Technical Report No. ENV-2020-010

Turquoise Lake 2017 Sedimentation Survey

Fryingpan-Arkansas Project, Colorado
Great Plains Region

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

February 2020

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Acknowledgements

Kent Collins, Robert Hilldale and Caroline Ubing from the Bureau of Reclamation's (Reclamation) Sedimentation and River Hydraulics Group at the Technical Service Center (TSC) conducted this survey in June of 2017. Vince Benoit completed the data processing and generated the surface presented in this report. Funding for this survey was provided by the Great Plains Regional Office.

Disclaimer

Cover: Turquoise Lake, looking downstream. Photo credit: Caroline Ubing.

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14. SHORT ABSTRACT The 2017 multibeam bathymetric survey of Turquoise Lake was combined with 2010 LiDAR and a tile from the National Elevation Dataset (15 foot grid resolution) to produce a combined digital surface of the reservoir bottom. Analysis of this data indicates that at the top of the surcharge pool elevation (9,872.8 feet, project vertical datum), the reservoir would have a surface area of 1,807 acres and a storage capacity of 136,265 acre-feet. Since the original filling in 1968 the reservoir is estimated to have lost storage capacity due to sedimentation. However, we cannot measure the change in storage area due to lack of repeat surveys using comparable survey techniques. We recommend a repeat survey in ten years to measure sediment accumulation rates, spatial distribution of deposited sediment and risk of sediment impacting reservoir operations.						
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Turquoise Lake 2017 Sedimentation Survey

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Acronyms and Abbreviations

ACAP	Reclamation's Area-Capacity program
cfs	cubic feet per second
DOI	Department of the Interior
ft	foot (feet)
GIS	Geographic Information System
GPS	Global Positioning System
HUC	Hydrologic Unit Code
LiDAR	Light Detection and Ranging
m	meters
mi^2	square miles
NAD 1983	North American Datum, established 1983
NAVD 1988	North American Vertical Datum, established 1988
NED	National Elevation Dataset
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
%	Percent
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

Sugar Loaf Dam and Turquoise Lake is on Lake Fork Creek approximately 5 miles west of Leadville, Colorado.

A bathymetric survey of Turquoise Lake was conducted in 2017 with these primary objectives:

1. Estimate reservoir sedimentation volume since the original reservoir filling began in 1968 and
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 Turquoise Lake was combined with 2010 LiDAR and 15 foot grid cell resolution (1/9 arc-second) National Elevation Dataset (DEM) data (USGS, 2014 and USGS, 2012; respectively) to produce a combined digital surface of the reservoir bottom.

This survey was conducted between June 23, 2017 and June 26, 2017 when the reservoir water surface elevation ranged between 9,858.9 and 9,860.5 feet (vertical project datum), 5.4 feet below the top of conservation pool elevation of 9,869.4 feet. The above-water topographic data were measured in 2010.

Analysis of the combined data sets indicates the following results:

- At top of the conservation pool water surface elevation of 9,869.4 feet (RPVD), which is approximately the same water surface elevation at the time of the survey, the reservoir surface area was 1,779 acres with a storage capacity of 130,169 acre-feet.

- At the maximum water surface elevation (9,872.8 feet, RPVD), the reservoir would have a surface area of 1,807 acres and a storage capacity of 136,265 acre-feet.

- While we can assume that sediment accumulation has occurred in Turquoise Lake since its filling in 1968, the loss in storage is smaller than the error between the two surveys and cannot be determined. A repeat survey is recommended by 2027 to quantify the basin's annual sediment yield and determine spatial deposition patterns.

- Additionally, no change in reservoir storage could be detected between the original and 2017 survey, the reduction in the dead storage pool volume is also unknown. However, the lowest elevation that was surveyed, which was against or near the dam, corresponds to the original design elevation. Therefore, the entire dead pool storage area is assumed to be available. The depth of sediment within the dead storage pool can determine the risk of sediment impacting the outlet structure, which can impact reservoir operations. A better understanding of reservoir sedimentation in Turquoise Lake will inform the reservoir's expected useful life.

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	Turquoise Lake	Region	Great Plains
Owner	Bureau of Reclamation	Area Office	Eastern Colorado
Stream	Lake Fork Creek	Vertical Datum	RPVD (0.31 feet above NGVD29)
County	Lake	Top of Dam (ft)	9879.0
State	Colorado	Spillway Crest (ft)	9869.4
Lat (deg min sec)	39 15 13.7	Power Penstock Elevation (ft)	
Long (deg min sec)	106 22 24.1	Low Level outlet (ft)	9770.0
HUC4	1102	Total Drainage Area (mi^2)	27.5
HUC8	11020001	Date storage began	1969
NID ID	CO01669	Date for normal operations	1969
Dam Purpose	water storage, recreation, municipal, and irrigation		

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	9872.8	1,816	6,127	135,525
CONSERVATION	9869.4	1,789	120,478	129,398
INACTIVE	9775.4	709	6,110	8,920
DEAD	9765.9	542	2,810	2,810

Survey Summary

Survey Date	Type of Survey	No. of Range lines or Contour Intervals	Contributing Sediment Drainage Area (mi^2)	Period Sediment-ation Volume (acre-feet)	Cumulative Sediment-ation (acre-feet)	Lowest Reservoir Elevation (feet)	Remaining Portion of Dead Storage (%)
1964	Unknown	5-ft	27.5			9750	100%
2017	Multibeam	1-ft	27.5	-740	-740	9750	>100%

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1. Introduction

Sugar Loaf Dam and Turquoise Lake are on the Lake Fork Creek approximately 5 miles west of Leadville, Colorado (Figure 1). The dam and reservoir are operated by the Eastern Colorado Area Office as part of the Fryingpan-Arkansas Project that supplies municipal and irrigation water to the Eastern Slope. Sugar Loaf Dam regulates water flowing from the Charles H. Boustead Tunnel before it enters the Mt. Elbert Conduit. Water is also used for recreation and fish and wildlife enhancement (Reclamation, 2005).

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. Reservoir sedimentation affects all elevations of the reservoir, even above and upstream of the full pool elevations. 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. These data provides information for forecasting when important dam and reservoir facilities will be impacted by sedimentation.

Sugar Loaf Dam was built on top of an existing dam. Historic USGS topographic maps show that the original structure was built between 1891 and 1949 (Figure 2). The exact date is unknown. The reservoir behind the original dam extended approximately 2.5 miles, whereas the current reservoir extends almost 5 miles. A topographic feature exists at the upstream end of the historic reservoir. This feature may be sediment deposits from the historic river delta or a natural geologic feature.

As part of ongoing operations and sediment monitoring activities, the Great Plains Regional 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 June 23, 2017 to June 26, 2017 with these primary objectives:

1. Estimate reservoir sedimentation volume since the original reservoir filling began in 1968 and

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

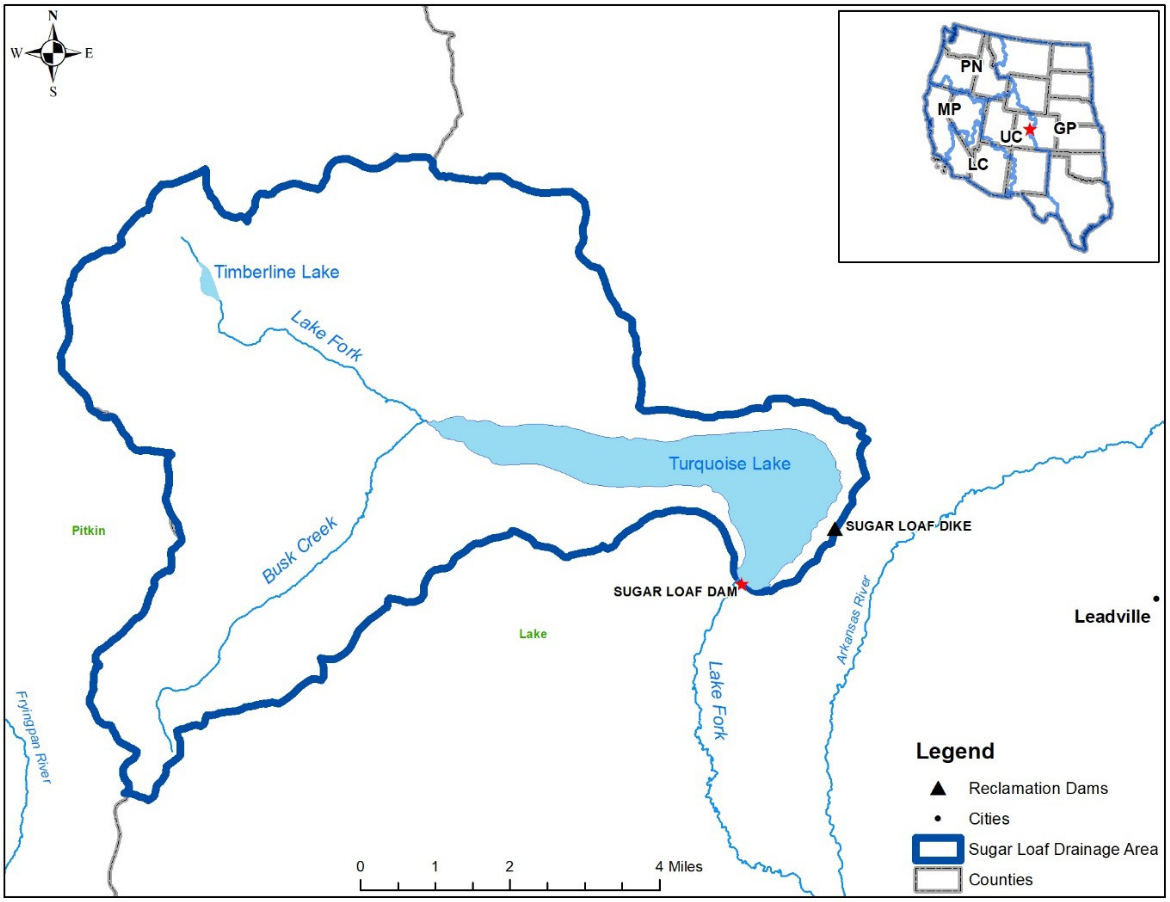

Figure 1. Location map of Sugar Loaf Dam and Turquoise Lake, 5 miles west from Leadville, CO.

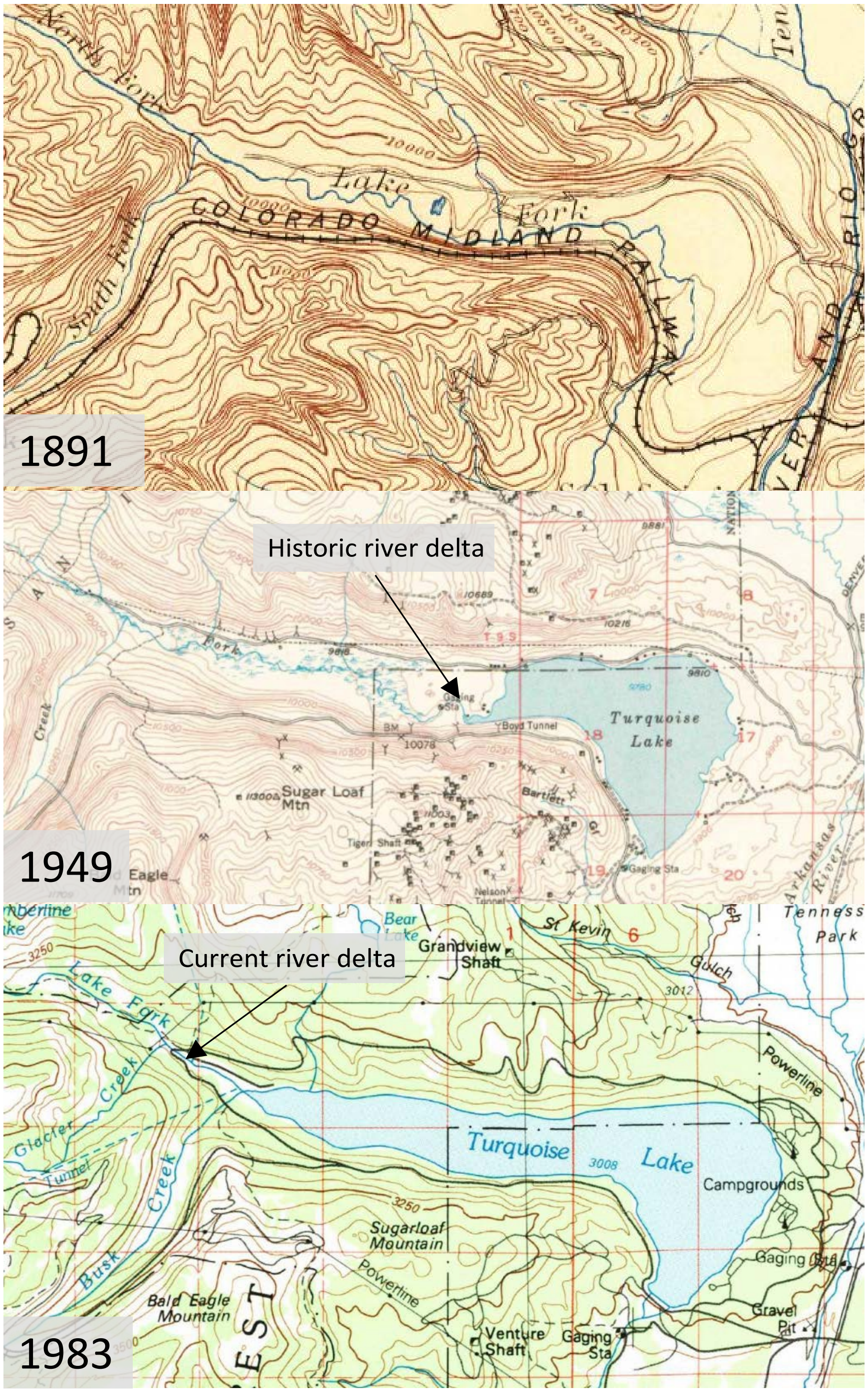

Figure 2. Historic USGS topographic maps giving evidence to a dam built prior between 1891 and 1949. Note the location of the historic and current river delta.

2. Watershed Description

The watershed upstream from Sugar Loaf Dam has a total contributing drainage area of 27.5 square miles (mi^2). Due to the lack of upstream lakes and reservoirs that trap sediment (as of 2019), the net sediment-contributing drainage area to Sugar Loaf Dam is also 27.5 mi^2 (Figure 3). This watershed is in the Sawatch Mountain Range.

Precipitation, land classification, and average basin slope can inform sediment supply from the contributing basin. Mean annual precipitation is 29 inches (91% of the mean annual precipitation of the United States). The three largest land classifications are forest (52%), grassland and herbaceous land (24%), and open water (10%, U.S. Geological Survey, 2011) from Timberline Lake. Average basin elevation is 11,000 ft, and maximum elevation is 13,100 ft. The mean basin slope computed from 10 m DEM is 30% (U.S. Geological Survey, 2019). Lower than average mean annual precipitation and vegetation in over 75% of the basin suggest low sediment runoff from the watershed. However, the steep hillslopes will encourage overland erosion, increasing the potential sediment supply to Turquoise Lake.

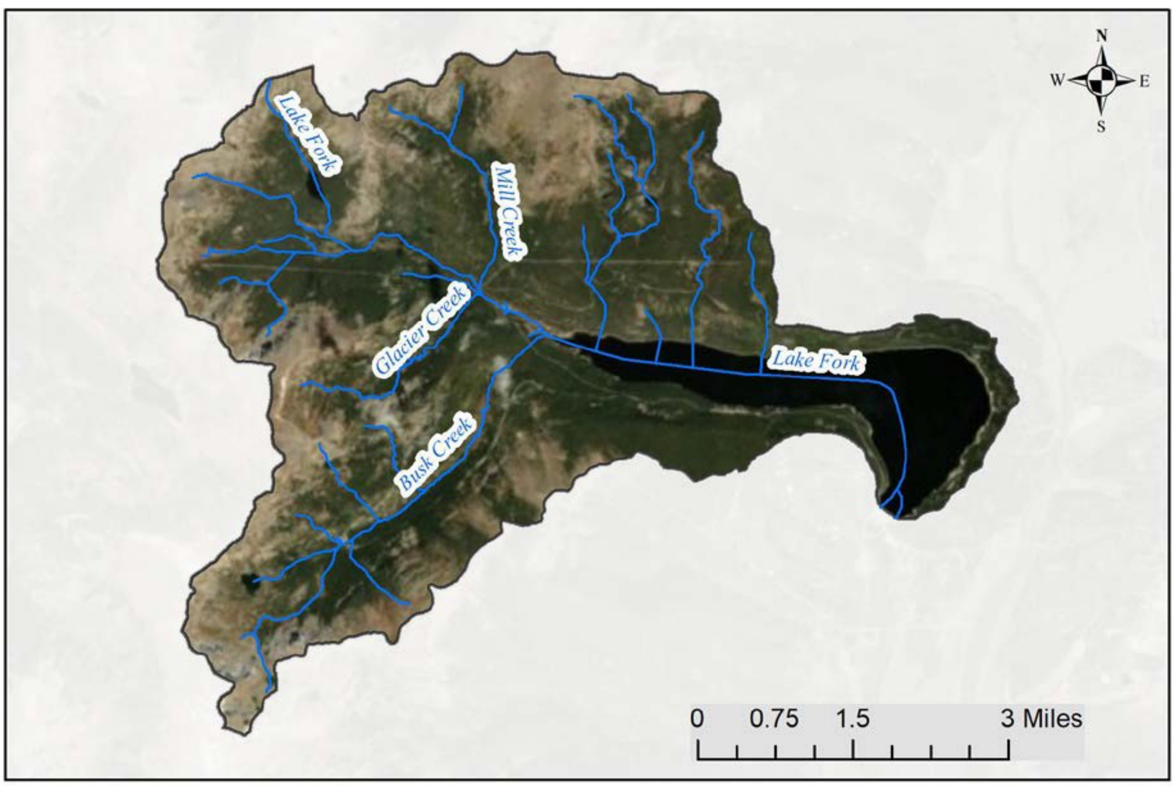

Figure 3. The watershed above Sugar Loaf Dam has a total drainage and sediment contributing area of 27.5 mi².

2.1. Geology

The Turquoise Lake contributing watershed is a U-shaped glacial valley with terminal and lateral moraines. Turquoise Lake and Lake Fork Creek are located on a terminal moraine, approximately 100 feet above the Arkansas River. The geology of the watershed's sediment-contributing drainage area consists of 61.2% granitic rocks 1,400-million-year age group, 17.6% glacial drift, and 11.4% biotitic gneiss, schist, and migmatite (Figure 4; Horton, 2017).

Soils are primarily loam and fine sandy loam (Figure 5). Loams are a combination of gravels, sands, silts and clays. These soil textures tend to have a high sand content and low clay content, meaning they have good infiltration properties and are easily eroded (Soil Survey Staff, 2017).

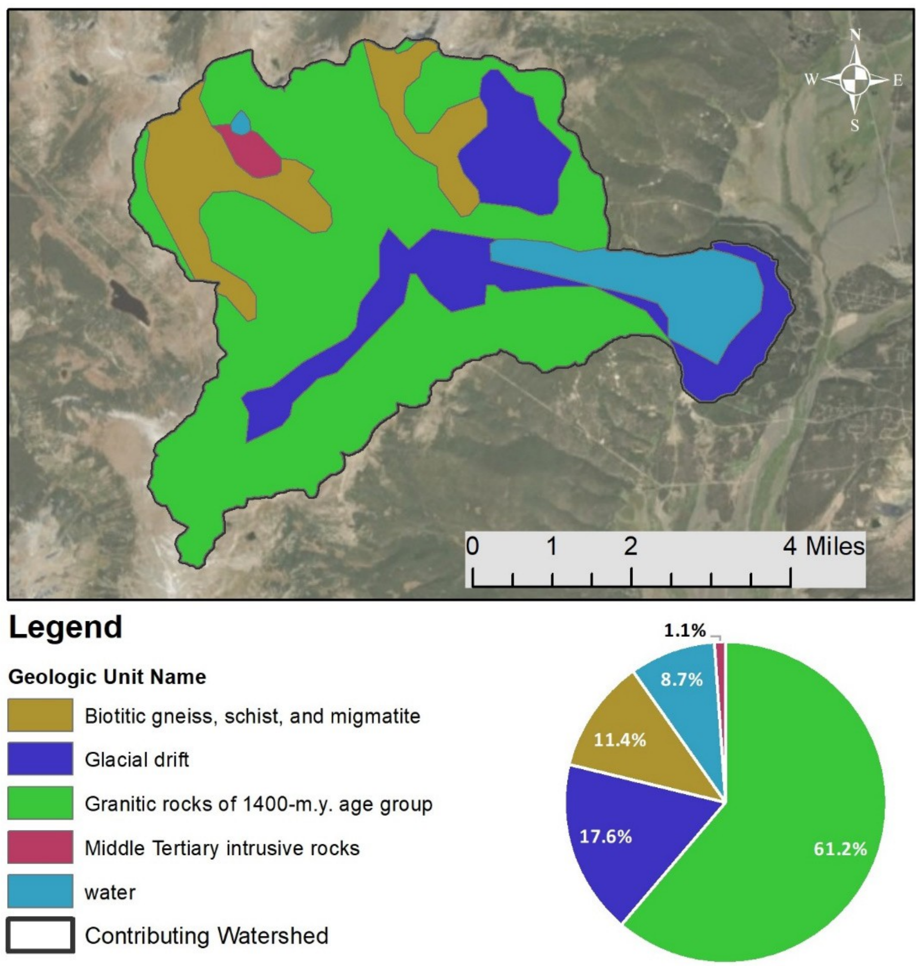

Figure 4. Geologic unit within the 27.5 mi² Turquoise Lake watershed.

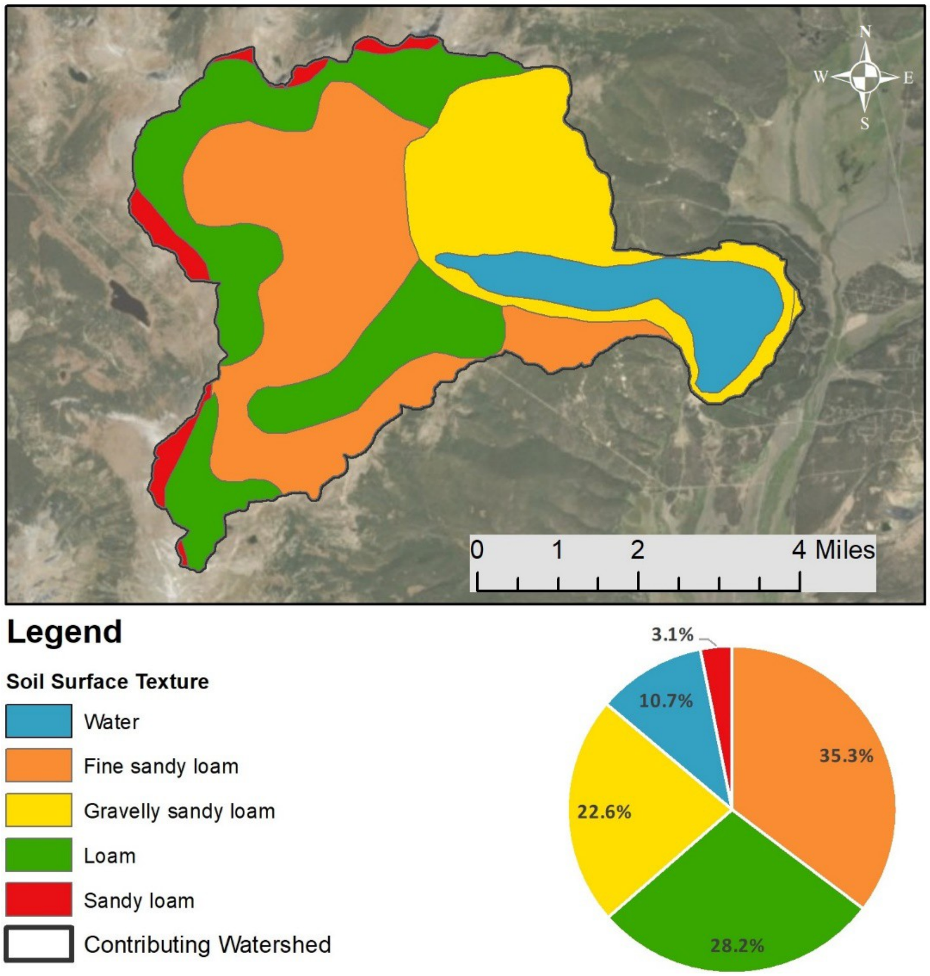

Figure 5. Soil texture within the Turquoise Lake Watershed.

2.2. Climate and Runoff

Reservoir inflows are primarily from the Lake Fork USGS stream gage records are available for the locations in presented in Table 1, which represents the total contributing drainage area. USGS gages presented in Table 1does not provide mean daily stream data. Peak annual streamflow data is provided for eight years before the dam was constructed, between 1890 and 1952.

Mean annual runoff to Turquoise Lake was calculated based on Hydromet data, which provides a calculated inflow. An estimated 86 inches per year or 125,588 acre-feet per year (Figure 6). This runoff is primarily from snowmelt, where stream flow peaks each year in May or June. On average, streamflow peaks around 1,100 cfs, with the highest recorded streamflow being 2,000 cfs. The mean annual stream flow to the reservoir is 173 cubic feet per second (cfs). The ratio of reservoir conservation pool storage capacity to the mean annual runoff is 1.0. This means that, when full, the reservoir stores a water volume equivalent to 379 days of mean annual stream flow.

Table 1. Reservoir Inflow Streams with USGS gages.

USGS Stream Gage		Gage Drainage Area (mi^2)	Mean Annual Runoff (cfs)	Data Available	Period of Record
Name	**Number**				
Lake Fork Below Sugar Loaf Reservoir	07082500	28.1	N/A	8 Peak streamflow values	1890 - 1952
Dinero Mine Drainage Tunnel below Turquoise Lake	391504106225200			Daily data	2003 – 2009
Bartlett Mine Drainage Tunnel below Turquoise Lake	391517106223801			Daily data	2005 - 2014

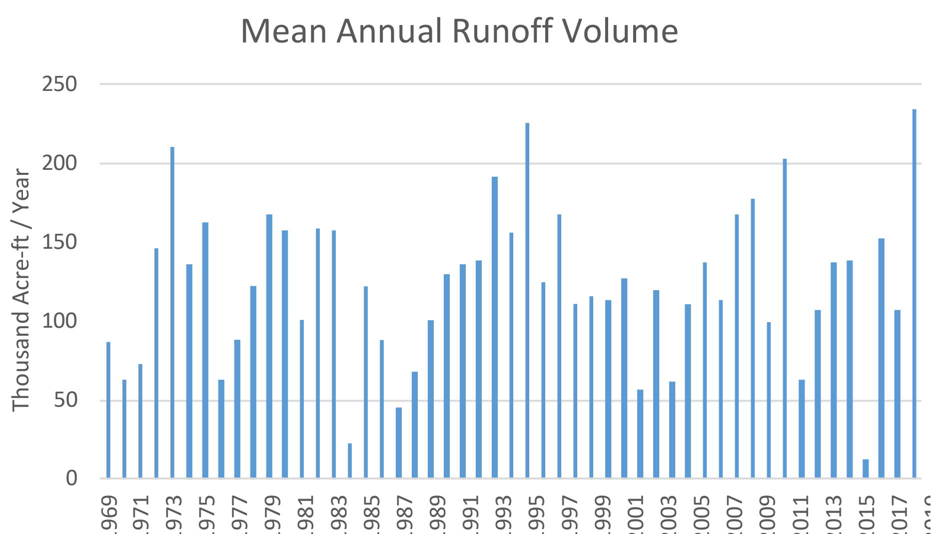

Figure 6. Mean annual runoff volume. Data web source: www.usbr.gov/gp/hydromet/. Reservoir capacity is 150,282 acre-ft; therefore, mean annual runoff volume ranges from 9% to 170% of total storage capacity. On average, Lake Creek produces approximately 90% of Turquoise Lake's storage capacity.

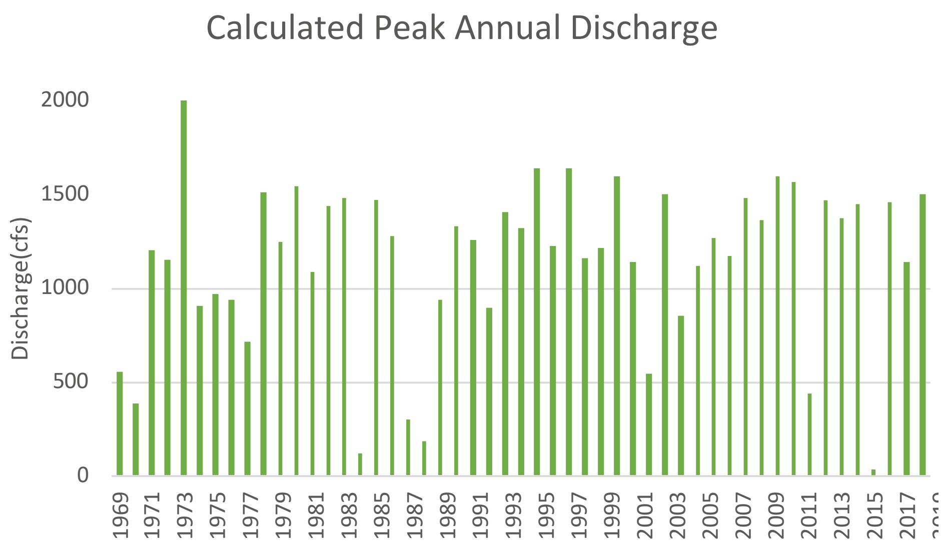

Figure 7. Calculated annual peak discharge (www.usbr.gov/gp/hydromet/).

2.3. Dam Operations and Reservoir Characteristics

Sugar Loaf is an earthfill dam. This project was completed and filled in 1968. The historic reservoir water surface elevations (project datum) is presented in Figure 8. On average, water surface elevation fluctuates 35 ft per year. The largest fluctuation in water surface elevation was 69 ft in 1977.

The dam has a height above the original stream bed of 129 feet and the reservoir had an original length of about 2,020 feet long at full pool with four headwater tributaries.

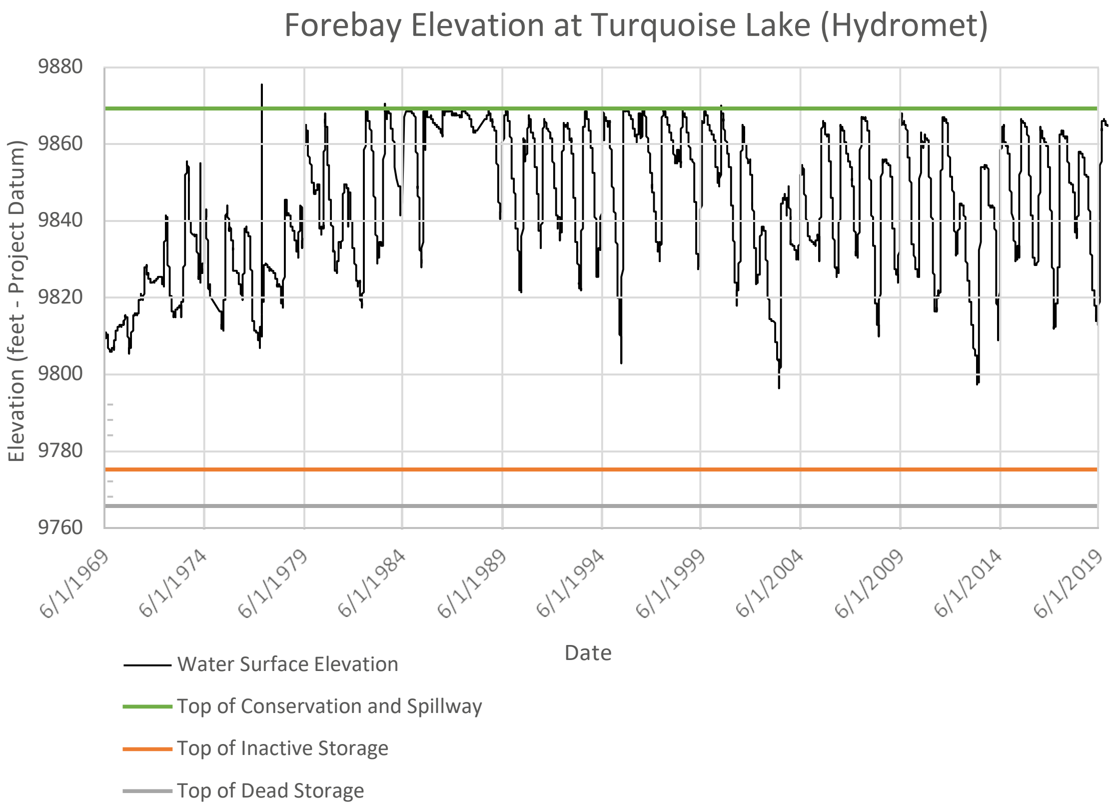

Figure 8. Historic Sugar Loaf water surface elevations (project datum). Data web source: www.usbr.gov/gp/hydromet/.

The reservoir is widest along the meander bend (near Tabor Campground, 1.2 miles wide) and narrowest at the river delta (800 feet or 0.15 miles wide; Figure 1). A delta has formed near the upstream end and has progressed 1,800 feet downstream. Reservoir geometry and fluctuations in water surface elevation can impact sedimentation patterns. High reservoir levels during 1985-1988 can result in delta deposition along the most upstream portions of the reservoir. Subsequent periods of consistent fluctuations can allow periodic incision within the delta, which can transport sediment further into the reservoir. There is no record of past reservoir sediment management activities.

3. Previous Reservoir Survey(s)

Prior to dam closure and initial reservoir filling, this is the first survey conducted to measure surface area and corresponding storage capacities. Pre-dam bathymetric data from 1964 was produced from lake bottom soundings collected from January 28 to March 20, 1964 (Bureau of Reclamation, 2005). No contour map has been found from this original survey. Area and capacity tables were produced in 5-foot increments.

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, Colorado Central, 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 Sugar Loaf Dam. The RPVD was determined to be 0.31 feet higher than the NGVD 1929 and 5.54 feet lower than NAVD 1988 (Geoid 12A).

The GPS base station receiver was set up over a temporary monument located on the beach near Bell of Colorado Campground (Figure 9).

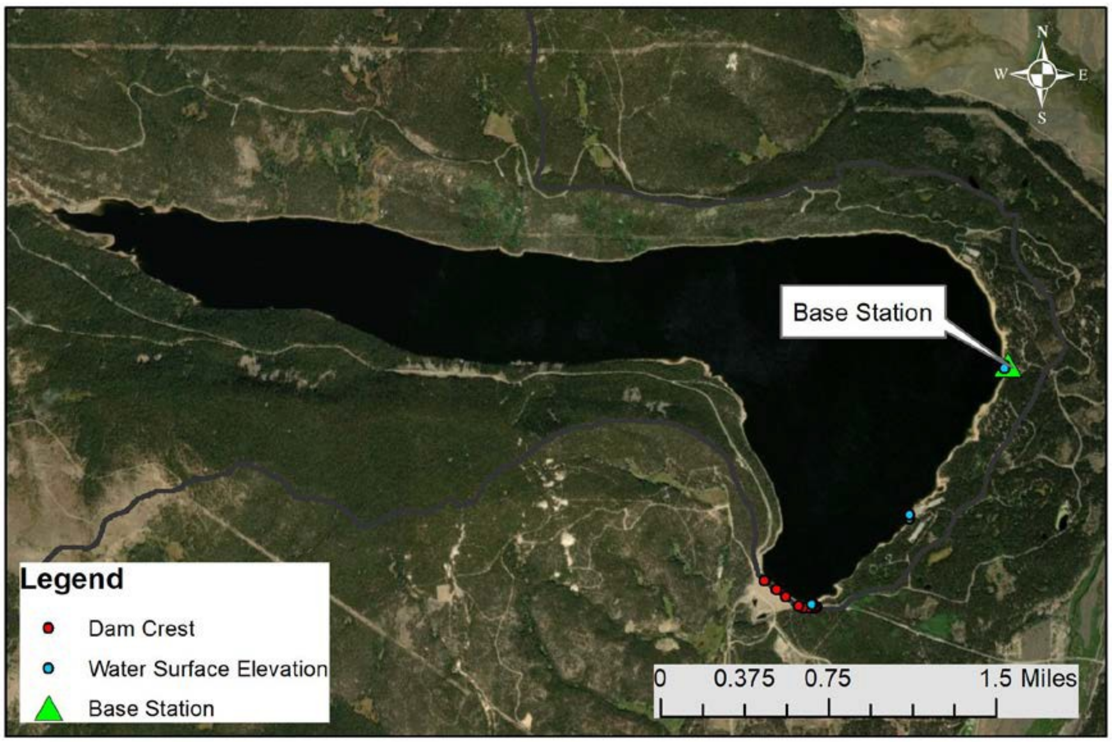

Figure 9. Location of GPS base station(s) along Turquoise Lake.

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/).

RPVD at Turquoise Lake was determined from RTK GPS measurements on the dam crest measured along the full 2,020 feet of the dam crest length.

The difference between NGVD 1929 and NAVD 1988 at Sugar Loaf 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 5.85 survey feet lower than NAVD 1988.

5. Methods Summary

A complete bathymetric survey was conducted during June 2017 from a boat using a multibeam depth sounder to continuously measure water depths. The horizontal position of the moving boat was continually tracked using RTK GPS. A map of the data points collected is presented in Figure 10.

Appendix A provides more details of the hydrographic survey methods. These bathymetric data were combined with LIDAR and 1/9 arc-second resolution (15 foot grid cells) National Elevation Dataset (NED) data collected above water during September and October of 2010 to produce a digital surface of the reservoir bottom surface.

Appendix B provides more details regarding the above the-water survey data. Surface areas at 1-foot contour intervals were computed using GIS software and a computer program (ACAP, Reclamation, 1985) that 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.

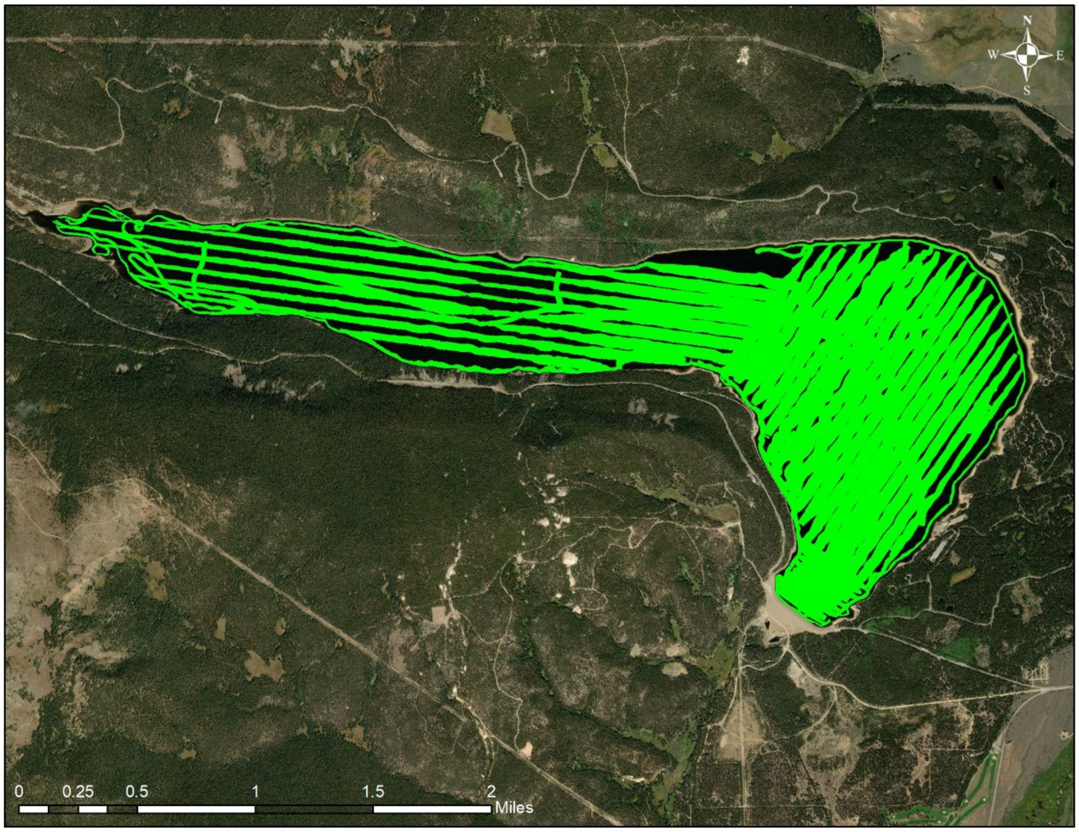

Figure 10. Map of bathymetric survey data coverage.

6. Reservoir Surface Area and Storage Capacity

Tables of reservoir surface area and storage capacity were produced for the full range of reservoir elevations (Turquoise Lake Area and Capacity Tables 2017). Plots of the 2017 area and capacity curves are presented in Figure 11 along with curves from the original 1964 survey. For the 2017 survey, area and capacity curves are based on the bathymetric (below-water) survey up to 9,862 feet elevation (project datum), while curves above this elevation are based on 2010 LiDAR and 15 foot resolution NED data (USGS, 2014 and USGS, 2012). A comparison of these curves indicates no reduction in storage volume between 1964 and 2017. The results indicate that the change in storage volume is within the error between the two survey techniques.

At the conservation pool elevation (9,869.4 feet project vertical datum), which is approximately 10 feet above water at the time of the survey, the reservoir surface area was 1,779 acres with a storage capacity of 130,169 acre-feet. At the top of surcharge pool elevation (9,872.8 feet, project vertical datum), the reservoir would have a surface area of 1,807 acres and a storage capacity of 136,265 acre-feet.

Table 2. Area capacity table comparing the 1964 survey and 2017 surveys.

	Area (acres)		Capacity (acre-ft)		
Elevation (ft)	1964 Survey	2017 Survey	1964 Survey	2017 Survey	
9750	0	0	0	0	
9760	202	221	530	429	
9770	649	666	5,252	5,365	
9780	756	780	12,290	12,655	
9790	834	847	20,255	20,792	
9800	947	954	29,037	29,647	
9810	1,140	1,152	39,510	40,254	
9820	1,286	1,292	51,700	52,496	
9830	1,417	1,446	65,232	66,189	
9840	1,551	1,558	80,112	81,237	
9850	1,645	1,637	96,107	97,230	
9860	1,718	1,684	112,920	113,842	
9869.4	1,789	1,779	129,398	130,169	Conservation pool elevation
9870	1,794	1,784	130,472	131,238	
9872.8	1,816	1,807	135,525	136,265	Surcharge pool elevation

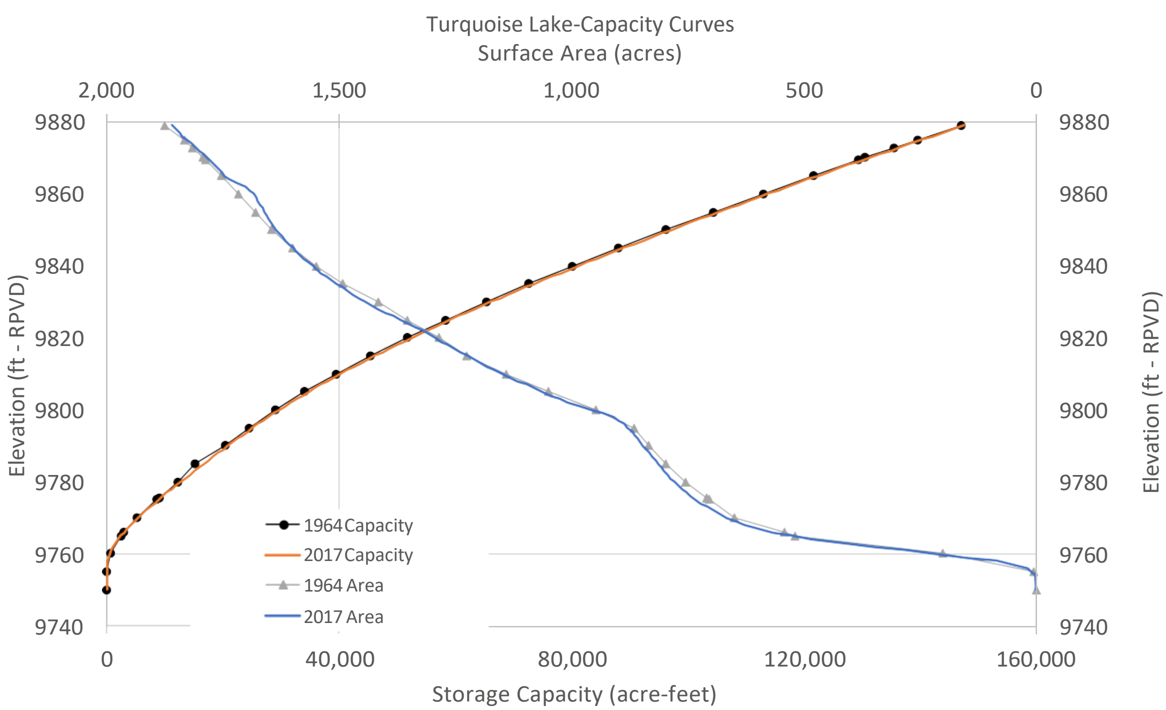

Figure 11. Plot of Turquoise Lake surface area and storage capacity versus elevation for the 1964 survey and the current conditions, surveyed in 2017 (Project Datum).

7. Reservoir Sedimentation Volume Spatial Distribution

A longitudinal profile and representative cross sections of the 2017 reservoir bottom surface were developed in GIS along the alignments presented in Figure 12. The longitudinal profile (Figure 13) show where approximately 40 feet of sediment accumulated on the historic river delta. Reservoir cross section plots (Figure 14 through Figure 16) show the lateral variation in reservoir bathymetry. We cannot say where sediment has deposited as there are no repeat surveys. However, we can make some assumptions based on theory and sediment depositional trends in other reservoirs. It is likely that sediment has historically deposited in the historic delta (Figure 15).

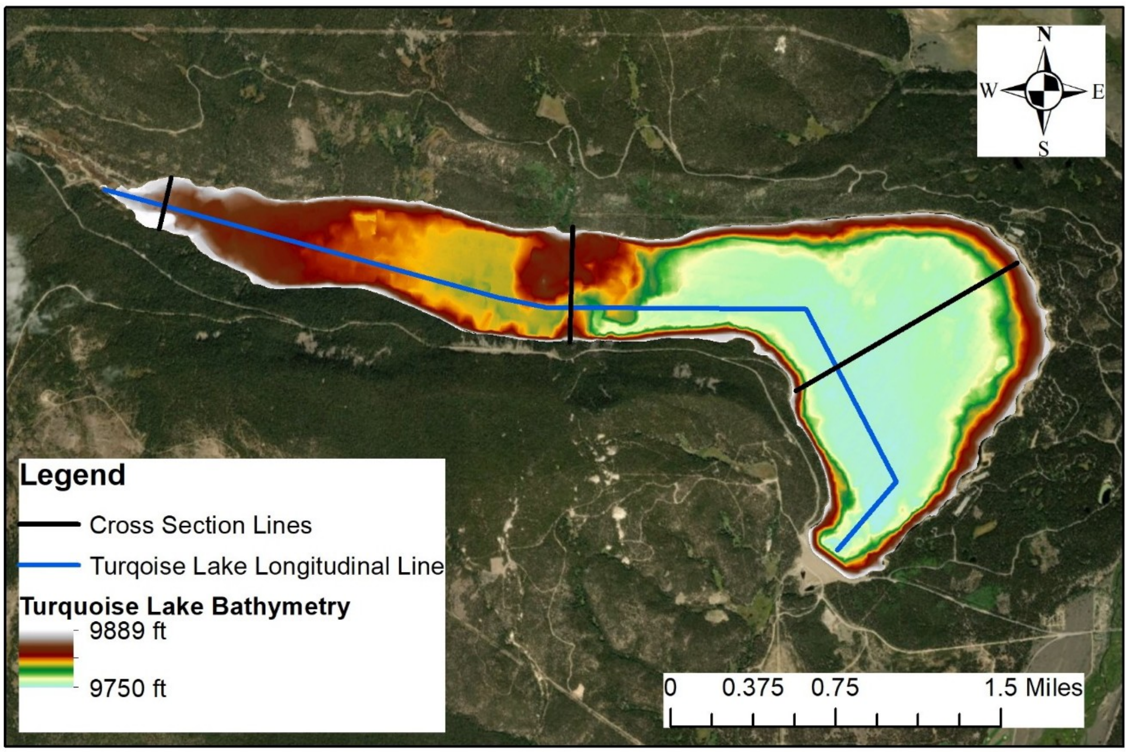

Figure 12. Reservoir surface elevation map and alignments of longitudinal profile(s) and representative cross sections.

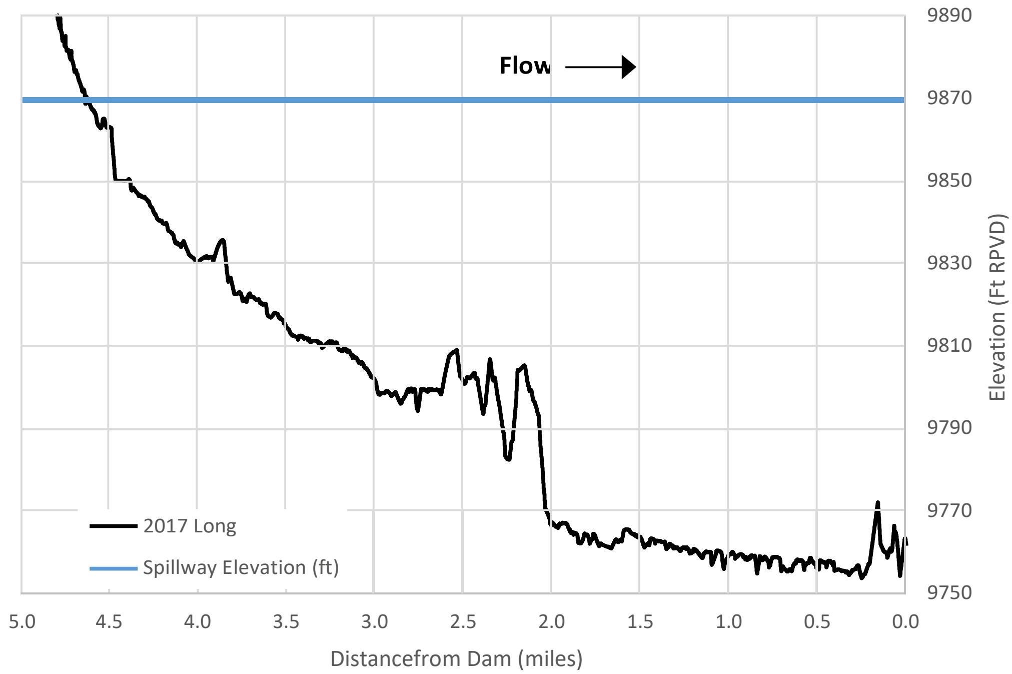

Figure 13. Longitudinal profile of Turquoise Lake bottom from the dam upstream to the current river delta. Note the assumed historic river delta at approximately 2.5 miles from Sugar Loaf Dam.

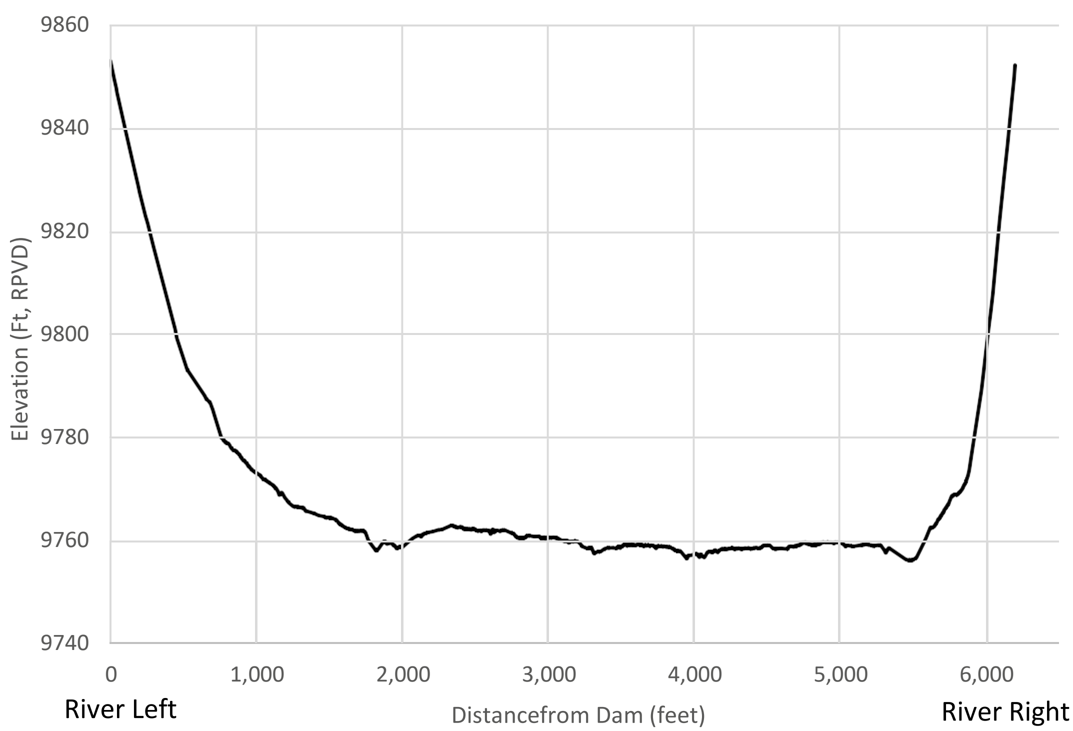

Figure 14. Representative cross section at the widest point in the reservoir, 1 mile upstream from the Sugar Loaf Dam.

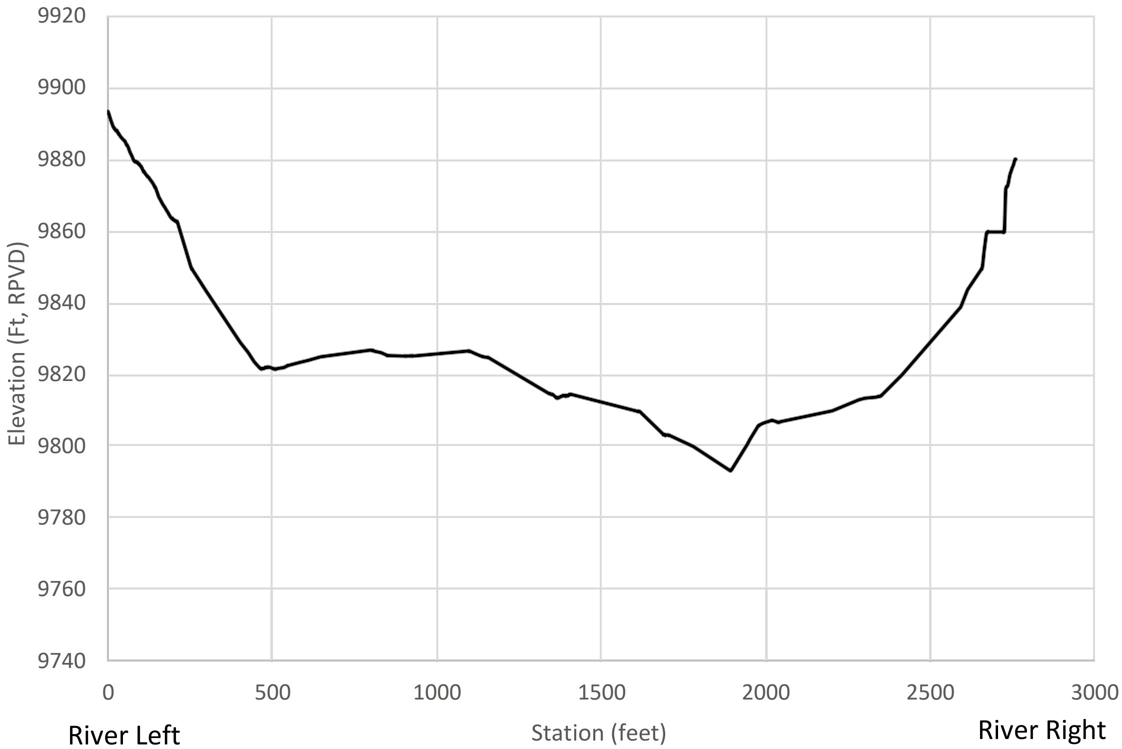

Figure 15. Representative cross section at the historic river delta, 2.4 miles upstream from Sugar Loaf Dam.

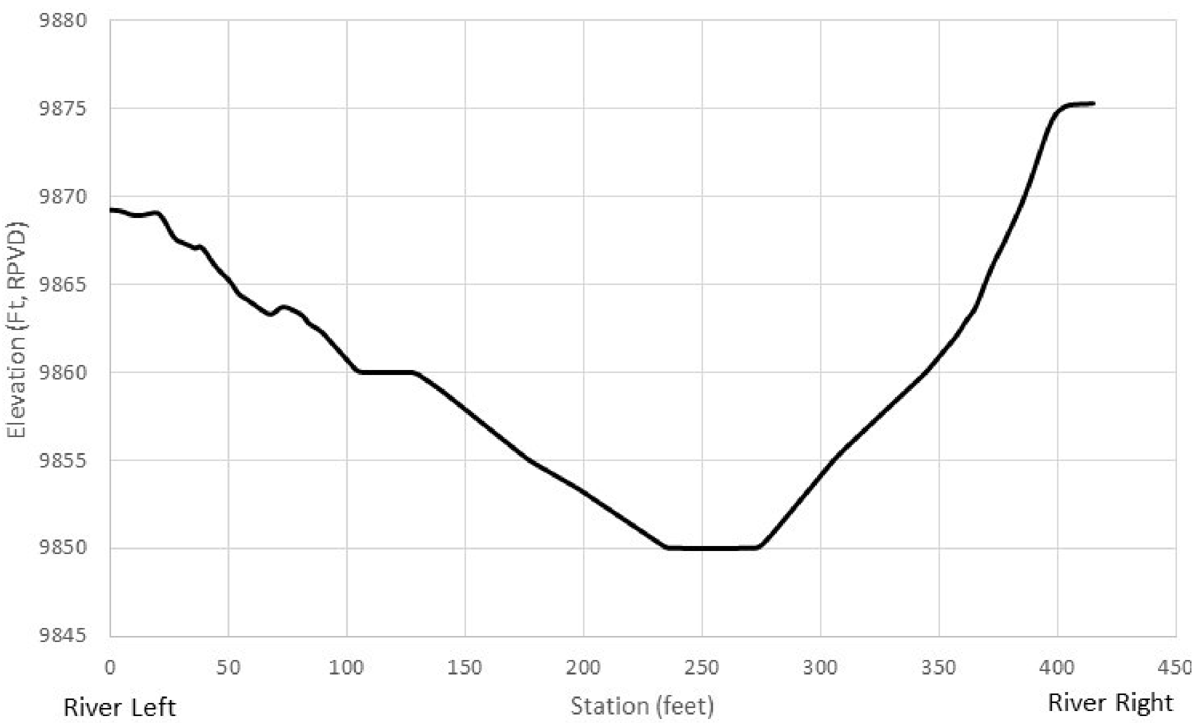

Figure 16. Representative cross section at the current river delta, 4.3 miles upstream from Sugar Loaf Dam.

8. Sedimentation Trends

There is no measurable change in reservoir capacity since the 1964 survey. The 2017 survey reports an increase of 3,300 acre-ft (2%) in storage capacity. The discrepancy is likely due to differences in survey styles and accuracy rather than an actual physical increase in reservoir storage. On the contrary, it is likely also that sediment has accumulated over time. The 1891 and 1949 topographic maps do not provide the necessary resolution to measure a change in surface elevation. Assuming it is not a natural geologic feature, the historic river delta may provide evidence of a high sediment load within the basin between 1891 and 1949. The sedimentation rate into Turquoise Lake is unknown. Repeat surveys using the same survey techniques could quantify the sedimentation accumulation rate. As this area is prone to episodic sediment events (landslides) it is unlikely that the sedimentation rate will be consistent through time.

Historically, Reclamation designs their outlet structures to avoid burial within the first 100 years of operation. Currently, the dead storage pool has 100% capacity remaining. As the sedimentation rate is unknown, we cannot predict when the dead storage capacity will be lost, risking the utility of the outlet works.

9. Conclusions and Recommendations

9.1. Survey Methods and Data Analysis

The 2017 bathymetric survey, combined with 2010 LiDAR and NED data for the above-water topography, has been used to produce a digital surface of the reservoir bottom. There was no overlapping bathymetric and above-water topographic data. Linear interpolation between breaklines was applied to fill in the spatial data gap.

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 can be attributed largely to differences in survey methods. The latest surface area and storage capacity curves are comparable with the original curves and with curves. The use of modern survey methods (RTK-GPS, multibeam depth sounder, LiDAR) have produced a more accurate and precise digital surface of the reservoir bottom than past surveys using older methods (plane table, level, photogrammetry).

9.2. Sedimentation Progression and Location

Over the span of 49 years, sedimentation was not measurable given the differing survey techniques. As there are no repeat surveys, we cannot determine the sediment accumulation rate, sediment deposition spatial trends, or remaining useful life of the reservoir *(*see Section 8 Sedimentation Trends*)*. As Lake Fork Creek is a headwater stream, we assume that it is a cobble- and gravel-bed stream. In these reservoir systems, most of the sediment will deposit in the river delta. If any fine sediments are present, they could deposit further into the reservoir. Any wash-load particles may deposit near the dam, risking the outlet works infrastructure. The volume and risk of this happening are unknown at this time.

9.3. Recommendation for Next Survey

Based on the past rates of sedimentation, the next survey of Turquoise Lake is recommended within the next 10 years, or by 2027. We recommend using the same survey technique documented in this report (multi-beam bathymetric survey combined with LiDAR data) to have comparable data sets.

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Appendix A — Hydrographic Survey Equipment and Methods

The 2017 bathymetric survey was conducted from 6/23/2017 to 6/26/2017. During this period, reservoir water surface elevations varied from 9,858.9 and 9,860.5 feet (RPVD).

The survey was conducted along a series of predetermined cross section, longitudinal, and shore line survey lines (Figure 10). The survey lines were spaced approximately every 300 ft, close enough for adequate interpolation between multi-beam depth data.

The survey employed an 18-foot, flat-bottom aluminum Wooldridge boat powered by outboard jet and kicker motors (Figure 17). 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 monitor the boat position and heading,
- an external GPS radio, and
- processor box for synchronization of all depth, sound velocity, position, heading, and motion sensor data.

Figure 17. Wooldridge boat with RTK-GPS and multibeam depth sounder system.

The multibeam transducer emits up to 512 beams (user selectable) capable of projecting a swath width up to 120 degrees in 100 feet (30 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 correct the depth measurements.

RTK GPS survey instruments were used to continuously monitor the survey boat position and measure other ground control points. The GPS base station and receiver was set up on a tripod over a point overlooking the reservoir (Figure 10). 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 18). The base station was powered by a 12-volt battery.

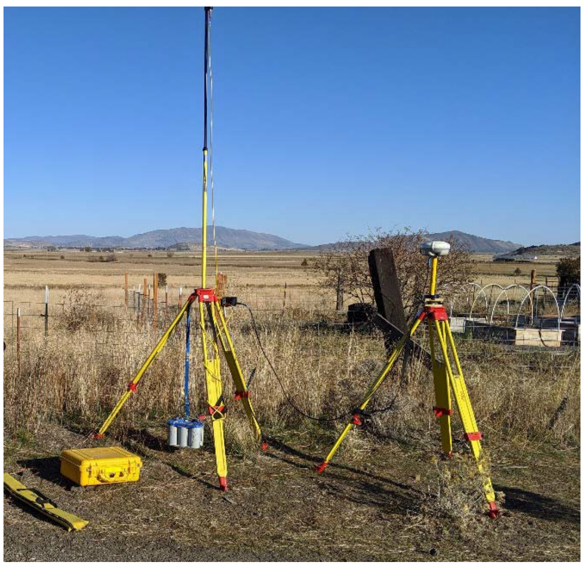


Figure 18. The RTK-GPS base station set-up used during the Klamath River Survey in Oregon is typical of the set up used for the Turquoise Lake survey.

The GPS rover receivers include an internal radio and external antenna mounted on a range pole (ground survey) or survey vessel (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 and within ±20 cm for the moving survey boat.

During the bathymetric 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 the user selected coordinate system, NAD 1983 State

Plane, Colorado Central. 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 generates hundreds of thousands of data points. Sometimes fish, underwater vegetation, or anomalies mean that a small portion of depth measurements do not represent the reservoir bottom and these data are deleted during the post processing. Final processing of the bathymetric data resulted in 820,000 data points used in the development of the reservoir surface. Filtering of this large data file is necessary, so a raster is created in GIS (2-foot square cells). For each raster cell, the reservoir bottom elevation is 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 within the cell.

Appendix B – Above Water Survey Methods

Data from the 2010 LiDAR survey and 1/9 arc-second (15 foot grid cell) resolution NED data were used to represent the above-water reservoir topography. These data were produced by the U.S. Geological Survey (USGS). LiDAR data were acquired in 2010 between September 9th and October 28th and published in 2014. The NED data were acquired during the same time frame but published in 2012. Both datasets are available through the National Map Viewer (https://viewer.nationalmap.gov/basic/).

The above water topographic data was flown seven years prior to the bathymetric survey. A comparison of aerial imagery within that timeframe suggests that the river delta and surrounding hillslopes have changed very little between the two surveys (Figure 19).

The water surface elevation during the LiDAR and NED data sets was 9,868 feet. During the 2017 bathymetric survey, the water surface elevation ranged from 9,858.9 and 9,860.5 feet (RPVD). No overlapping data were collected as collecting data in less than 5 ft of water depth put the multibeam system at risk. Furthermore, the multibeam system is less effective in shallow water depths (< 5 ft). Breaklines were digitized in both the bathymetric and LiDAR data. Linear interpolation was applied to fill the gap between datasets.

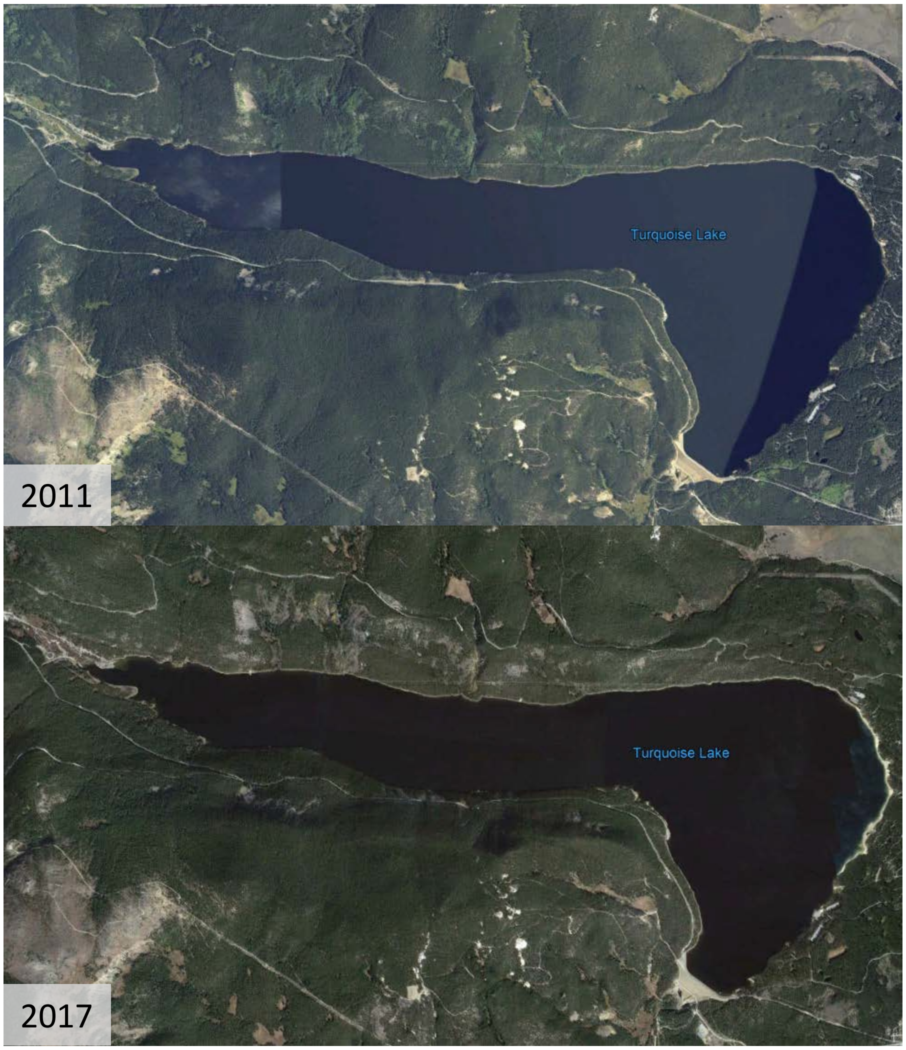


Figure 19. Comparison of aerial imagery of Turquoise Lake between 2011 and 2017 at a comparable water surface elevation.

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 1-foot increments, using functions within ArcGIS Pro, for the complete range of reservoir elevations (9,750 to 9,872 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 1-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:

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

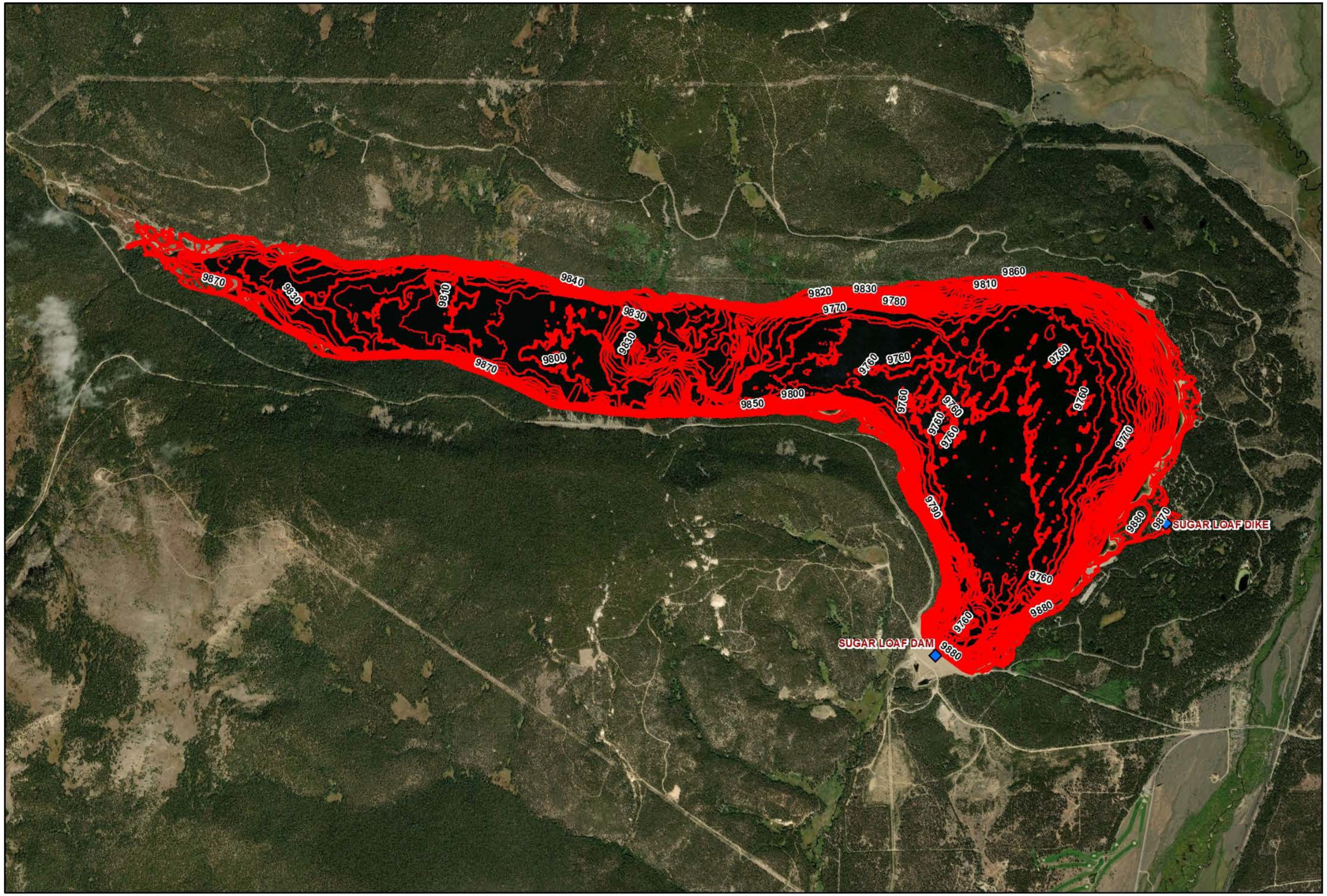
where: S = surface area (acres)

This method ensures that the given surface areas, and corresponding storage capacities, at the 1-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, 2017).

The sedimentation volume can be computed by subtracting digital surfaces of the predam reservoir surface from the 2017 digital reservoir surface. However, a predam topographic map and digital surface is not available for Turquoise Lake. A storage volume curve is available from the predam surface. It can be compared to the 2017 area capacity table to determine the change in reservoir storage. This method works well when the topographic map of the predam surface has good accuracy and precision. The accuracy and precision of the original storage capacity curve is unknown for Turquoise Lake. In this case, the original area and capacity tables underestimated the actual storage capacity and subsequent surveys show an increased storage capacity even though reservoir sedimentation has likely reduced the actual storage capacity.

Maps

Contour maps documenting the survey are included in the following figures.



Turquoise Lake Colorado Elevation Contour Map

Overview Map

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface Elevation Gage at Sugar Loaf Dam Referenced to Reclamation Project Vertical Datum (RPVD)
NAVD88 – RPVD = 5.54 sft
NAVD88 – NGVD29 = 5.85 sft

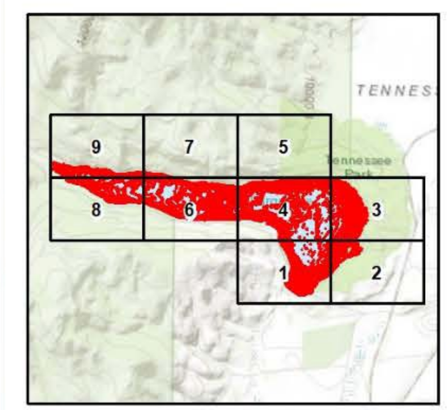
Five Foot Contour Interval

Primary Data Source:
2017 Turquoise Lake Study

N

Scale 1:25,000

0 1,950 3,900 Feet



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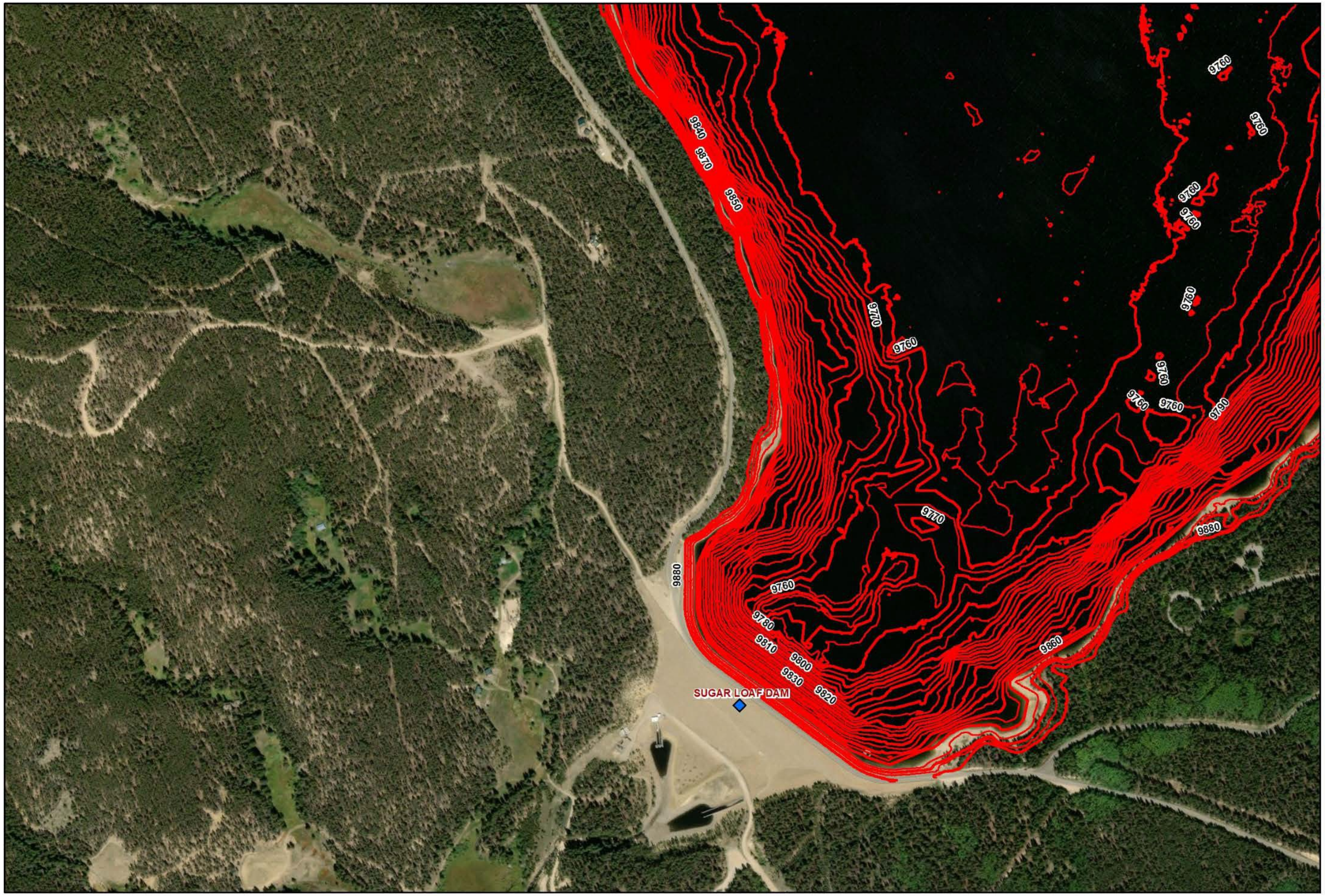


Turquoise Lake Colorado Elevation Contour Map

Sheet 1

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface
Elevation Gage at Sugar Loaf Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
NAVD88 – RPVD = 5.54 sft
NAVD88 – NGVD29 = 5.85 sft

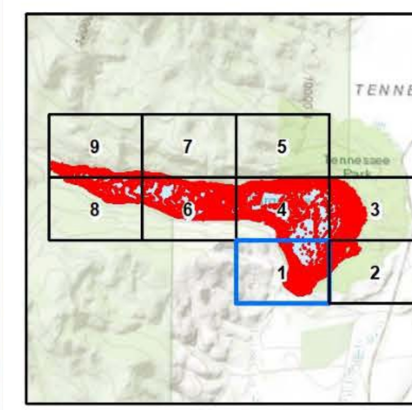
Five Foot Contour Interval

Primary Data Source:
2017 Turquoise Lake Study

N

Scale 1:6,000

0 487.5 975 Feet



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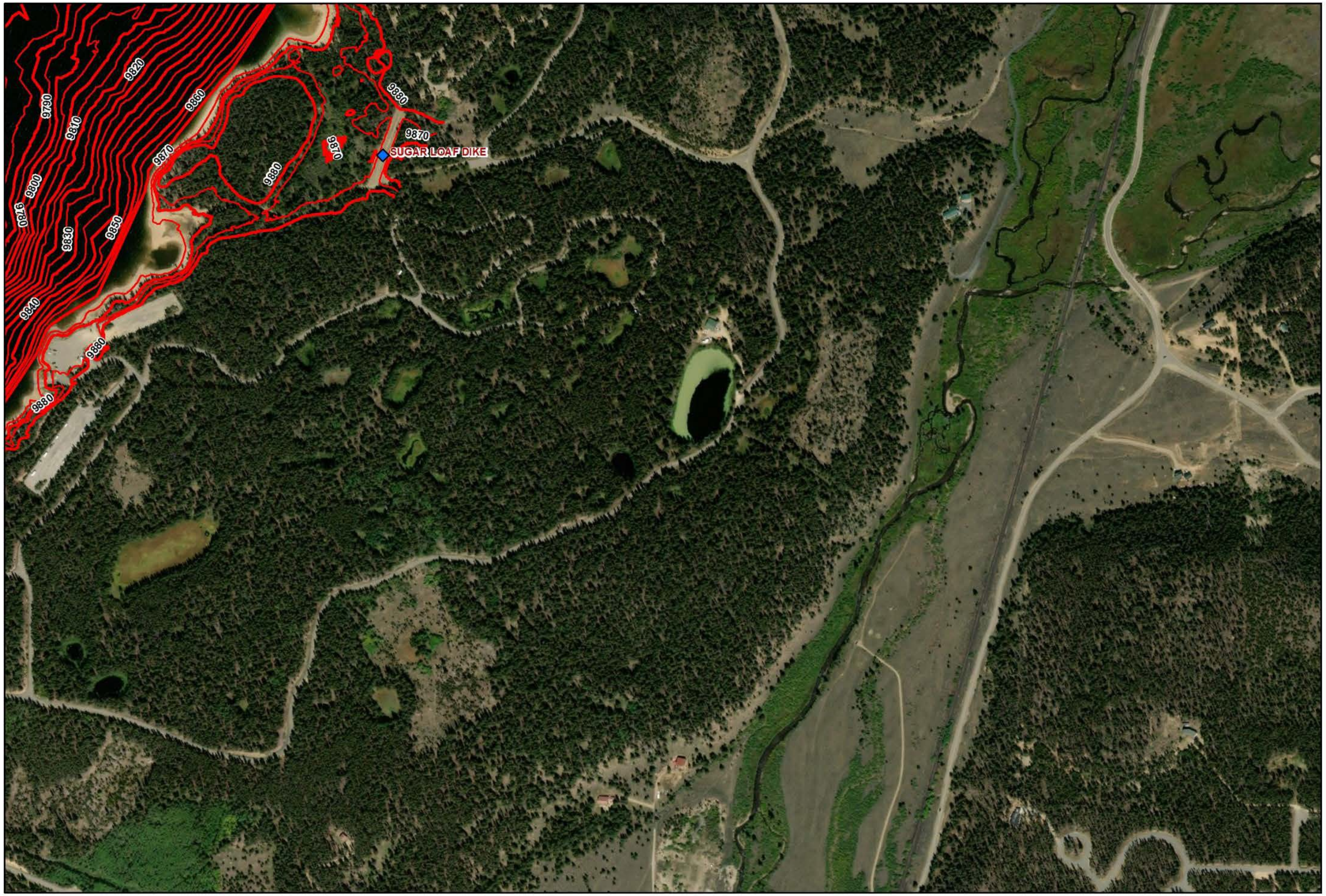


Turquoise Lake Colorado Elevation Contour Map

Sheet 2

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface Elevation Gage at Sugar Loaf Dam Referenced to Reclamation Project Vertical Datum (RPVD)
NAVD88 – RPVD = 5.54 sft
NAVD88 – NGVD29 = 5.85 sft

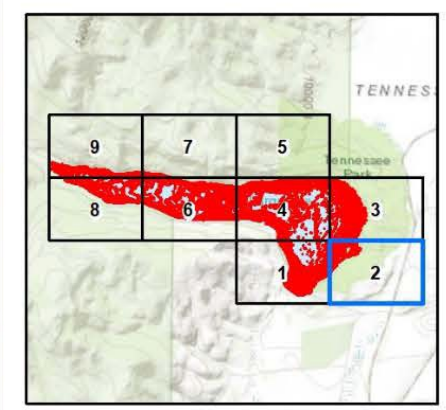
Five Foot Contour Interval

Primary Data Source:
2017 Turquoise Lake Study

N

Scale 1:6,000

0 487.5 975 Feet



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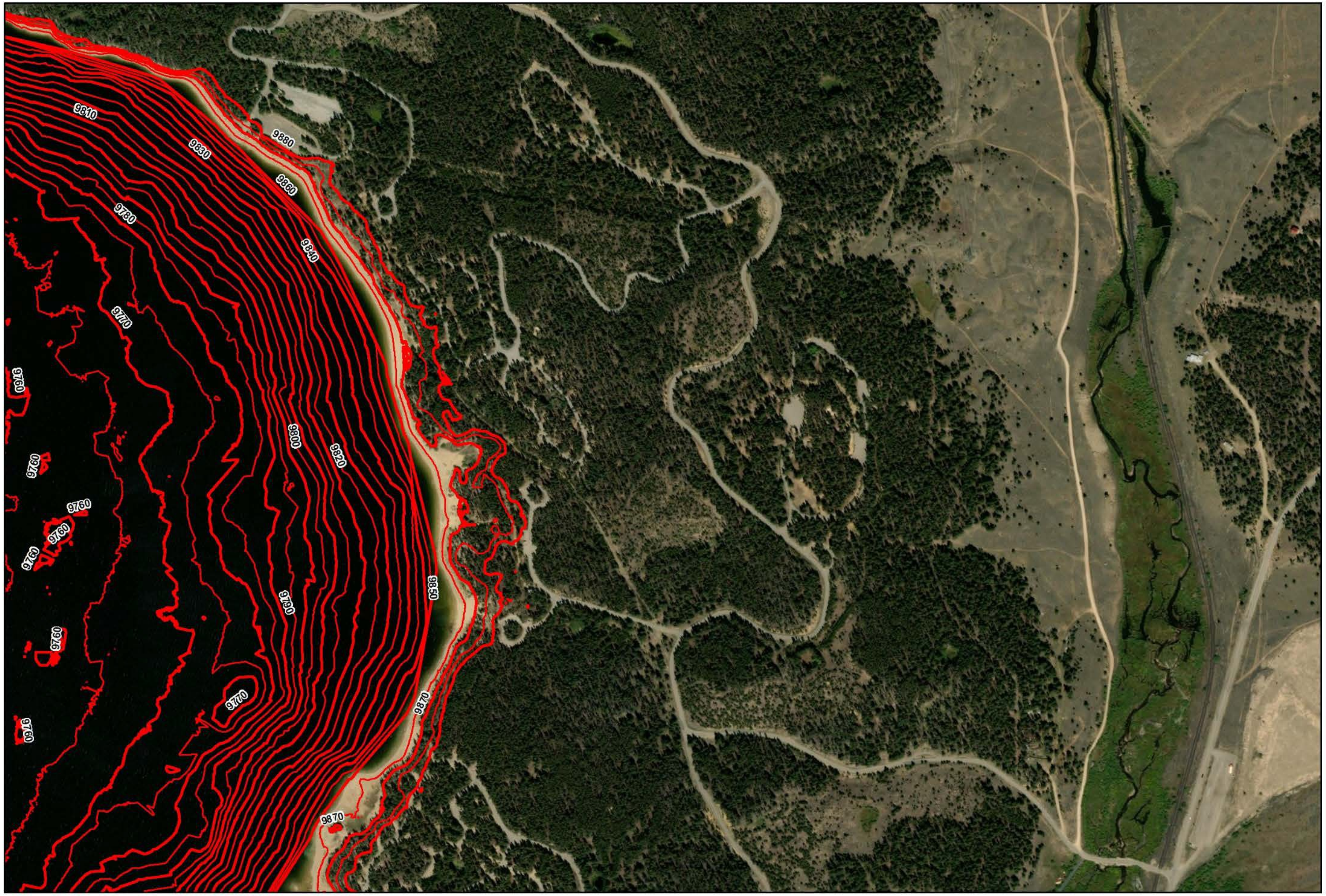


Turquoise Lake Colorado Elevation Contour Map

Sheet 3

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface
Elevation Gage at Sugar Loaf Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
NAVD88 – RPVD = 5.54 sft
NAVD88 – NGVD29 = 5.85 sft

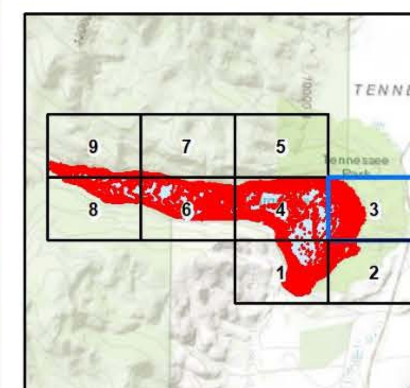
Five Foot Contour Interval

Primary Data Source:
2017 Turquoise Lake Study

N

Scale 1:6,000

0 487.5 975 Feet



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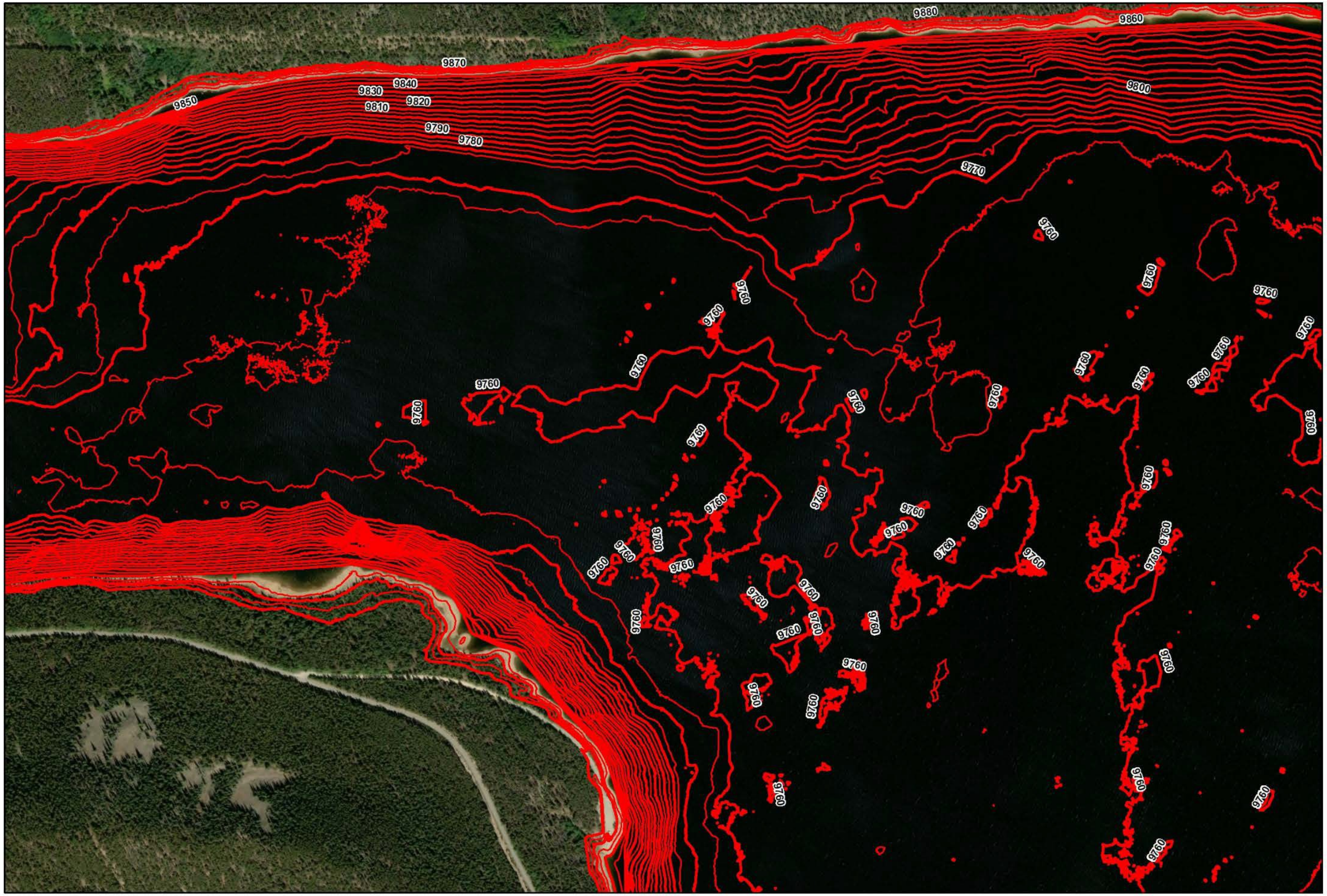


Turquoise Lake Colorado Elevation Contour Map

Sheet 4

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface
Elevation Gage at Sugar Loaf Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
NAVD88 – RPVD = 5.54 sft
NAVD88 – NGVD29 = 5.85 sft

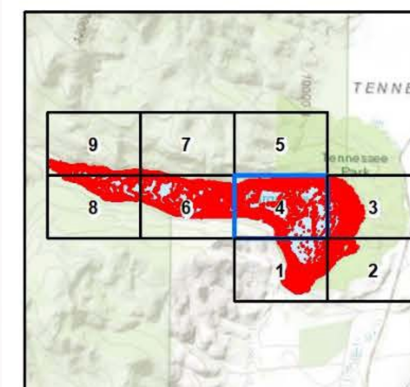
Five Foot Contour Interval

Primary Data Source:
2017 Turquoise Lake Study

N

Scale 1:6,000

0 487.5 975 Feet



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**Turquoise Lake
Colorado
Elevation
Contour Map**

Sheet 5

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface
Elevation Gage at Sugar Loaf Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
NAVD88 – RPVD = 5.54 sft
NAVD88 – NGVD29 = 5.85 sft

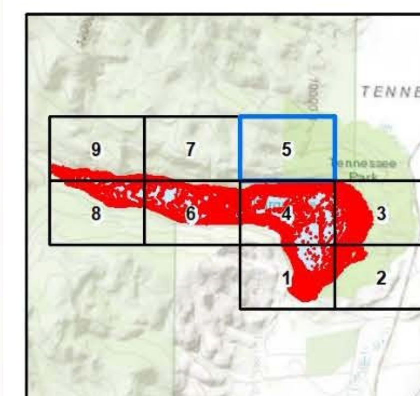
Five Foot Contour Interval

Primary Data Source:
2017 Turquoise Lake Study

N

Scale 1:6,000

0 487.5 975 Feet



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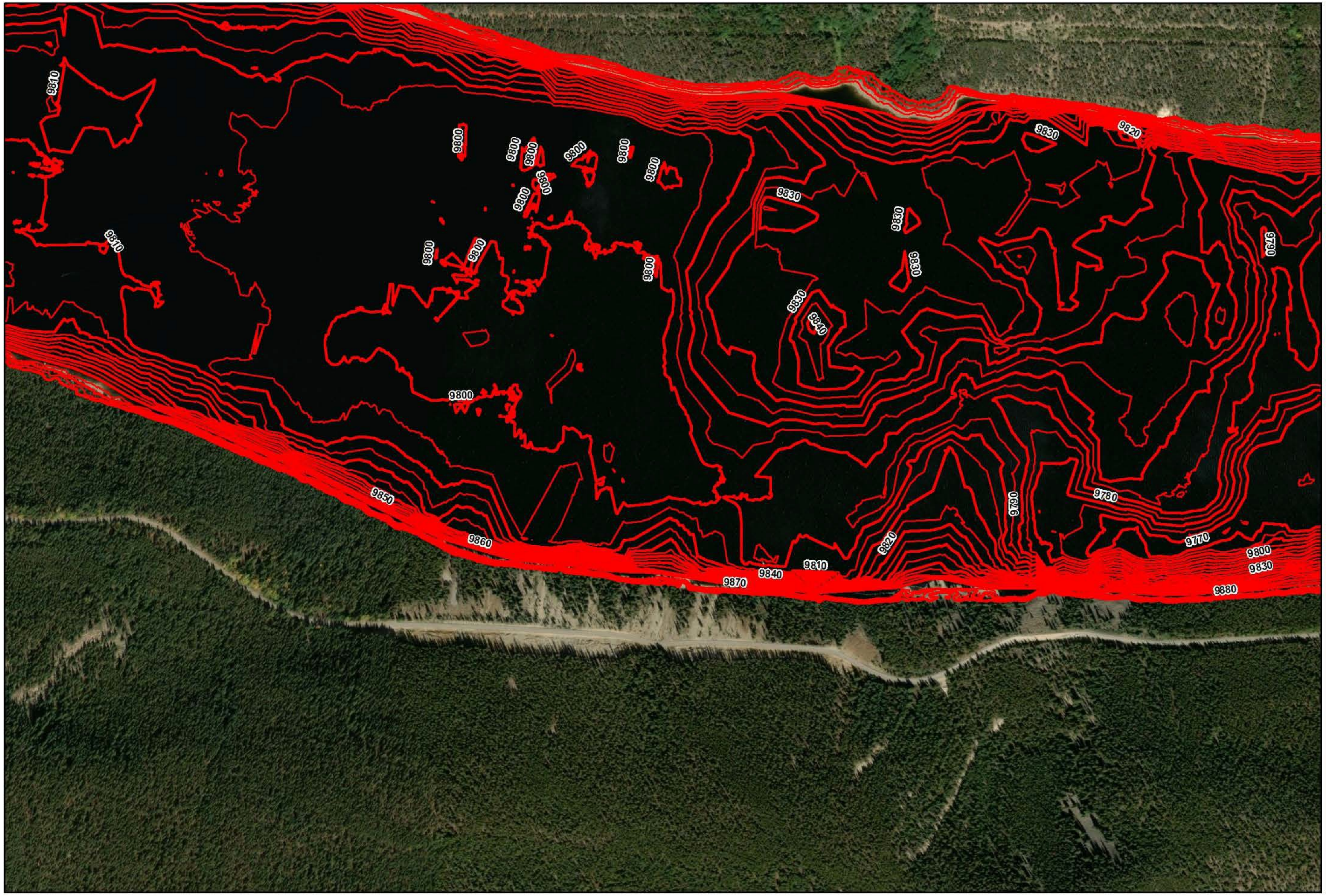


Turquoise Lake
Colorado
Elevation
Contour Map

Sheet 6

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface
Elevation Gage at Sugar Loaf Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
NAVD88 – RPVD = 5.54 sft
NAVD88 – NGVD29 = 5.85 sft

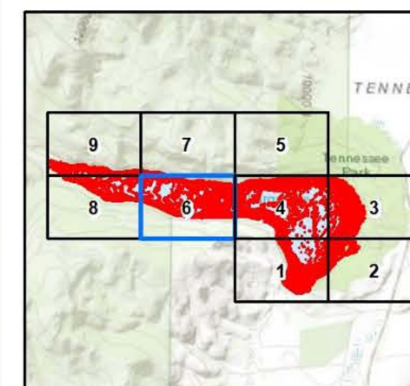
Five Foot Contour Interval

Primary Data Source:
2017 Turquoise Lake Study

N

Scale 1:6,000

0 487.5 975 Feet



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Turquoise Lake Colorado Elevation Contour Map

Sheet 7

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface
Elevation Gage at Sugar Loaf Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
NAVD88 – RPVD = 5.54 sft
NAVD88 – NGVD29 = 5.85 sft

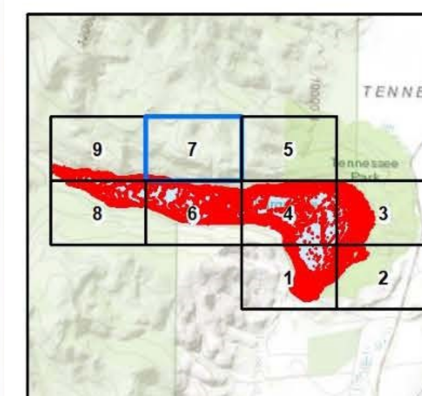
Five Foot Contour Interval

Primary Data Source:
2017 Turquoise Lake Study

N

Scale 1:6,000

0 487.5 975 Feet



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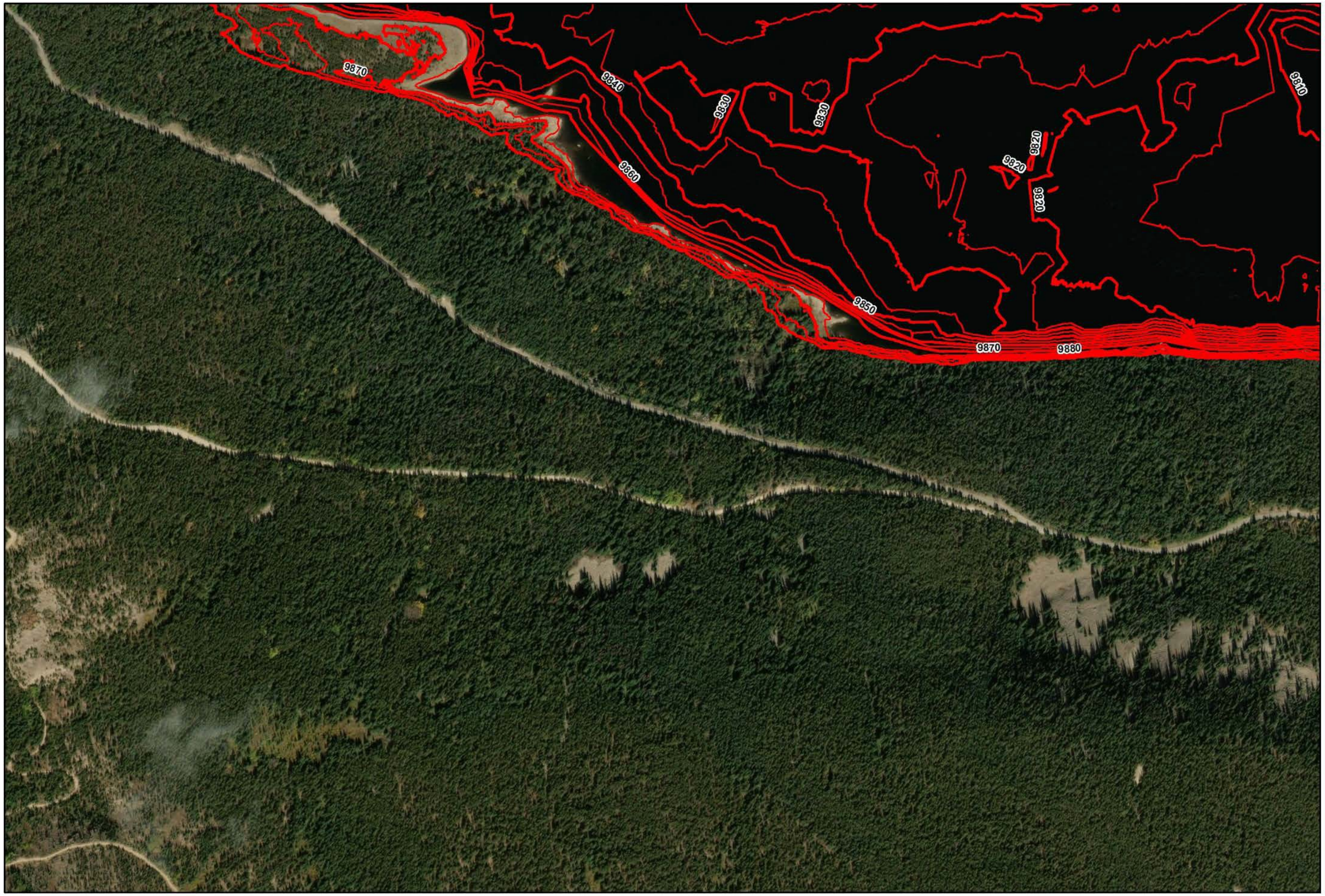


Turquoise Lake Colorado Elevation Contour Map

Sheet 8

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface
Elevation Gage at Sugar Loaf Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
NAVD88 – RPVD = 5.54 sft
NAVD88 – NGVD29 = 5.85 sft

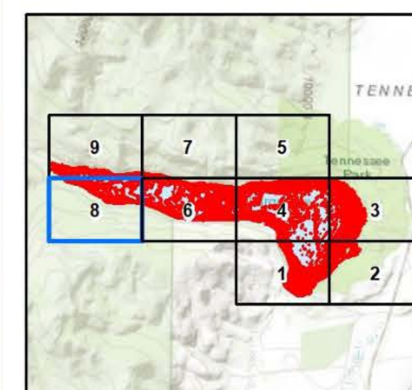
Five Foot Contour Interval

Primary Data Source:
2017 Turquoise Lake Study

N

Scale 1:6,000

0 487.5 975 Feet



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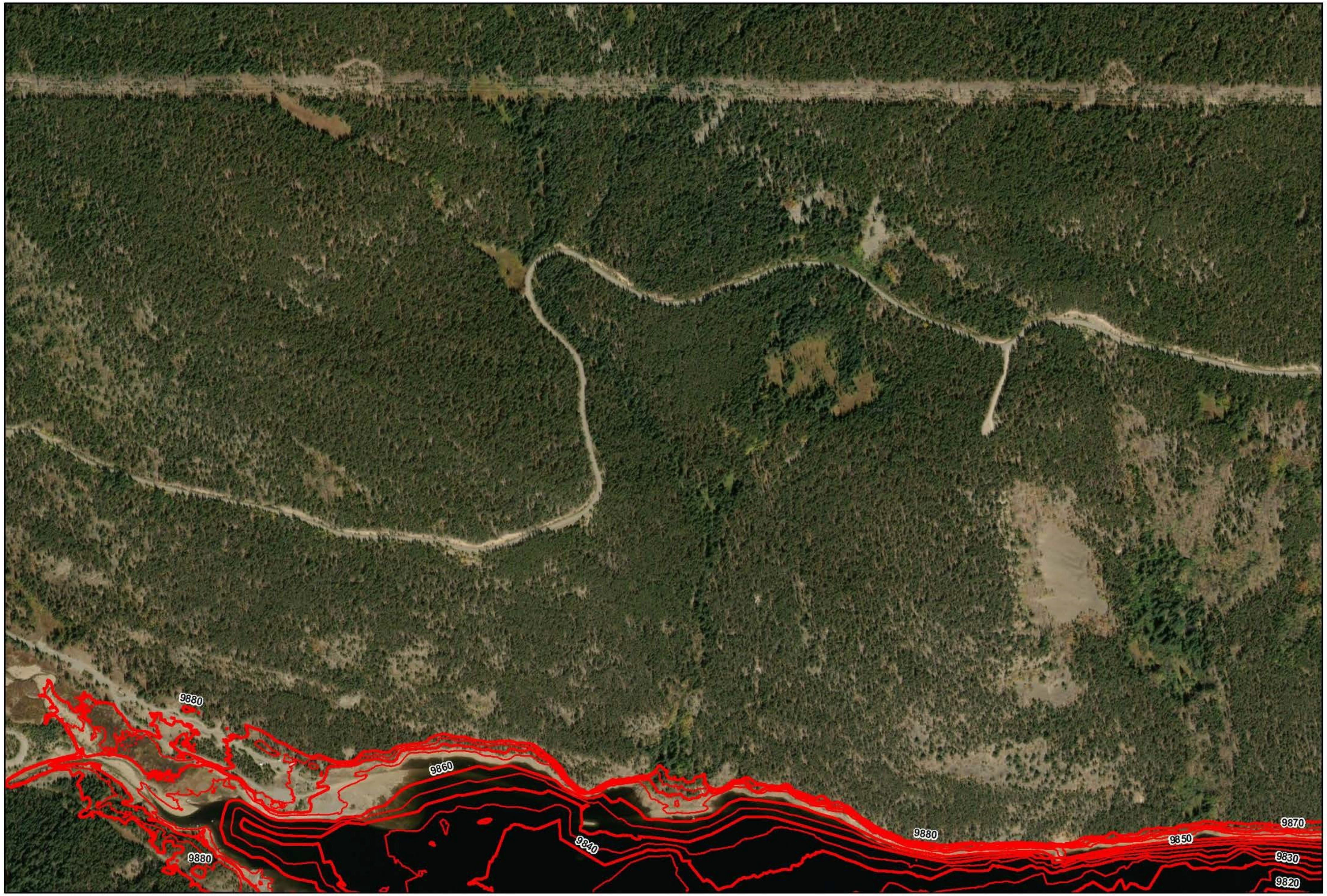


Turquoise Lake Colorado Elevation Contour Map

Sheet 9

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface
Elevation Gage at Sugar Loaf Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
NAVD88 – RPVD = 5.54 sft
NAVD88 – NGVD29 = 5.85 sft

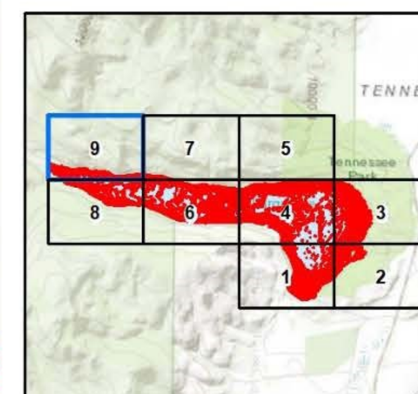
Five Foot Contour Interval

Primary Data Source:
2017 Turquoise Lake Study

N

Scale 1:6,000

0 487.5 975 Feet



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