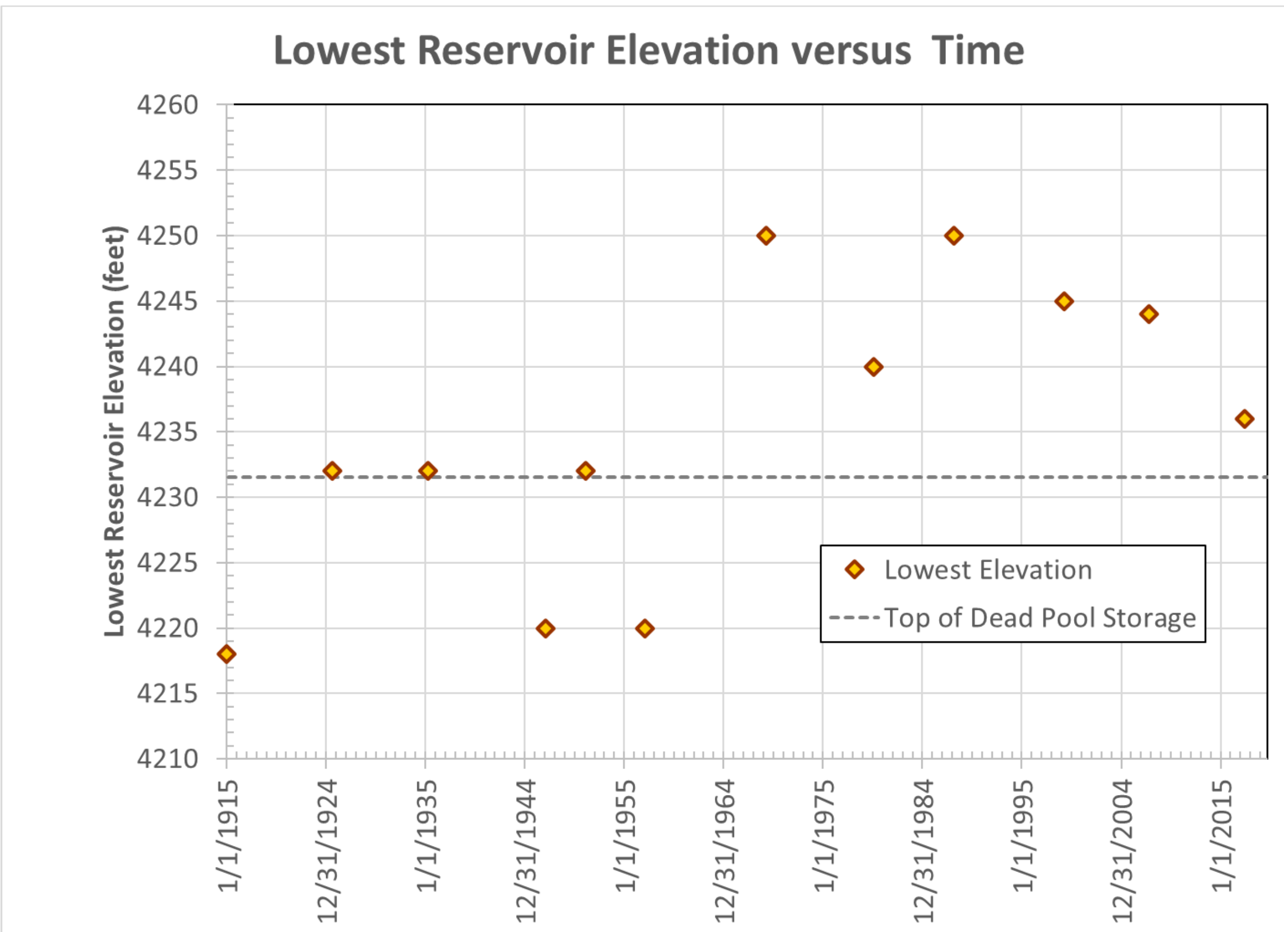

Figure 16. Sedimentation near the dam increase the lowest reservoir elevation over time.

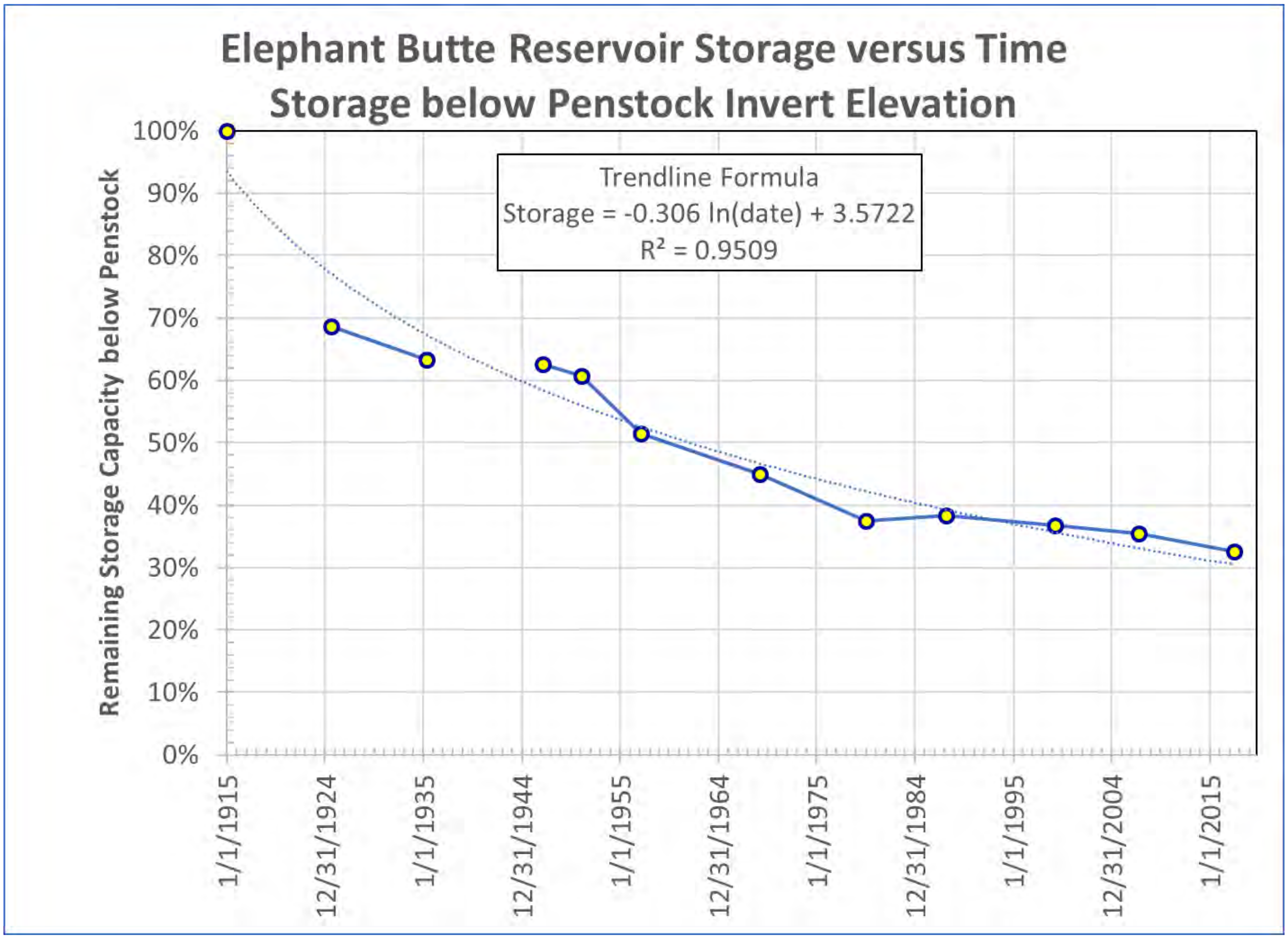

Figure 17. Sedimentation is reducing the reservoir storage capacity below the elevation of the power penstock over time. Extrapolation of the trendline suggests the storage capacity below the power penstock will be filled with sediment within the next two centuries.

9. Conclusions and Recommendations

The combined 2017 multibeam bathymetric survey and 2019 LiDAR survey of Elephant Butte Reservoir are the most comprehensive surveys yet performed. The 2017 and 2019 surveys provided near complete coverage of the reservoir and the digital surface was the most accurate to date. The 2007 multibeam bathymetric survey was comprehensive, but these data were combined with above water data from USGS quadrangle map contours for the downstream 4 miles of reservoir, 2004 LiDAR survey for the next 30 miles, and 2007 LiDAR survey for the remaining 8 miles of upstream reservoir.

9.1. Survey Methods and Data Analysis

Data from the June 2017 bathymetric survey and January 2019 LiDAR survey of the above-water topography were used to produce an accurate digital surface of the reservoir bottom. Surface elevations of the overlapping bathymetric and above-water topographic data agreed within ±0.1 to ±1.0 foot and most elevations agreed within ±0.4 foot.

Reservoir surface areas were computed from this digital surface at 1-foot intervals to determine the 2017 storage capacity. Surface area and storage capacity were then interpolated at 0.01-foot intervals. The difference in reservoir surfaces over time are largely attributed to sedimentation, and to the differences in survey methods beginning in 1957 and 2007.

9.2. Sedimentation Progression and Location

Over the span of 104 years (1915 to 2019), sedimentation has filled in 24 percent of the original storage capacity. The 2017 and 2019 reservoir survey indicates that sedimentation is located throughout the entire length of the reservoir and upstream from the reservoir pool. Sediment has deposited near the dam and filled the reservoir dead storage pool and two-thirds of the storage below the power penstock elevation. Without reservoir sediment management, extrapolation of historic sedimentation rates suggests that remaining storage below the power penstock will be lost within the next two centuries (see Section 8 Sedimentation Trends). Continued sedimentation and large wood may reduce the reliability of the dam outlet works long before the remaining storage below the power penstocks has completely filled with sediment.

9.3. Recommendation for Next Survey

Based on the past rates of sedimentation, the next survey of Elephant Butte Reservoir is recommended within the next decade (by 2029), after a 10-year flood peak on the Rio Grande, or after a large wildfire in the sediment-contributing watershed. The next reservoir survey should again employ a multibeam depth sounder for the bathymetric survey and LiDAR for the above-water topography. The bathymetric and LiDAR surveys should be conducted in the same water year if possible.

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Appendix A — Hydrographic Survey Equipment and Methods

The 2017 bathymetric survey was conducted from May 31 to June 8, 2017 using a multibeam depth sounder. During this period, reservoir water surface elevations varied from 4340.75 and 4341.45 feet (vertical RPVD), nearly 66 feet below the top of normal operations pool elevation of 4407 feet (RPVD).

The survey was conducted along a series of established range lines (cross sections), parallel longitudinal survey lines, and survey lines along the shorelines (Figure 6). In the downstream most 11 miles of the reservoir, the survey lines were spaced closely enough so there would be overlapping coverage from the multibeam depth sounder or nearly overlapping coverage that linear interpolation between survey lines would be adequate. In the upstream area of the reservoir pool, water depths were less than 50 feet and survey focused primarily on established range lines, shorelines, two longitudinal survey lines, and any areas deep enough for the survey boat to navigate. However, Elephant Butte Reservoir water levels decreased below 4300 feet (RPVD) during the LiDAR survey of January 2019 exposing the reservoir bottom upstream of the area densely surveyed by the multibeam depth sounder.

The bathymetric survey employed an 18-foot, flat-bottom aluminum Wooldridge boat powered by outboard jet and kicker motors (Figure A-1). Reservoir depths were measured using multibeam echo sounder which consisted of the following equipment:

- variable-frequency transducer with integrated motion reference unit,
- near-surface sound velocity probe,
- two GPS receivers to measure the boat position and heading,
- an external GSP radio,
- processor box for synchronization of all depth, sound velocity, position, heading, and motion sensor data, and
- laptop computer with hydrographic surveying software to collect and store the bathymetric data.

The multibeam transducer emits up to 512 beams (user selectable) capable of projecting a swath width up to 120 degrees in 390 feet (120 meters) of water. Sound velocity profiles were collected over the full water depth at various locations throughout the reservoir. These sound velocity profiles measure the speed of sound through the water column, which can be affected by multiple characteristics such as water temperature and salinity. These sound velocity profiles were used to calibrate the depth sounder during post-processing of the data.

RTK GPS survey instruments were used to continuously measure the survey boat position and to measure other ground control points. The GPS base station receiver and radio were set up on a tripod over two different points that overlooked the reservoir (Figure 6 and Figure). The coordinates of this point were computed using the Online Positioning User Service (OPUS) developed by the National Geodetic Survey (NGS) (www.ngs.noaa.gov/OPUS/). During the survey, position corrections were transmitted to the GPS rover receiver using an external GPS radio and UHF antenna (Figure 19). The base station was powered by a 12-volt battery.

A-1. Wooldridge boat with RTK-GPS and multibeam depth sounder system.

Figure A-2. The RTK-GPS base station set-up used during the survey Flaming Gorge Reservoir in Utah and Wyoming is typical of the set up used for other reservoir surveys.

The GPS rover receivers include an internal or external radio and external antenna mounted on a range pole (ground survey) or survey boat (bathymetric survey). The rover GPS units receive the same satellite positioning data as the base station receiver, and at the same time. The rover units also receive real-time position correction information from the base station via radio transmission. This allows rover GPS units to measure accurate positions with precisions of ±2 cm horizontally and ±3 cm vertically for stationary points. Positions measured on a moving survey boat are less accurate (perhaps within ±20 cm).

During the survey, a laptop computer was connected to the GPS rover receivers and echo sounder system. Corrected positions from one GPS rover receiver and measured depths from the multibeam transducer were transmitted to the laptop computer through cable connections to the processor box. Using real-time GPS coordinates, the HYPACK software provided navigational guidance to the boat operator to steer along the predetermined survey lines.

The HYPACK hydrographic survey software was used to combine horizontal positions and depths to map the reservoir bathymetry in North American Datum 1983 (NAD 1983) State Plane (horizontal) coordinates, New Mexico West Zone FIPS 3003, US survey feet and North American Vertical Datum 1988 (NAVD 1988, Geoid 12A, US survey feet elevations. Water surface elevations from dam gage records and RTK GPS measurements were used to convert the sonar depth measurements to reservoir-bottom elevations in the RPVD. The multibeam depth sounder generated over 100 million data points. A small portion of depth measurements did not represent the reservoir bottom and these data are deleted during post processing. Final processing of the bathymetric data resulted in 50 million to 100 million data points used in the development of the reservoir surface. Filtering of the large data file was necessary, so a raster mesh was created in GIS using 5-foot square cells. For each raster mesh cell, the reservoir bottom elevation was assigned equal to the median elevation of all available data points within that raster cell. The use of the median value reduces the influence of the highest and lowest elevations measured within the cell.

Appendix B — Above Water Survey Methods

A LiDAR survey of Elephant Butte Reservoir was conducted January 17, 2019 when the reservoir water surface was 4300.7 feet elevation (RPVD), which exposed the reservoir bottom upstream from range line 70 (8.5 miles upstream from Elephant Butte Dam). The LiDAR data were used to represent the above-water reservoir topography.

The LiDAR were collected in the North American Datum of 1983 (2011), State Plane New Mexico Central horizontal coordinate system. Elevations were in the North American Vertical Datum of 1988, geoid model: Geoid12B. The LiDAR data were converted to New Mexico West Zone and RPVD to match the 2017 bathymetric horizontal and vertical datums, respectively. The LiDAR point cloud statistics are presented in Table B-1.

Table B-1. LiDAR point cloud statistics.

Category	Value
Total Points	9,696,535,958
Nominal Pulse Spacing (m)	0.4084
Nominal Pulse Density (pls/m²)	6.00
Nominal Pulse Spacing (ft)	1.3398
Nominal Pulse Density (pls/ft²)	0.56
Aggregate Total Points	9,327,447,192
Aggregate Nominal Pulse Spacing (m)	0.2941
Aggregate Nominal Pulse Density (pls/m²)	11.56
Aggregate Nominal Pulse Spacing (ft)	0.9648
Aggregate Nominal Pulse Density (pls/ft²)	1.07

Between June 2017 and January 2019, reservoir elevations decreased to a low of 4285 feet (RPVD). Even though reservoir inflows did not exceed 3,200 ft^3/s and were generally less than 500 ft^3/s (Figure B-1), some erosion of the exposed reservoir delta likely eroded in response to the reservoir draw down. Most of this eroded sediment likely redeposited in the receded reservoir pool.

Survey elevations of overlapping bathymetric and LiDAR data agreed within ±0.1 to ±1.0 foot and most elevations agreed within ±0.4 foot. Once the general agreement between bathymetric and LiDAR data was verified, the LiDAR data were used instead of the bathymetric data to develop the digital surface in overlapping areas of the reservoir.

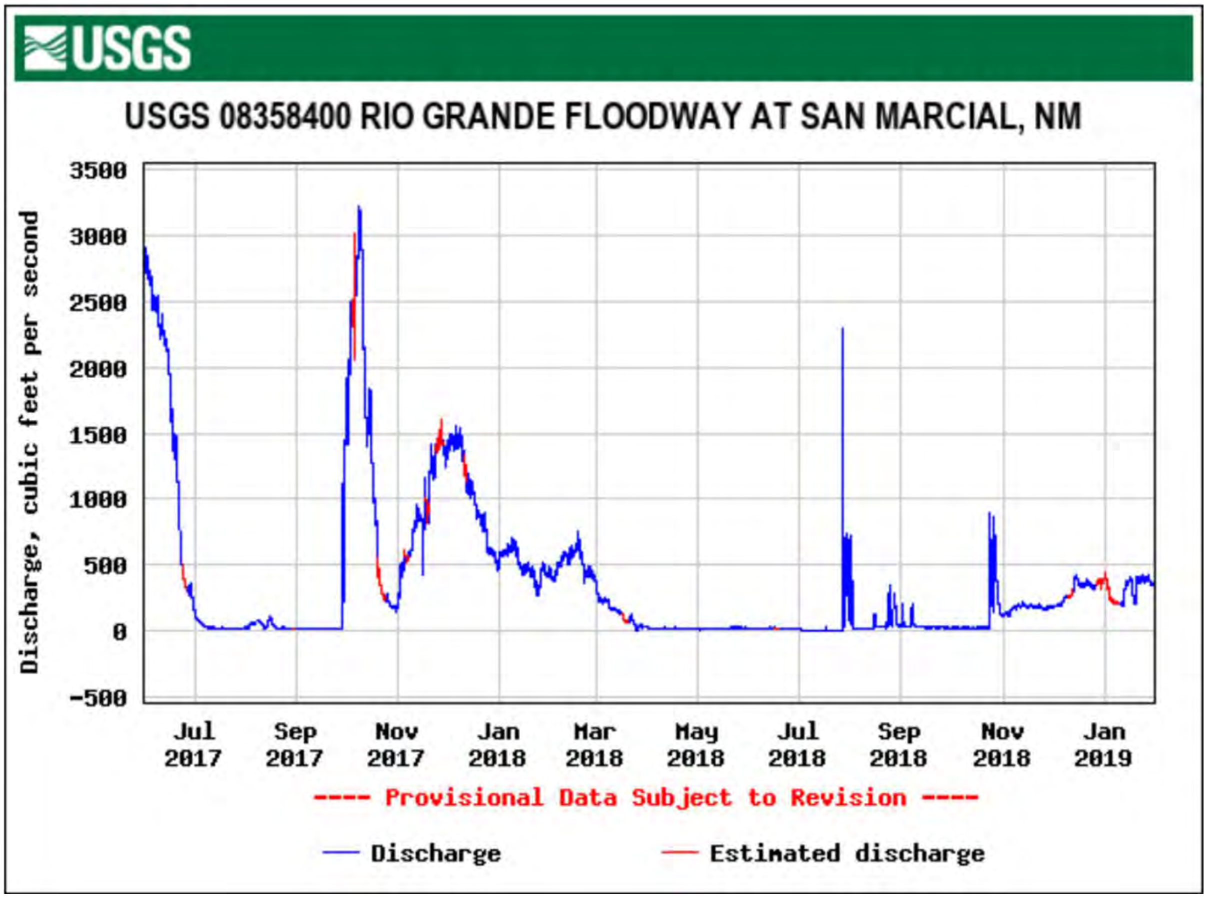


Figure B-1. Discharge hydrograph of the Rio Grande Floodway at San Marcial, NM between the bathymetric survey (June 2017) and LiDAR survey (January 2019).

Appendix C — Computation of Reservoir Surface Area, Storage Capacity, and Sedimentation Volume

A digital surface of the reservoir bottom was generated in GIS using the processed bathymetric data points (easting, northing, and elevation) combined with available above-water data. Horizontal surface areas were then computed at 2-foot increments, using functions within ArcGIS Pro, for the complete range of remaining reservoir elevations (4234 to 4412 feet, RPVD). These reservoir surface areas were then used in Reclamation's Area-Capacity (ACAP) Program, 1985 Version (Reclamation, 1985), to compute the storage capacity at these increments and then interpolate surface areas and storage capacities at 0.01-foot increments between each 1-foot interval.

The program uses the least squares method to predict the reservoir storage capacity between 2-foot intervals using the following equation over a certain elevation interval:

$$V = A_1 + A_2(y - y_b) + A_3(y - y_b)^2$$

where: V = storage capacity (acre-feet)
y = reservoir elevation
y_b = reservoir elevation at bottom of elevation increment
A_1 = intercept and storage capacity at elevation y_b (acre-feet)
A_2 = surface area at elevation y_b (acres) and coefficient for linear rate of increase in storage capacity
A_3 = coefficient (feet) for nonlinear rate of increase in storage capacity

The reservoir surface area is computed from the derivative of the volume equation:

$$S = A_2 + 2A_3(y - y_b)$$

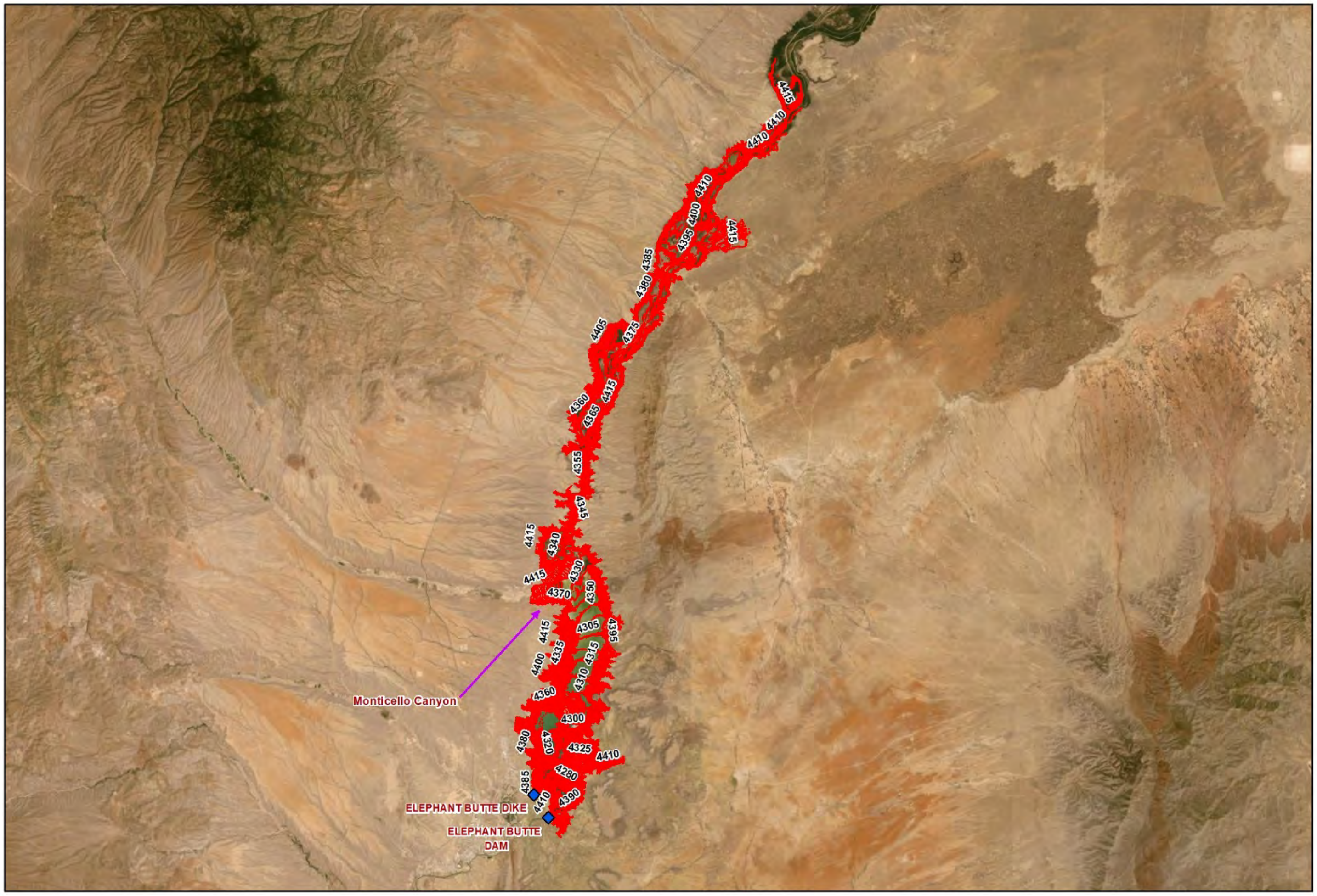
where: S = surface area (acres)

This method ensures that the given surface areas, and corresponding storage capacities, at the 2-foot intervals are not changed and there is a smooth transition in the interpolated values at the 0.01-foot intervals. The ACAP program produces the area and capacity tables for the full range of reservoir elevations. These data are documented in the report (Reclamation, 2019).

The sedimentation volumes were computed by subtracting the 2017 and 2019 storage volume curve (produced from the 2017 and 2019 surface) from the 1915 storage volume curve (representing the predam surface) and from the 2007 storage volume curve.

Appendix D — Contour Maps

An overview contour map of Elephant Butte Reservoir and seven more detailed 10-foot and 5-foot interval contour maps are presented in this Appendix.



Elephant Butte Reservoir New Mexico Elevation Contour Map

Overview Map

Horizontal Datum Based on NAD83 (2011) State Plane Coordinates
New Mexico West Zone FIPS 3003
US Survey Feet

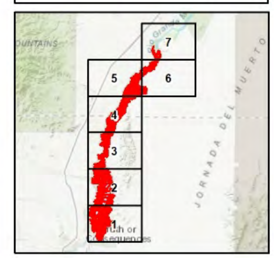
Vertical Datum Based on Water Surface Elevation Gage at Elephant Butte Dam Referenced to Reclamation Project Vertical Datum (RPVD)
NAVD88 – RPVD = 45.02 sft
NAVD88 – NGVD29 = 2.14 sft

Primary Data Source:
2017 Elephant Butte Reservoir Study

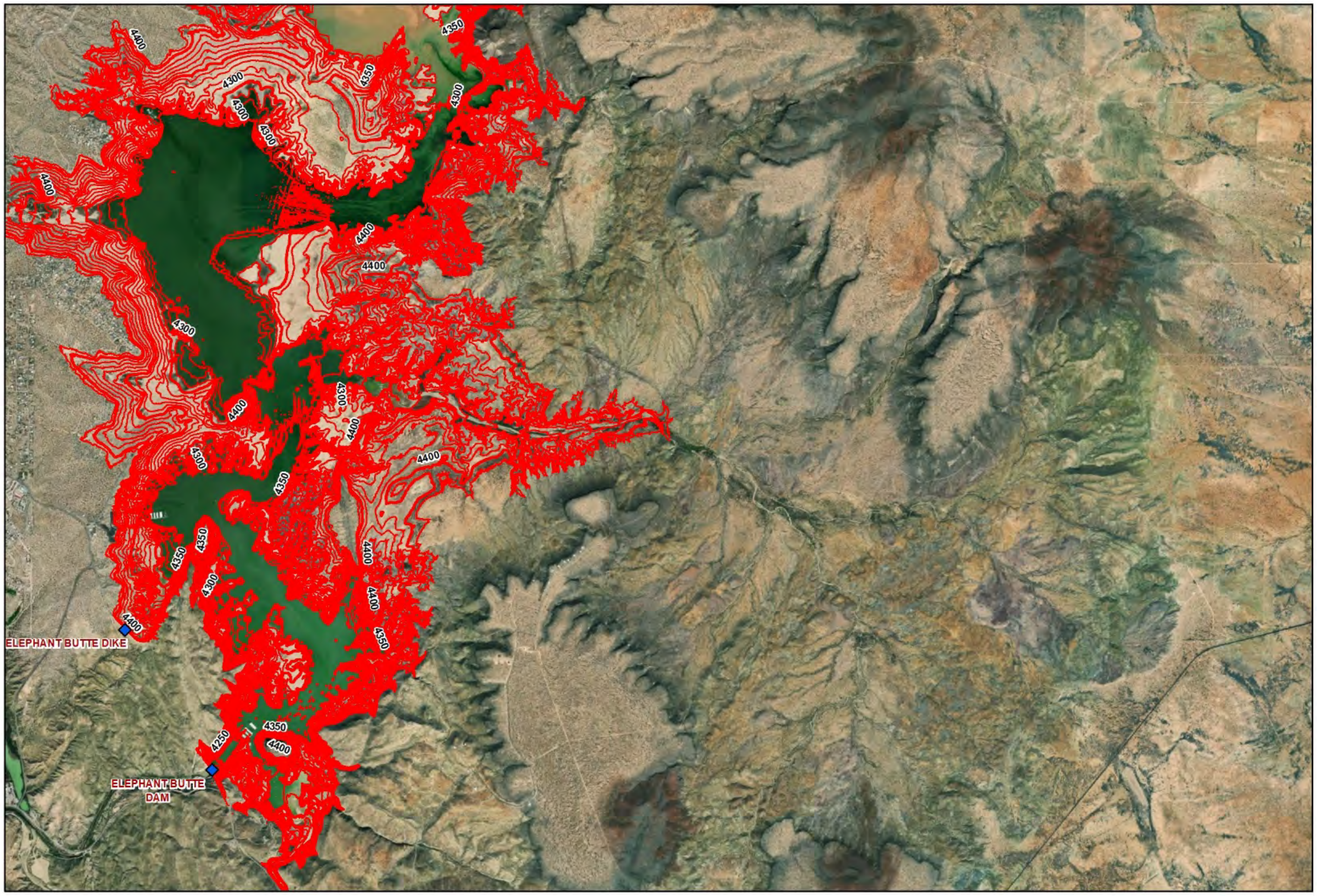
N

Scale 1:275,000

0 21,000 42,000 Feet



Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Sources: Esri, HERE, Garmin, Intermap,



Elephant Butte Reservoir New Mexico Elevation Contour Map

Sheet 1

Horizontal Datum Based on NAD83 (2011) State Plane Coordinates New Mexico West Zone FIPS 3003 US Survey Feet

Vertical Datum Based on Water Surface Elevation Gage at Elephant Butte Dam Referenced to Reclamation Project Vertical Datum (RPVD)
NAVD88 – RPVD = 45.02 sft
NAVD88 – NGVD29 = 2.14 sft

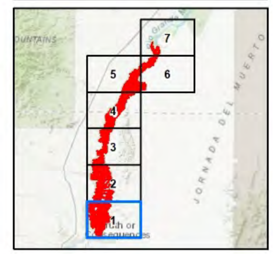
Ten Foot Contour Interval

Primary Data Source:
2017 Elephant Butte Reservoir Study

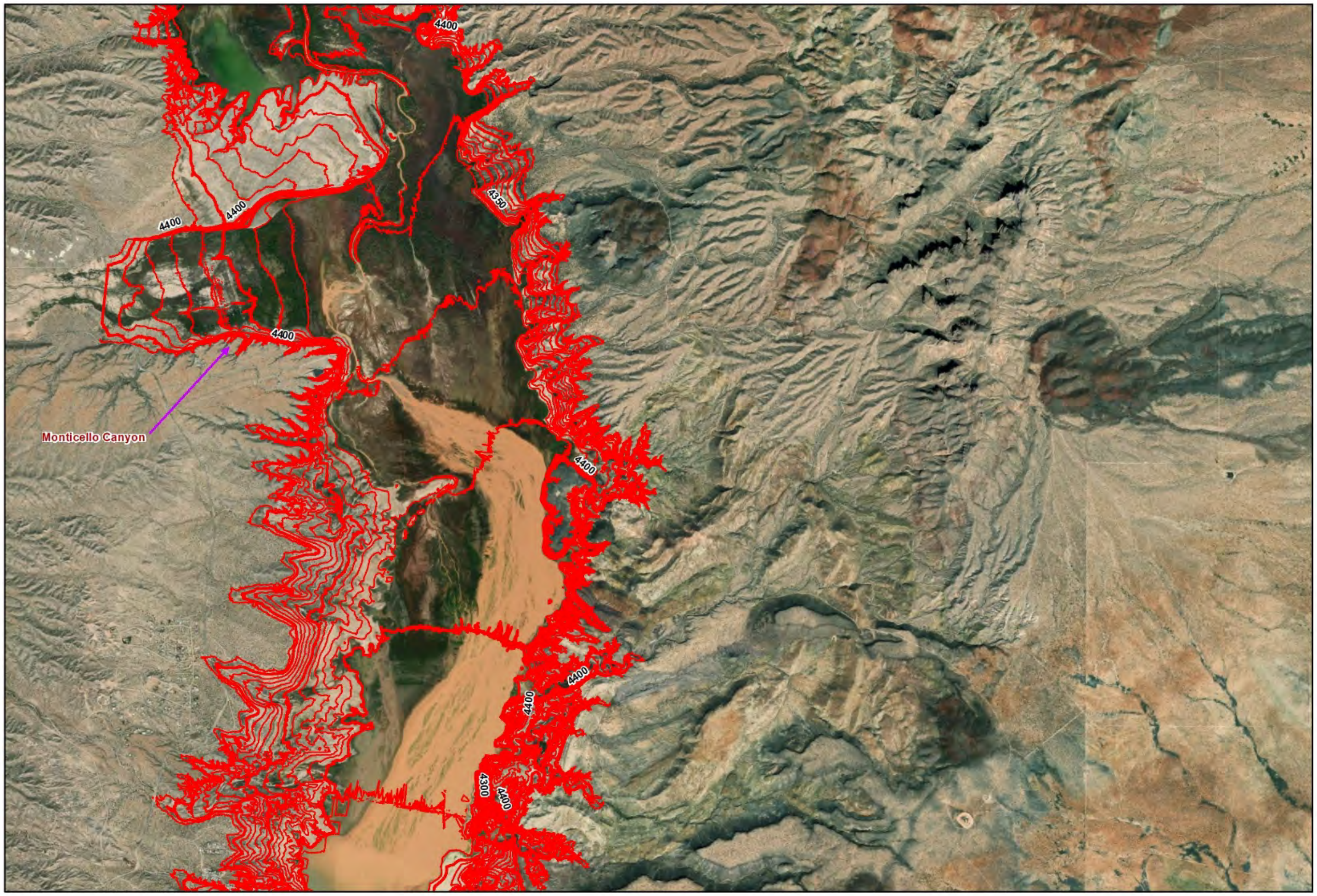
N

Scale 1:45,000

0 3,500 7,000 Feet



Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Sources: Esri, HERE, Garmin, Intermap,



Elephant Butte Reservoir New Mexico Elevation Contour Map

Sheet 2

Horizontal Datum Based on NAD83 (2011) State Plane Coordinates New Mexico West Zone FIPS 3003 US Survey Feet

Vertical Datum Based on Water Surface Elevation Gage at Elephant Butte Dam Referenced to Reclamation Project Vertical Datum (RPVD)
NAVD88 – RPVD = 45.02 sft
NAVD88 – NGVD29 = 2.14 sft

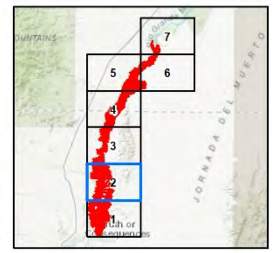
Ten Foot Contour Interval

Primary Data Source:
2017 Elephant Butte Reservoir Study

N

Scale 1:45,000

0 3,500 7,000 Feet



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Sources: Esri, HERE, Garmin, Intermap,

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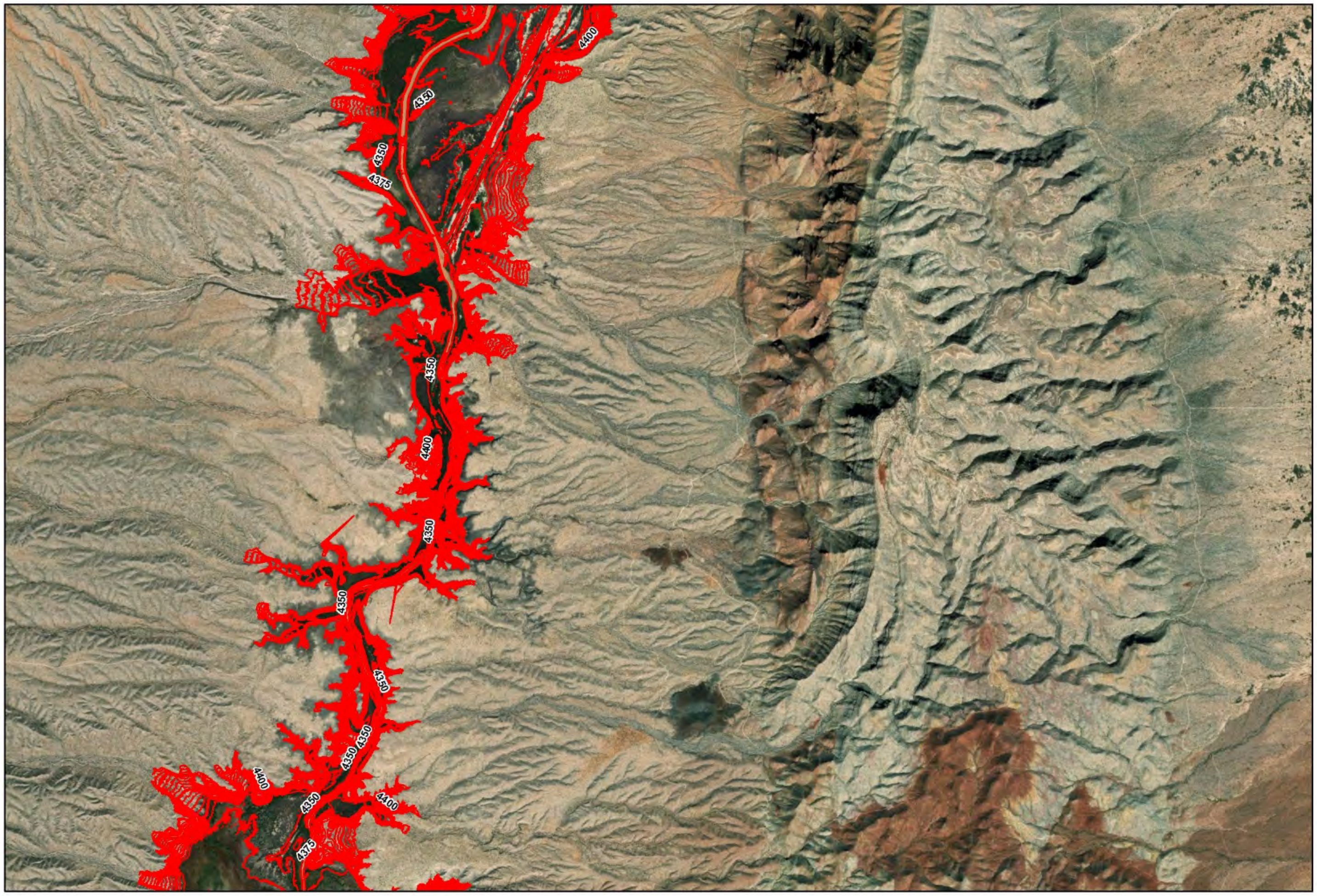


Elephant Butte Reservoir New Mexico Elevation Contour Map

Sheet 3

Horizontal Datum Based on NAD83 (2011) State Plane Coordinates
New Mexico West Zone FIPS 3003
US Survey Feet

Vertical Datum Based on Water Surface Elevation Gage at Elephant Butte Dam Referenced to Reclamation Project Vertical Datum (RPVD)
NAVD88 – RPVD = 45.02 sft
NAVD88 – NGVD29 = 2.14 sft

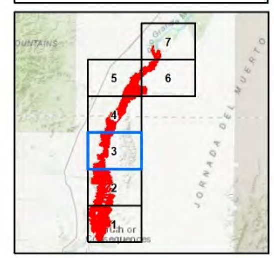
Five Foot Contour Interval

Primary Data Source:
2017 Elephant Butte Reservoir Study

N

Scale 1:45,000

0 3,500 7,000 Feet



Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
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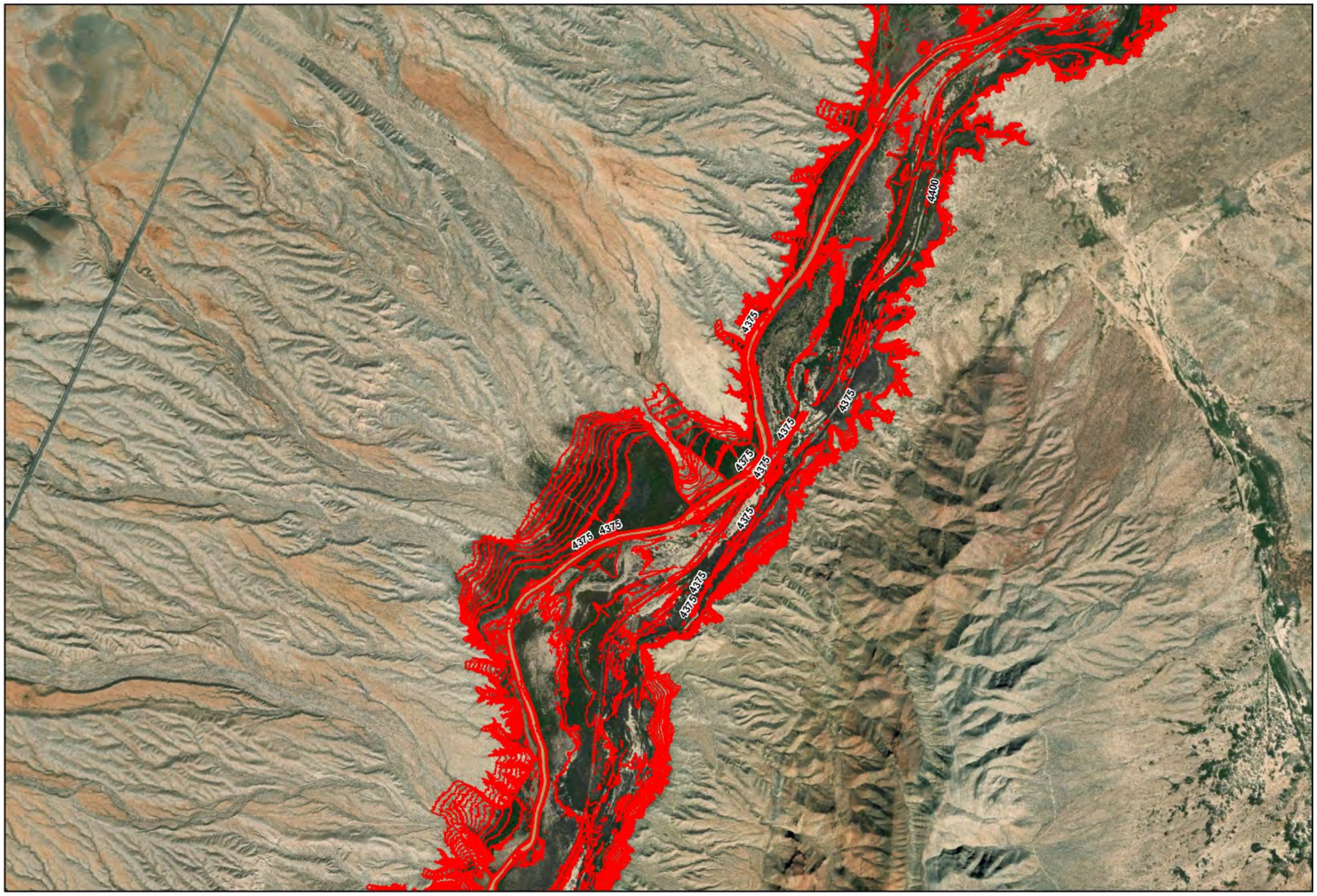


Elephant Butte Reservoir New Mexico Elevation Contour Map

Sheet 4

Horizontal Datum Based on NAD83 (2011) State Plane Coordinates
New Mexico West Zone FIPS 3003
US Survey Feet

Vertical Datum Based on Water Surface Elevation Gage at Elephant Butte Dam Referenced to Reclamation Project Vertical Datum (RPVD)
NAVD88 – RPVD = 45.02 sft
NAVD88 – NGVD29 = 2.14 sft

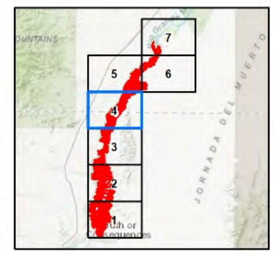
Five Foot Contour Interval

Primary Data Source:
2017 Elephant Butte Reservoir Study

N

Scale 1:45,000

0 3,500 7,000 Feet



Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Sources: Esri, HERE, Garmin, Intermap,

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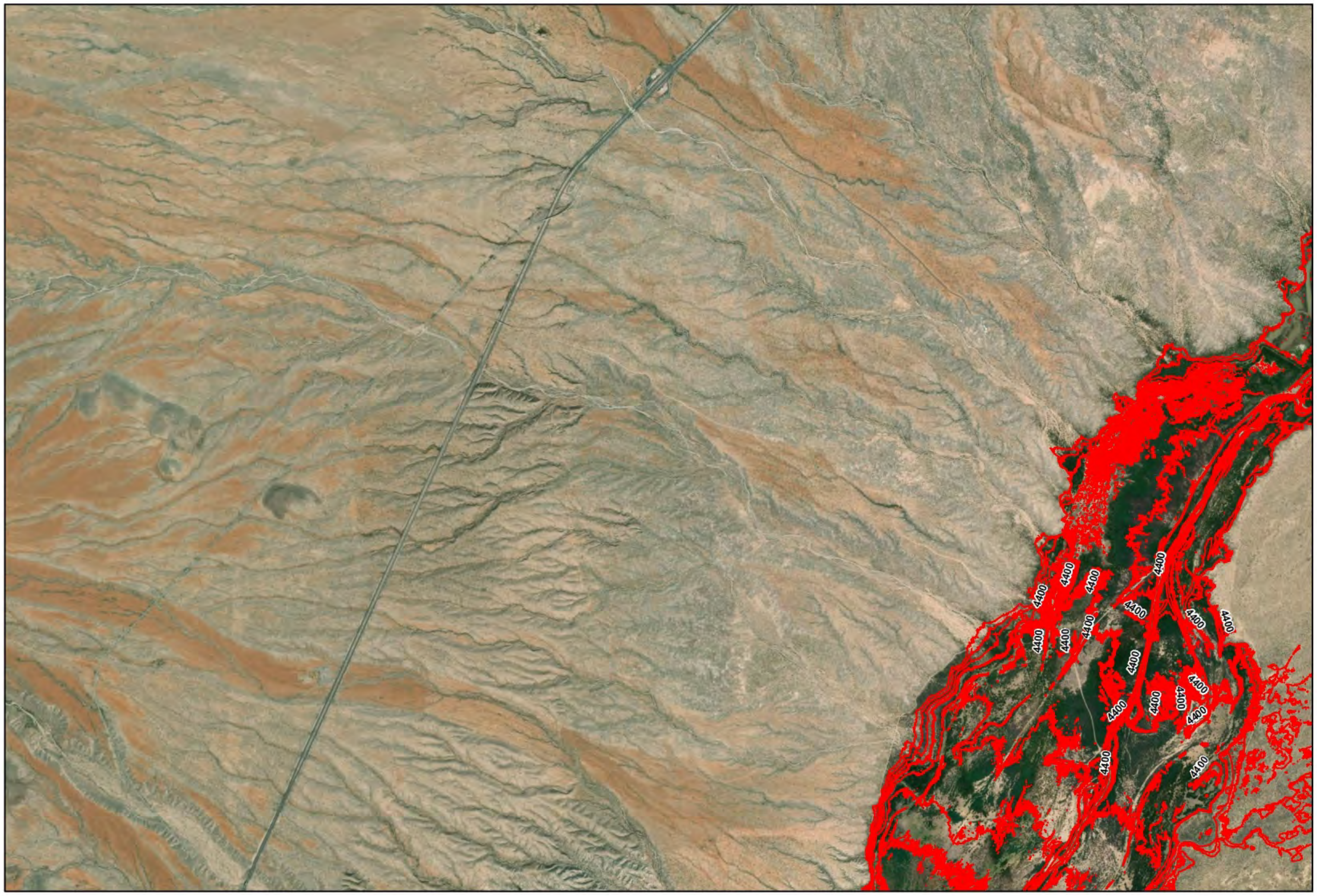


Elephant Butte Reservoir New Mexico Elevation Contour Map

Sheet 5

Horizontal Datum Based on NAD83 (2011) State Plane Coordinates New Mexico West Zone FIPS 3003 US Survey Feet

Vertical Datum Based on Water Surface Elevation Gage at Elephant Butte Dam Referenced to Reclamation Project Vertical Datum (RPVD)
NAVD88 – RPVD = 45.02 sft
NAVD88 – NGVD29 = 2.14 sft

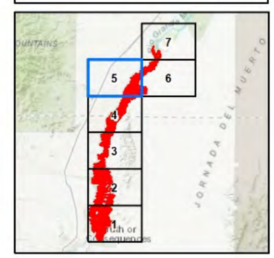
Five Foot Contour Interval

Primary Data Source:
2017 Elephant Butte Reservoir Study

N

Scale 1:45,000

0 3,500 7,000 Feet



Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Sources: Esri, HERE, Garmin, Intermap,

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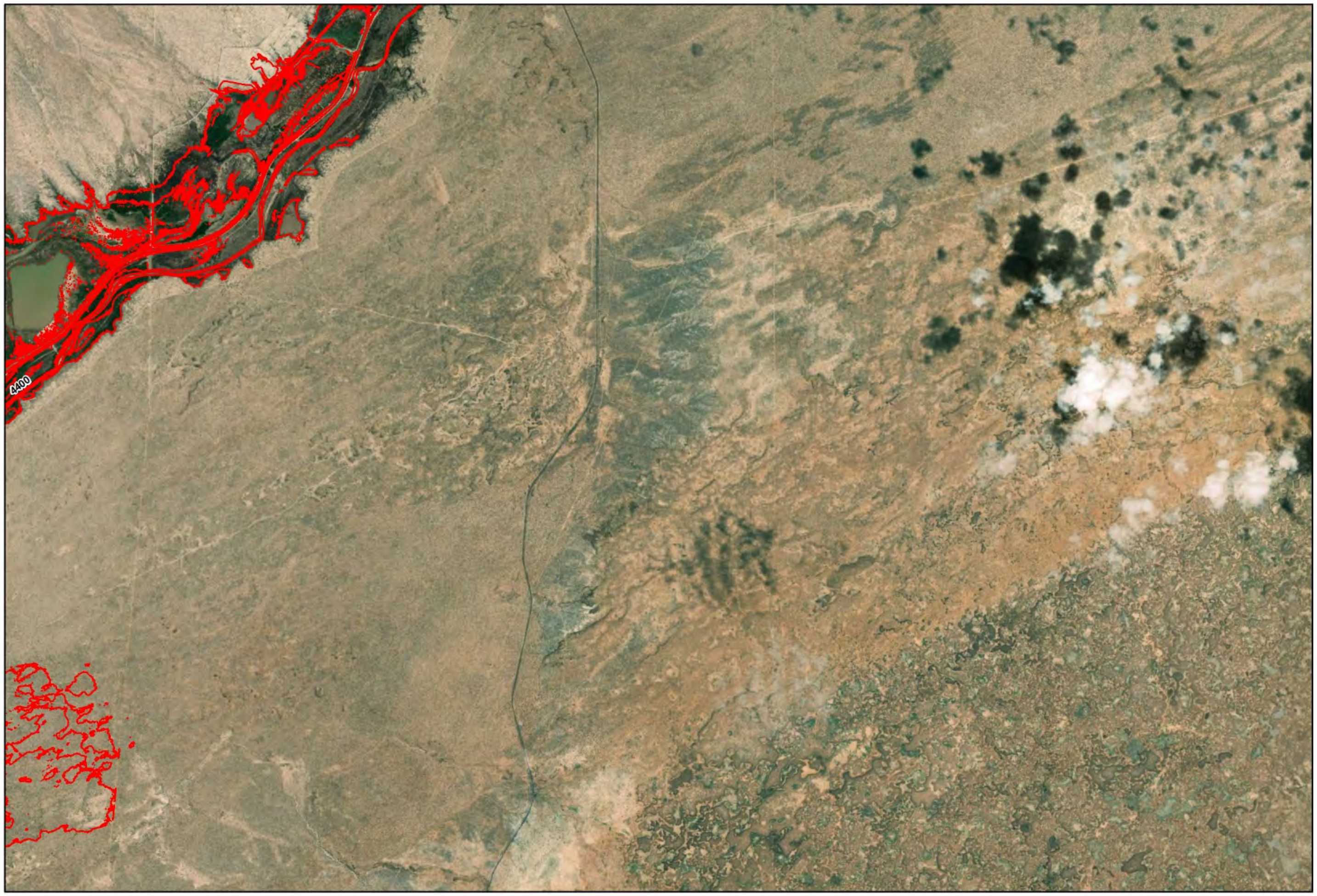


Elephant Butte Reservoir New Mexico Elevation Contour Map

Sheet 6

Horizontal Datum Based on NAD83 (2011) State Plane Coordinates New Mexico West Zone FIPS 3003 US Survey Feet

Vertical Datum Based on Water Surface Elevation Gage at Elephant Butte Dam Referenced to Reclamation Project Vertical Datum (RPVD)
NAVD88 – RPVD = 45.02 sft
NAVD88 – NGVD29 = 2.14 sft

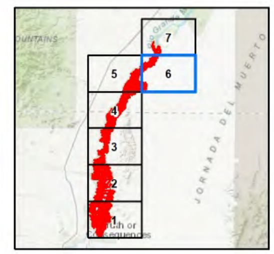
Five Foot Contour Interval

Primary Data Source:
2017 Elephant Butte Reservoir Study

N

Scale 1:45,000

0 3,500 7,000 Feet



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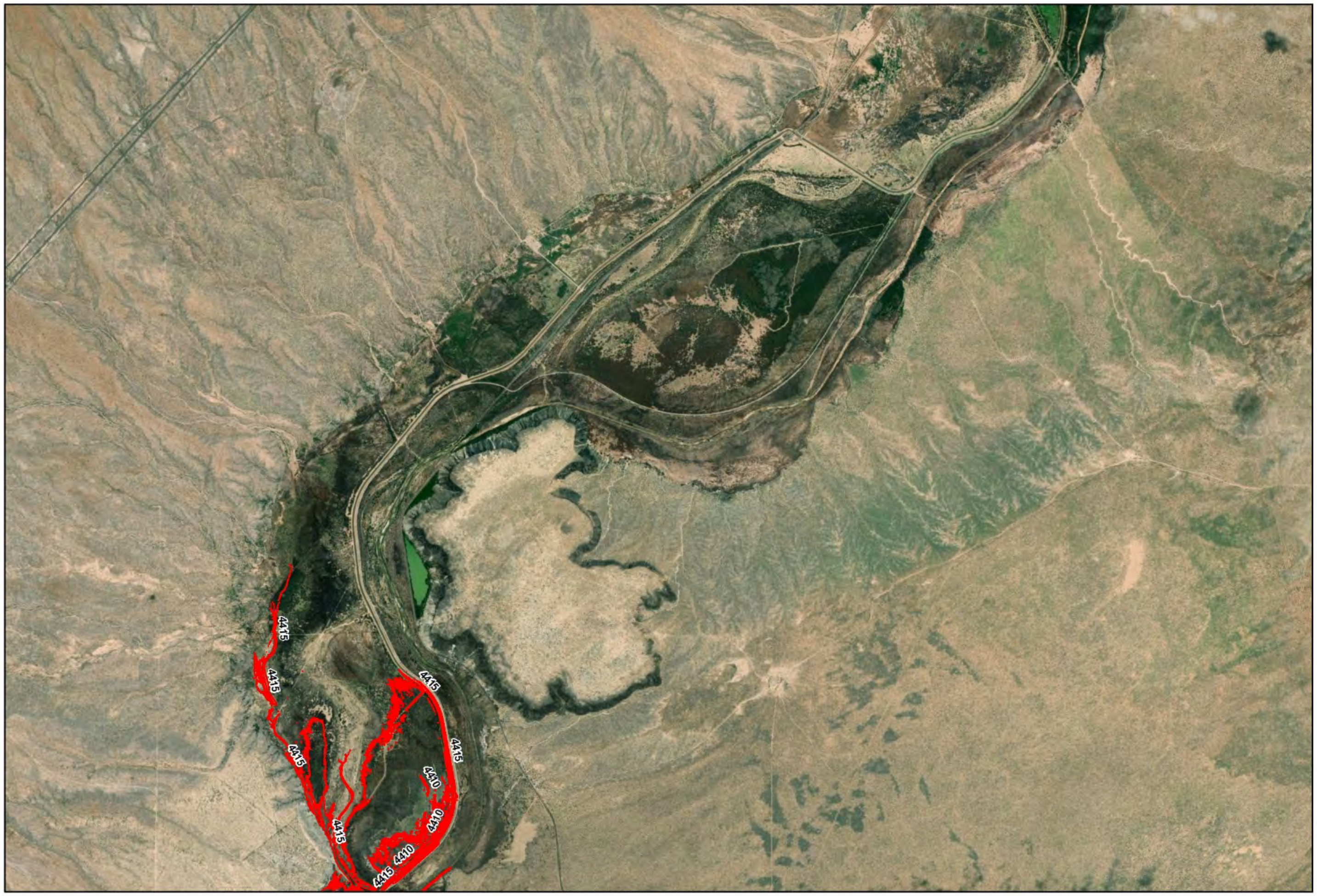


Elephant Butte Reservoir New Mexico Elevation Contour Map

Sheet 7

Horizontal Datum Based on NAD83 (2011) State Plane Coordinates
New Mexico West Zone FIPS 3003
US Survey Feet

Vertical Datum Based on Water Surface Elevation Gage at Elephant Butte Dam
Referenced to Reclamation Project Vertical Datum (RPVD)
NAVD88 – RPVD = 45.02 sft
NAVD88 – NGVD29 = 2.14 sft

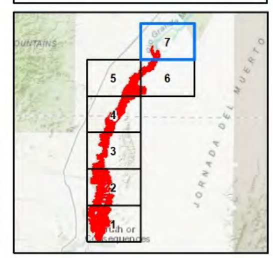
Five Foot Contour Interval

Primary Data Source:
2017 Elephant Butte Reservoir Study

N

Scale 1:45,000

0 3,500 7,000 Feet



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Sources: Esri, HERE, Garmin, Intermap,