BUREAU OF RECLAMATION

Technical Memorandum No. ENV-2022-043

Willow Creek Reservoir (CO)
2021 Sedimentation Survey

Colorado Big Thompson Project, Colorado
Missouri Basin and Arkansas – Rio Grande – Texas Gulf Region

U.S. Department of the Interior **February 2022**

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Cover Photo – Willow Creek Reservoir near Grand Lake, Colorado (Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group).

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Prepared by:

Bureau of Reclamation
Technical Service Center
Denver, Colorado

U.S. Department of the Interior **February 2022**

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14. SHORT ABSTRACT

The 2021 multibeam bathymetric survey of Willow Creek Reservoir was merged with photogrammetry to produce a combined digital surface of the reservoir. The photogrammetry was collected via drone to capture the portion of the reservoir that was above water at the time of the bathymetric survey. The above-water topography data were processed by Dr. Luke Javernick (River Science, Cañon City, Colorado). Analysis of these data indicates that at the top of flood control pool elevation (8130 feet [ft], Reclamation Project Vertical Datum [RPVD]), the reservoir has a surface area of 311 acres and a storage capacity of 10,004 acre-feet. Since the original filling in 1953, the reservoir is estimated to have lost 549 acre-feet of storage capacity (5.2 percent) due to sedimentation (measured at 8130 feet (RPVD). The dead storage pool volume has reduced to 82.4 percent of the original dead storage volume. The sedimentation level at the dam is at 8043.91 ft (RPVD), which is 17.5 percent of the height between the original reservoir bottom (reported streambed elevation of 8037 ft in Bureau of Reclamation (1981) and the top of the dead storage pool (elevation 8077 ft).

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Missouri Basin and Arkansas – Rio Grande – Texas Gulf Region

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Acronyms and Abbreviations

acre-feet/mi^2/yr	acre-feet per square mile per year
ACAP	AreaCAPacity
ADCP	Acoustic Doppler Current Profiler
cm	centimeter(s)
DEM	digital elevation model
ft	foot/feet
ft^3/s	cubic feet per second
GIS	Geographic Information System
GPS	Global Positioning System
HUC	Hydrologic Unit Code
mi^2	square mile(s)
N/A	not applicable
NAD83	North American Datum, established 1983
NAVD88	North American Vertical Datum, established 1988
NGS	National Geodetic Survey
NID	National Inventory of Dams
OPUS	Online Positioning User Service
Reclamation	Bureau of Reclamation
RPVD	Reclamation Project Vertical Datum
RTK-GPS	real-time kinematic Global Positioning System
usft	U.S. survey feet
USGS	U.S. Geological Survey

Symbols

>	greater than
<	less than
%	percent
±	plus or minus

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Executive Summary

Willow Creek Dam and Reservoir are on Willow Creek about 3 miles east of Lake Granby, which lies between the towns of Granby and Grand Lake in Grand County, Colorado. This location is in the Rocky Mountains 60 miles northwest of Denver. A complete and full coverage bathymetric survey of Willow Creek Reservoir was performed from August 16 to 17, 2021, using a multibeam sonar deployed from a boat. In addition, aerial photography was flown to survey the above-water topography September 2, 2021 (Dr. Luke Javernick, River Science, Cañon City, Colorado). This survey is the second annual survey to track sedimentation following the East Troublesome Fire that burned 91 percent of the Willow Creek watershed. The fire was reported on the afternoon of October 14, 2020, and was declared contained on November 30, 2020 (https://inciweb.nwcg.gov/incident/7242/). Additional annual surveys are planned for 2022, 2023, and 2024. The 2021 bathymetric survey was performed with these primary objectives:

- Estimate reservoir sedimentation volume since the previous surveys in November 2020 and February 2021; combined, they are considered to be the 2020 survey.

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

- Collect reservoir surface samples to measure sediment particle size distributions, bulk densities, and chemical attributes of the bottom sediment throughout the delta region of the reservoir. Samples were collected with a PONAR sampler in August 2021. The results will be reported in a later report for the 2022 bathymetric survey.

The bathymetric survey was conducted from a boat using a multibeam depth sounder that was interfaced with real-time kinematic Global Positioning System (RTK-GPS) instruments (for horizontal positioning) to map the reservoir bottom. Water surface elevation records (Bureau of Reclamation [Reclamation] Hydromet, https://www.usbr.gov/gp/hydromet/dayfile_form.html) in Reclamation Project Vertical Datum (RPVD) were used as the vertical reference. The 2021 bathymetric survey of Willow Creek Reservoir was combined with 2021 aerial photogrammetry by Dr. Luke Javernick (River Science, Cañon City, Colorado) to produce a combined digital surface of the reservoir bottom.

The bathymetric survey was conducted between Aug 16 and 17, 2021, when the reservoir water surface elevation ranged from between 8118.70 to 8118.87 feet (ft) (RPVD), just over 11 ft below the top of the active conservation pool elevation of 8130.00 ft. The above-water topographic data were collected between August 31 and September 2, 2021, when water elevations were between 8118.51 and 8118.78 ft (RPVD).

Analysis of the combined datasets indicates the following results:

- At reservoir water surface elevation 8113.50 ft (RPVD), which is nearly 5 ft below water at the time of survey, the reservoir surface area was 186 acres with a storage capacity of 5,935 acre-feet.

  At the top of the surcharge pool elevation (8132 ft, RPVD), the reservoir had a surface area of 328 acres and a storage capacity of 10,643 acre-feet.

- Since the original survey of the reservoir in 1956, the reservoir is estimated to have lost 549 acre-feet of storage capacity (5.2 percent) due to sedimentation, measured at the top of the surcharge pool. This volume represents a sediment yield rate of 0.06 acre-feet/ mi^2/yr, which is considered a very low sedimentation rate as defined in Reclamation (2006).

- By 2021, the dead storage pool volume had reduced to 82.4 percent of the original dead storage volume. The sedimentation level at the dam is at 8043.91 ft (RPVD), which is 82.5 percent of the height between the original reservoir bottom 8137 ft (RPVD) as referenced in the allocation table) and the top elevation of the dead storage pool.

- Using the original capacity (1956 survey) and the capacity as determined in the 2021 survey, the sedimentation rate is 8 acre-feet/year. The 2021 survey indicated an increase in reservoir capacity compared to the results of the 2020 survey due to the difference in survey methods and bottom coverage of the 2020 and 2021 surveys. The 2020 survey used a combination of a single beam transducer and an Acoustic Doppler Current Profiler (ADCP) and only achieved limited bottom coverage. This required a nontrivial amount of interpolation across the reservoir bottom to create the reservoir map. The 2021 survey used a multibeam transducer and achieved full bottom coverage.

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	Willow Creek Reservoir	**Region**	Missouri Basin and Arkansas – Rio Grande – Texas
Owner	Area Office Manager	**Area office**	Eastern Colorado
Stream	Willow Creek	**Vertical datum**	RPVD
County	Grand	**Top of dam (ft)**	8140.00
State	Colorado	**Spillway crest (ft)**	8130.00
Latitude (deg min sec)	40 08 50.00	**Power penstock elevation (ft)**	N/A
Longitude (deg min sec)	105 56 31.24	**Low-level outlet (ft)**	8077.00
HUC4*	1401	**Hydraulic height (ft)**	95.0
HUC8*	14010001	**Total drainage area (mi^2)**	133
NID ID**	CO01670	**Date storage began**	10/1/1953
Dam purpose	Storage, C-BT***) operation	**Date for normal operations**	1953

* HUC = Hydrologic Unit Code.
** NID = National Inventory of Dams.
***C-BT = Colorado-Big Thompson.

Original design				
Storage allocation	**Elevation (ft)**	**Surface area (acres)**	**Capacity (acre-feet)**	**Gross capacity (acre-feet)**
Surcharge	8132.00	321	11,177	11,177
Flood control	N/A	N/A	N/A	N/A
Multiple use	N/A	N/A	N/A	N/A
Joint use	N/A	N/A	N/A	N/A
Conservation	8130.00	303	10,553	3,329
Inactive	8117.00	212	7,224	5,738
Dead	8077.00	100	1,486	1,486

Survey summary							
Survey date	**Type of survey**	**Number of range lines or contour intervals**	**Contributing sediment drainage area (mi^2)**	**Period sedimentation volume (acre-feet)**	**Cumulative sedimentation (acre-feet)**	**Lowest reservoir elevation (ft)**	**Remaining portion of dead storage (%)**
1956	Unknown	N/A	133	Unknown	Unknown	8037.00	100
2020	Bathymetric	N/A	133	752	752	8035.00	77
2021	Bathymetric	M/A	133	-203	549	8043.91	82.4

Notes: The 2021 survey indicates a slight gain in reservoir capacity relative to the 2020 survey due to the type of surveys performed and the equipment used. The 2020 survey used a single beam transducer and an ADCP as sonar devices, achieving partial coverage (< 35%), requiring interpolation across large portions of the reservoir bottom. The 2021 survey utilized a multibeam transducer and obtained full coverage of the reservoir, except in the uppermost delta (> 90%).

1.0 Introduction

Willow Creek Dam and Reservoir are on Willow Creek about 3 miles east of Lake Granby, which lies between the towns of Granby and Grand Lake in Grand County, Colorado. This location is in the Rocky Mountains 60 miles northwest of Denver (figure 1). A complete and full coverage bathymetric survey of Willow Creek Reservoir was performed from August 16 to 17, 2021, using a multibeam sonar deployed from a boat. Sediment samples were collected from August 17 to 18, 2021. In addition, aerial photography was flown to survey the above-water topography (Dr. Luke Javernick, River Science, Cañon City, Colorado). This survey is the second annual survey to track sedimentation following the East Troublesome Fire that burned 91 percent of the watershed. The fire was reported on the afternoon of October 14 and was declared contained November 30, 2020 (https://inciweb.nwcg.gov/incident/7242/). Additional annual surveys are planned for 2022, 2023, and 2024 to monitor the reservoir for increased sedimentation following the fire. The dam and reservoir are operated by the Northern Colorado Water Conservation District as part of the Colorado-Big Thompson Project that supplies water for municipal, industrial, and recreational uses, power generation, and irrigation of 720,000 acres of farmland. The reservoir provides an annual average of 40,000 acre-feet of water to Lake Granby via a pumping plant.

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 a delta at the upstream end 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 following the East Troublesome Fire, the Bureau of Reclamation (Reclamation), Technical Service Center's Sedimentation and River Hydraulics Group (86-68240) requested funding from the Science and Technology Program to conduct a bathymetric survey of the underwater portions of the reservoir that were accessible by boat in 2021. A complete and full coverage bathymetric survey was conducted from August 16 to 17, 2021, with these primary objectives:

1. Estimate reservoir sedimentation volume since the previous survey in November 2020 and February 2021 (considered to be the 2021 survey).

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

3. Measure sediment particle size distributions, bulk densities, and chemical attributes of the bottom sediment throughout the delta region of the reservoir. Samples were collected with a PONAR sampler in August 2021. The results will be reported in a later report for the 2022 bathymetric survey.

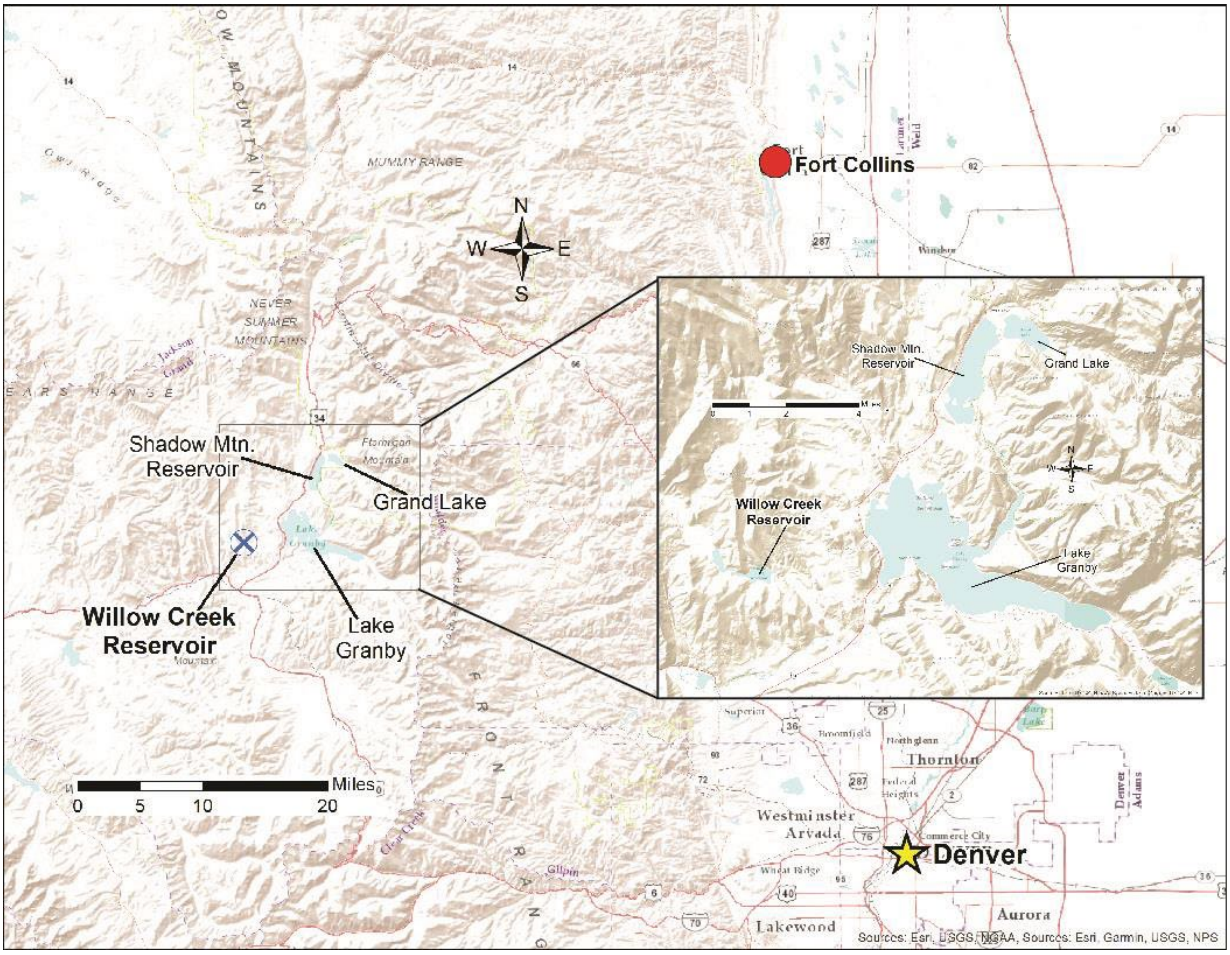

Figure 1.—Location map of Willow Creek Reservoir and Dam, 60 miles northwest of Denver, Colorado.

2.0 Watershed Description

2.1 Location and Drainage

The watershed upstream of Willow Creek Dam has a total contributing drainage area of 133.4 mi^2. Basin elevation ranges from 12,300 feet (ft) in the headwaters to 8130 ft Reclamation Project Vertical Datum (RPVD) at the top of the conservation pool. The entire basin contributes sediment to the reservoir, as there do not appear to be any dams upstream of the reservoir, and only about 0.4 percent of the basin is occupied by lakes (table 1; figure 2). All information in this section was taken from Hilldale and Bradley (2021).

Table 1.—Willow Creek watershed characteristics from U.S. Geological Survey (USGS) StreamStats (USGS 2021)

Watershed characteristic	Value
Drainage area	133.4 mi^2
Unregulated drainage area	133.0 mi^2
Mean annual precipitation	24.8 inches
Mean basin elevation	9514 ft
Maximum elevation	12,300 ft
Minimum elevation (at top of conservation pool)	8130 ft
Percent of impervious area	2.8%
Percent of drainage area covered by forest	54.6%

Figure 2.—The watershed above Willow Creek Reservoir has a total drainage area of 133 mi^2 and a sediment-contributing drainage area of 133 mi^2 (Hilldale and Bradley 2021).

2.2 Geology

The surface geology in the Willow Creek watershed consists primarily of the Tertiary arkosic conglomerate and shale of the Coalmont Formation. At the eastern side of the watershed a sequence of upturned Mesozoic volcanic and sedimentary rocks rest unconformably on the pre-Cambrian igneous and metamorphic basement. The Mesozoic sequence is overlain by interlayered Tertiary volcanic and sedimentary rocks in the vicinity of the reservoir and by bouldery gravel mantling Pliocene erosion surfaces further to the north. The western half of the reservoir is underlain by Cretaceous Pierre Shale. Basalt flows and Miocene to Pliocene sandstones and shales of the Troublesome Formation underly the eastern half of the reservoir. At the dam site, the bedrock is the sandstones and shales of the Troublesome Formation (table 2; figure 3) (Horton 2017).

Table 2.—Surface geology of the Willow Creek watershed (Horton 2017)

Name	Major components	Area (mi^2)	Percent of watershed
Coalmont Formation	Arkose, conglomerate, shale	94.4	70.7
Pierre Shale, undivided	Shale	12.9	9.6
Bouldery gravel on old erosion surfaces	Gravel	8.7	6.5
Windy Gap Member of Middle Park Formation	Conglomerate	4.5	3.4
Biotitic gneiss, schist, and migmatite	Biotite-gneiss, schist, migmatite	3.2	2.4
Landslide deposits	Unconsolidated	2.3	1.7
Middle Tertiary intrusive rocks	Mafic-hypabyssal, felsic-hypabyssal	1.6	1.2
Basalt flows and associated tuff, breccia, and conglomerate of late-volcanic bimodal suite	Basalt	1.6	1.2
Troublesome Formation	Sandstone, siltstone	1.4	1.0
Mesozoic rocks	Clastic	1.0	0.7
Volcanic rocks in northwestern Colorado	Mafic-volcanic	0.7	0.5
Colorado Group	Shale	0.5	0.4
Glacial drift	Unconsolidated	0.0	0.0

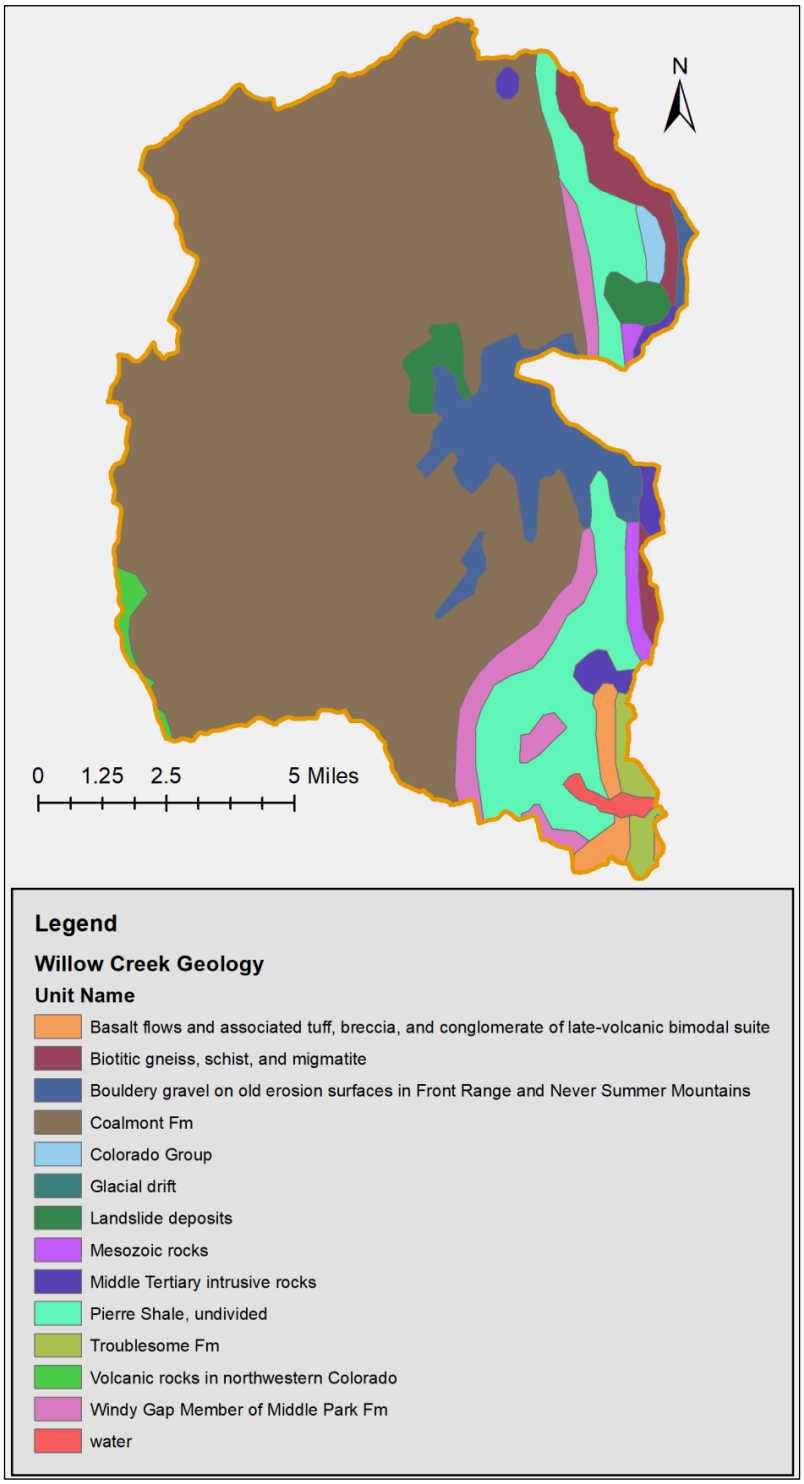

Figure 3.—Surface geology of the Willow Creek watershed (Hilldale and Bradley 2021).

2.3 Vegetation and Land Management

The watershed is primarily undeveloped. Forests (54.6 percent of area), shrubland (33.7 percent), and grasslands (7.2 percent) cover 95.5 percent of the basin area. Ninety-one percent of the basin is public land managed by the U.S. Forest Service (84 percent) and Bureau of Land Management (7 percent).

2.4 Climate and Runoff

The Willow Creek watershed has a cold, relatively dry climate. The nearby town of Granby, about 5 miles south, has a climate classified as sub-arctic due to the high elevation (Dfc in the Köppen–Geiger climate classification system). Inflows to the reservoir are from Willow Creek, which along with its tributaries, comprises nearly all the total drainage area. The Willow Creek watershed is ungauged upstream of the reservoir, and U.S. Geological Survey (USGS) gage number 09021000 is immediately downstream from the dam. StreamStats (USGS 2021) estimates that mean annual flow in Willow Creek is 87.7 ft^3/s, which corresponds to a mean annual runoff volume of 63,492 acre-feet. The Willow Creek Reservoir capacity at the top of the conservation pool (elevation 8130 ft) in 2021 was estimated to be 9,801 acre-feet. The ratio of reservoir storage capacity to the mean annual runoff is 0.15, meaning that the entire reservoir can store about one sixth of the average annual Willow Creek runoff.

2.5 Dam Operations and Reservoir Characteristics

Willow Creek Reservoir provides 3,353 acre-feet of operating capacity (active conservation) between elevations 8117 and 8130 ft (RPVD). Water from Willow Creek Reservoir is diverted via the Willow Creek Pump Canal and Pumping Plant to Lake Granby for storage. This water is then pumped from Lake Granby to Shadow Mountain Reservoir and gravity fed to Grand Lake and then through the Alva B. Adams tunnel to the eastern slope of the Rocky Mountains. A plot of water elevations is shown on figure 4.

Willow Creek Dam is an earth and rock dam with a structural height of 127 ft and a crest length of 1,100 ft. Dam construction was completed in 1953, and it began storing water in that same year. Historic records of water level began on October 1, 1953. Due to the small reservoir volume relative to runoff volume, the reservoir is often operated to fill multiple times throughout each year. An example of this is shown on figure 4. Operation of Willow Creek Reservoir is coordinated with the needs of Lake Granby and the Colorado-Big Thompson Project. Reservoir levels are generally kept within the active conservation pool (8117 to 8130 ft, RPVD). Historic water elevation records (1953 to present) are shown on figure 5.

The reservoir is widest from 1,000 to 4,000 ft upstream of the dam, where the average width is about 2,000 ft. Upstream of the widest portion the reservoir, it narrows to between 250 and 400 ft. The delta portion of the reservoir is generally 1,200 ft wide.

There have been no known sediment management activities in this reservoir.

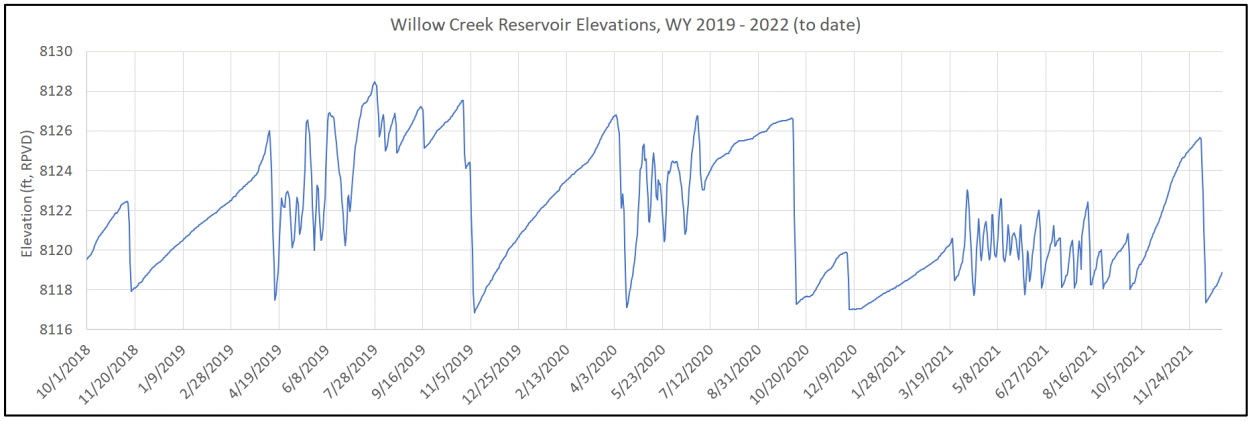

Figure 4.—Plot of Willow Creek Reservoir elevations for water years 2019–2022 (to date), demonstrating the multiple fill cycles per year.

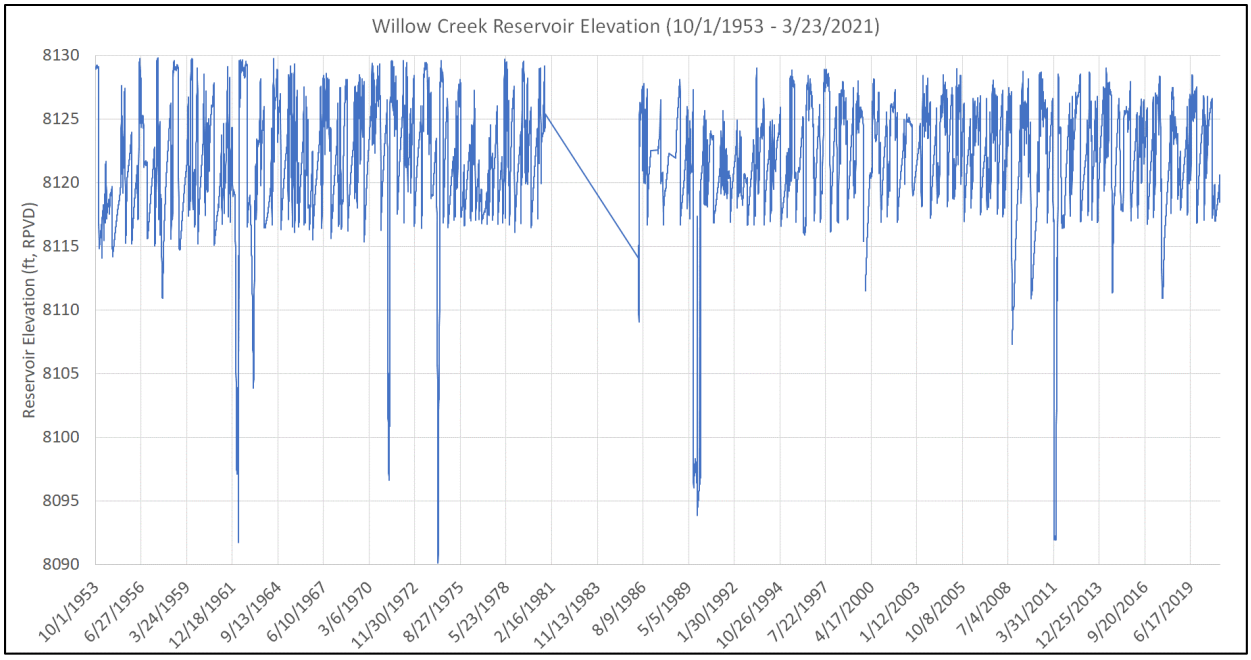

Figure 5.—Historic Willow Creek Reservoir water surface elevations (RPVD). Spillway elevation is 8130 ft, and top of dead pool elevation is 8,077 ft.
Data web source: https://www.usbr.gov/gp/hydromet/hydromet_arcread.html. Water elevation data unavailable from October 1980 until May 1986.

3.0 Previous Reservoir Surveys

Following dam closure and initial reservoir filling, a survey was conducted in 1956 to measure the original surface areas and corresponding storage capacities. The documentation summarizing the original survey methods has not been located for this analysis. Previous surveys are shown in table 3.

Table 3.—Previous bathymetric reservoir surveys

Survey year	Extent of survey	Survey method	Depth sounder	Above-water survey
1956	Unknown	Unknown	Unknown	Unknown
2020	Full	Surface mapping	ADCP and single beam	Aerial photogrammetry 2020
2021	Full	Surface mapping	Multibeam	Aerial photogrammetry 2021

In November 2020 and February 2021, Willow Creek Reservoir was surveyed as soon as access was possible following the East Troublesome Fire, which burned 91 percent of the Willow Creek watershed above the reservoir (Hilldale and Bradley 2021). At the time, the intent was to survey this reservoir annually to monitor the sediment inflow that may occur at an increased rate following the fire. The 2020 survey was intended to serve as the pre-fire baseline survey of the reservoir. No significant runoff occurred during or immediately following the East Troublesome Fire, which was declared contained on November 30, 2020.

The 2020 Willow Creek sedimentation survey was considered an emergency response. As a result, the Sedimentation and River Hydraulics Group was unable to perform a full-coverage survey of Willow Creek Reservoir and was not able to utilize a multibeam sonar (see figure 6 for a coverage map). The survey was performed using a vessel of opportunity with a SonTek M9 Acoustic Doppler Current Profiler (ADCP) and a single beam Hydrolite transducer. The upper reservoir was under ice during the bathymetric survey in November, making it necessary to perform a survey through ice in February 2021. More details on this survey and the East Troublesome Fire can be found in Hilldale and Bradley (2021).

More details on these previous surveys are described in these reservoir survey reports:

- 1956 survey (Reclamation 1981)
- 2020 survey (Hilldale and Bradley 2021)

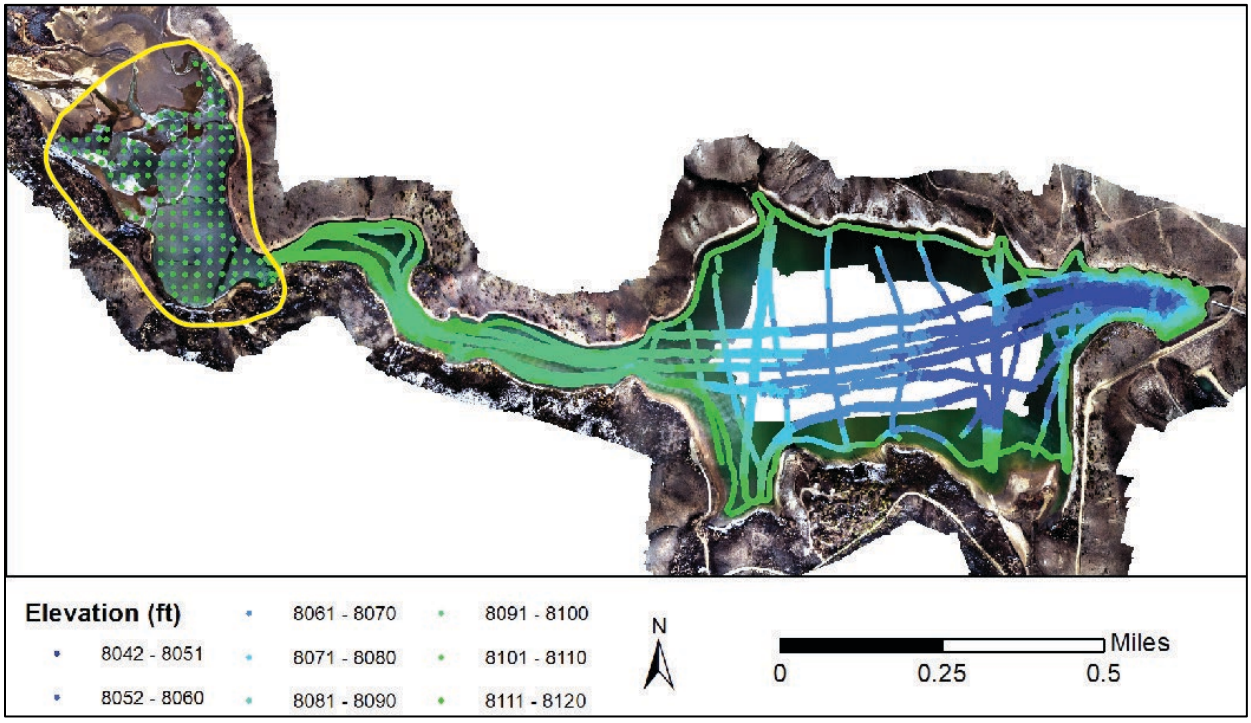

Figure 6.—Figure showing the survey coverage of the 2020 Willow Creek bathymetric survey. The area outlined in yellow was surveyed through the ice in February 2021. Image created by Dr. Luke Javernick (River Science, Cañon City, Colorado) and reported in Hilldale and Bradley (2021).

4.0 2021 Reservoir Survey Methods and Extent

4.1 Survey Methods

A complete and full coverage bathymetric survey was conducted during August 2021 from a boat using a multibeam depth sounder to continuously measure water depths. The horizontal position of the moving boat was continually tracked using a real-time kinematic Global Positioning System (RTK-GPS). A map of the data points collected is presented on figure 7.

Appendix A provides more details of the hydrographic survey methods. These bathymetric data were combined with photogrammetry data collected above water during September 2021 using a drone. Dr. Luke Javernick produced the combined digital surface of the reservoir bottom (Javernick 2021). Appendix B provides more details about the above-water survey data that were collected with a camera and drone and processed using structure from motion. Appendix C provides more details about the methods used to generate surface area and storage capacity tables. Appendix D contains contour maps of the reservoir.

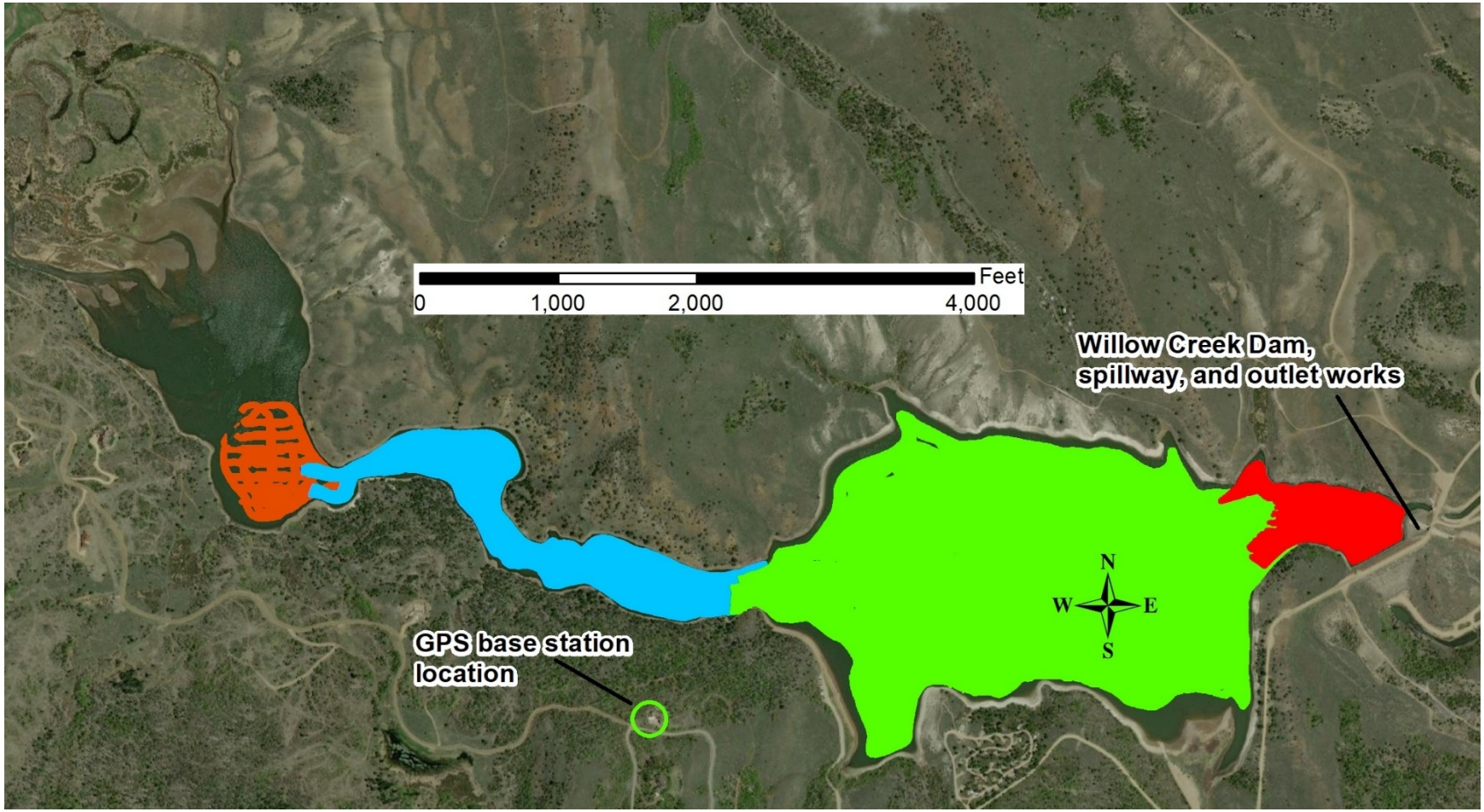

Figure 7.—Map of multibeam bathymetric survey data coverage.
Different colors represent bathymetry data that were processed together.

4.2 Survey Control, Datum, and Monuments

For the 2021 Willow Creek Reservoir survey, a new benchmark was placed in the vicinity of the former benchmarks used. The new benchmark is 18-inch rebar with an aluminum cap (see figure 8). The cap is labeled "USBR Sedimentation Survey WCR 21." This benchmark is approximately 50 ft from the road near the eastern edge of the clearing (see figure 9). It is likely that vegetation will regrow at this site as the area recovers from the fire, making recovery a bit more difficult. This new benchmark should be used for future surveys. The coordinates are shown in table 4. The location of the Global Positioning System (GPS) base station and benchmark, relative to the reservoir, is shown on figure 7.

Table 4.—Coordinates for the new benchmark, used for 2021 survey

North American Datum 1983 (NAD83) State Plane Coordinates, Colorado North		
Northing	**Easting**	**Elevation**
394906.829 meters	875094.345 meters	2557.527 meters
1295623.488 usft*	2871038.697 usft*	8390.820 usft*

* U.S. survey feet.

For the 2021 survey, all bathymetry and GPS control measurements were collected in North American Datum 1983 (NAD83) State Plane (horizontal) coordinates, Colorado North, U.S. survey feet and North American Vertical Datum 1988 (NAVD88), Geoid 18, U.S. survey feet elevations. During processing, all bathymetry and vertical GPS measurements were converted to RPVD for Willow Creek Dam. The RPVD was determined to be 6.48 ft lower than NADV88 (Geoid 18). This vertical shift to RPVD is the same shift that was used for the 2020 survey. The RPVD at Willow Creek Reservoir was determined from multiple RTK-GPS measurements on the spillway crest. The RPVD elevation of the spillway crest (8130 ft) was determined from the original design drawings.

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) (National Oceanic and Atmospheric Administration 2022).

Figure 8.—Image of the cap on the new benchmark.

Figure 9.—GPS base station set up over the new benchmark (note burned tree in the background).

5.0 Sediment Sampling

Sediment samples were collected from the reservoir bottom at 14 locations in the upper reservoir (figure 10; table 5). The downstream (eastern) samples (numbers 10, 11, 12, and 14) were taken at various depths on the delta face. Sample number 13 is downstream of the delta face. These samples were collected using a PONAR sampler (figure 11). A PONAR sampler is allowed to free-fall to the bottom, where the jaws close and grab a sample of the surface sediment. The volume of the sediment sample is approximately 0.5 gallon. The positions of the samples were marked using "targets" in Hypack and are stored electronically in the archived project.

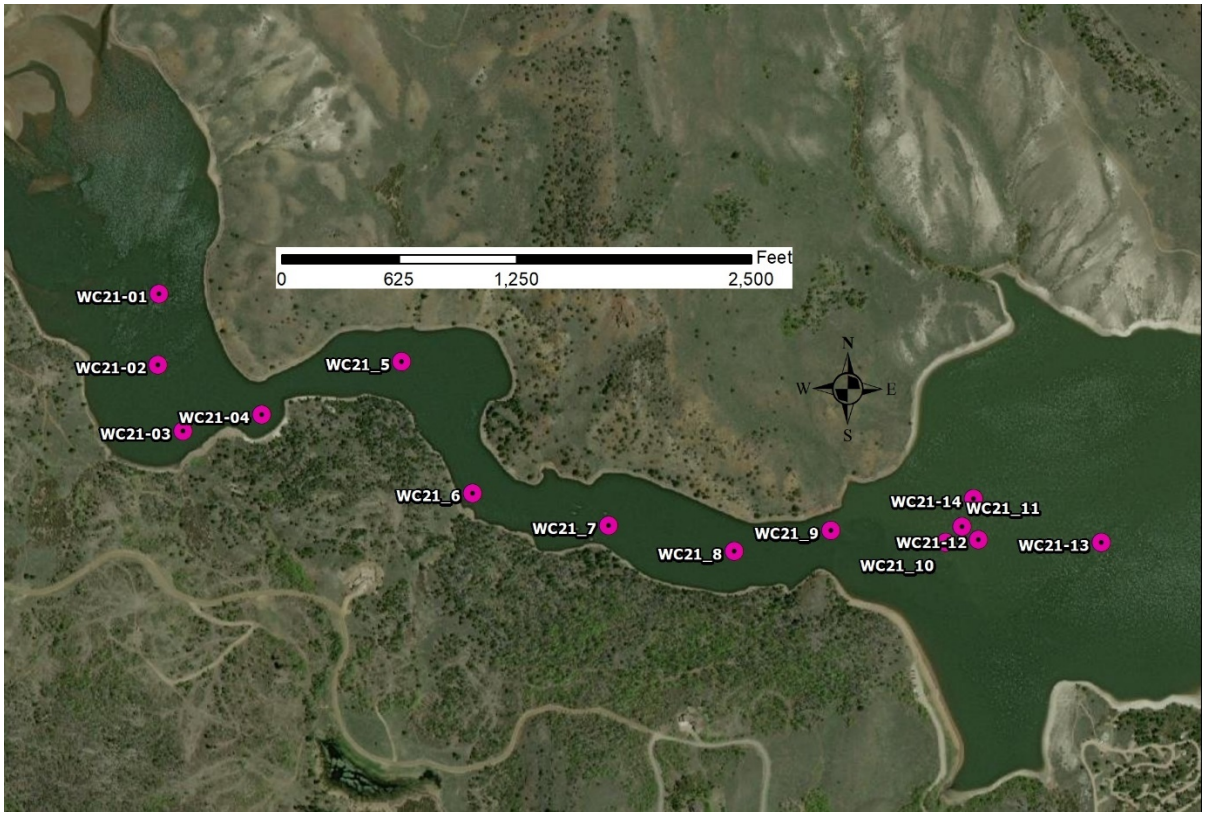

Figure 10.—Locations of the sediment samples taken in Willow Creek Reservoir, August 2021.

The sediment samples have not been processed as of this writing and have been stored in a freezer since collection in August 2021. The sediment samples may be of interest to a concurrent water quality study on Willow Creek Reservoir and will be available for additional analysis. The Sedimentation and River Hydraulics Group will have the samples processed for particle size and organic content. Samples can be collected in consecutive years for annual comparison. These data may lead to conclusions about sediment and organic content deposition in the reservoir following the East Troublesome Fire.

Table 5.—Table of sediment sample coordinates and depth below water surface

Sample number	Latitude	Longitude	Depth (ft)
WC21-01	40° 9'0.87"N	40° 9'0.87"N	5.5
WC21-02	40° 8'57.12"N	105°58'15.75"W	8.7
WC21-03	40° 8'53.66"N	105°58'14.01"W	10.5
WC21-04	40° 8'54.54"N	105°58'8.64"W	12.3
WC21-05	40° 8'57.36"N	105°57'59.07"W	15.5
WC21-06	40° 8'50.49"N	105°57'54.19"W	18.8
WC21-07	40° 8'48.82"N	105°57'44.84"W	22.4
WC21-08	40° 8'47.50"N	105°57'36.25"W	23.7
WC21-09	40° 8'48.62"N	105°57'29.62"W	24.7
WC21-10	40° 8'48.03"N	105°57'21.75"W	25.3
WC21-11	40° 8'48.86"N	105°57'20.66"W	35.3
WC21-12	40° 8'48.16"N	105°57'19.52"W	43.5
WC21-13	40° 8'48.07"N	105°57'11.10"W	54.0
WC21-14	40° 8'50.32"N	105°57'19.88"W	42.3

Figure 11.—Photograph of the PONAR sampler (on the bow of the boat) used to collect the reservoir bottom sediment samples.

6.0 Reservoir Surface Area and Storage Capacity

Tables of reservoir surface area and storage capacity were produced for the full range of reservoir elevations (Willow Creek Reservoir (CO) Area and Capacity Tables 2021). Plots of the 2021 area and capacity curves are presented on figure 12 along with curves from the 1956 and 2020 surveys. An abbreviated table with 5-ft increments and key elevations is contained in table 6. For the 2021 survey, area and capacity curves are based on the bathymetric (below-water) survey up to elevation 8113.5 feet (RPVD), while curves above this elevation are based on 2021 aerial photogrammetry (Javernick 2021). A comparison of these curves indicates that the largest reduction in surface area and storage capacity occurs between elevations 8080 and 8120 ft (RPVD).

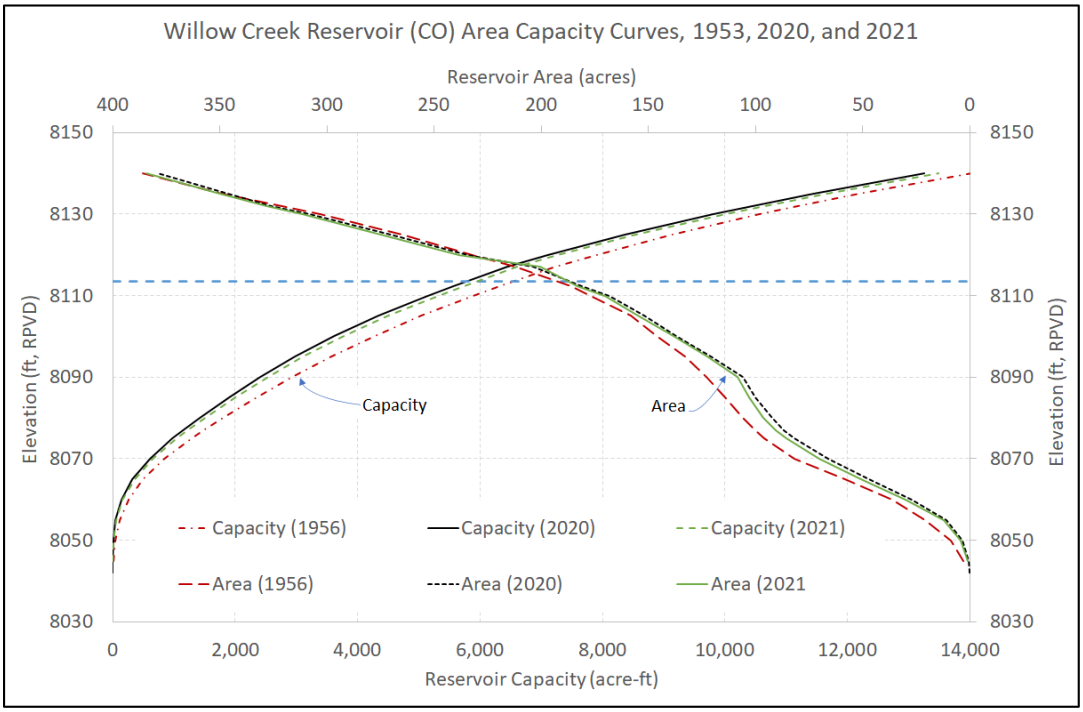

Figure 12.—Plot of Willow Creek Reservoir surface area and storage capacity versus elevation. Three surveys are included 1956, 2020, and 2021.
Data below the dashed horizontal line represents the portion of the reservoir surveyed with sonar.

At reservoir water surface elevation 8113.5 ft (RPVD), which is approximately 5 ft below water at the time of survey, the reservoir surface area was 185.8 acres with a storage capacity of 5,935.2 acre-feet. At the top of dead pool elevation (8077 ft, RPVD) the reservoir would have a surface area of 90.5 acres and a storage capacity of 1,224.1 acre-feet.

Table 6.—Historical summary of reservoir surface area, storage capacity, and sedimentation volume

Elevation (ft, RPVD)	Reservoir surface area (acres)			Reservoir storage capacity (acre-feet)			Sedimentation volume (acre-feet)		
	1956	2020	2021	1956	2020	2021	1953 to 2020	1953 to 2021	2020 to 2021
8045	3	0.5	0.8	12	0.4	4	12	8	-3
8050	9	3.4	4	42	9.6	16	32	26	-6
8055	21	11	12	117	43	52	74	65	-9
8060	36	27	30	260	141	158	119	102	-17
8065	58	47	51	495	323	356	172	139	-33
8070	82	66	70	844	601	654	243	190	-53
8075	96	82	86	1,290	975	1,048	315	242	-73
8077[1]	100	87	90	1,486	1,144	1,224	342	262	-80
8080	106	92	96	1,795	1,414	1,505	381	290	-91
8085	114	100	103	2,345	1,894	2,006	451	339	-112
8090	123	106	109	2,937	2,407	2,535	530	402	-128
8095	133	121	123	3,577	2,970	3,110	607	467	-140
8100	146	137	138	4,275	3,618	3,767	657	508	-149
8105	158	152	155	5,035	4,345	4,502	690	533	-157
8110	177	168	170	5,873	5,144	5,311	729	562	-167
8112.38[2]	186	181	183	6,311	5,559	5,730	752	581	-171
8117[3]	212	204	201	7,224	6,448	6,611	776	613	-163
8120	232	234	238	7,891	7,100	7,260	791	631	-160
8125	265	270	275	9,133	8,360	8,541	773	592	-181
8130[4]	303	308	311	10,553	9,801	10,004	752	549	-203
8132[5]	321	326	328	11,177	10,436	10,643	741	534	-207
8135	349	346	350	12,185	11,446	11,662	739	523	-216
8140[6]	386	379	384	14,020	13,257	13,495	763	525	-238

[1] Top of dead storage, lowest outlet.
[2] Canal invert.
[3] Top of inactive storage.
[4] Top of active conservation storage.
[5] Top of surcharge pool.
[6] Top of dam crest

7.0 Reservoir Sedimentation Volume Spatial Distribution

A longitudinal profile of the 2021 reservoir bottom surface was developed in a Geographic Information System (GIS) along the alignment presented on figure 13. The longitudinal profile (figure 14) shows that some sedimentation has occurred in the delta region (station 4,000 and upstream through the normally wetted portion of the delta).

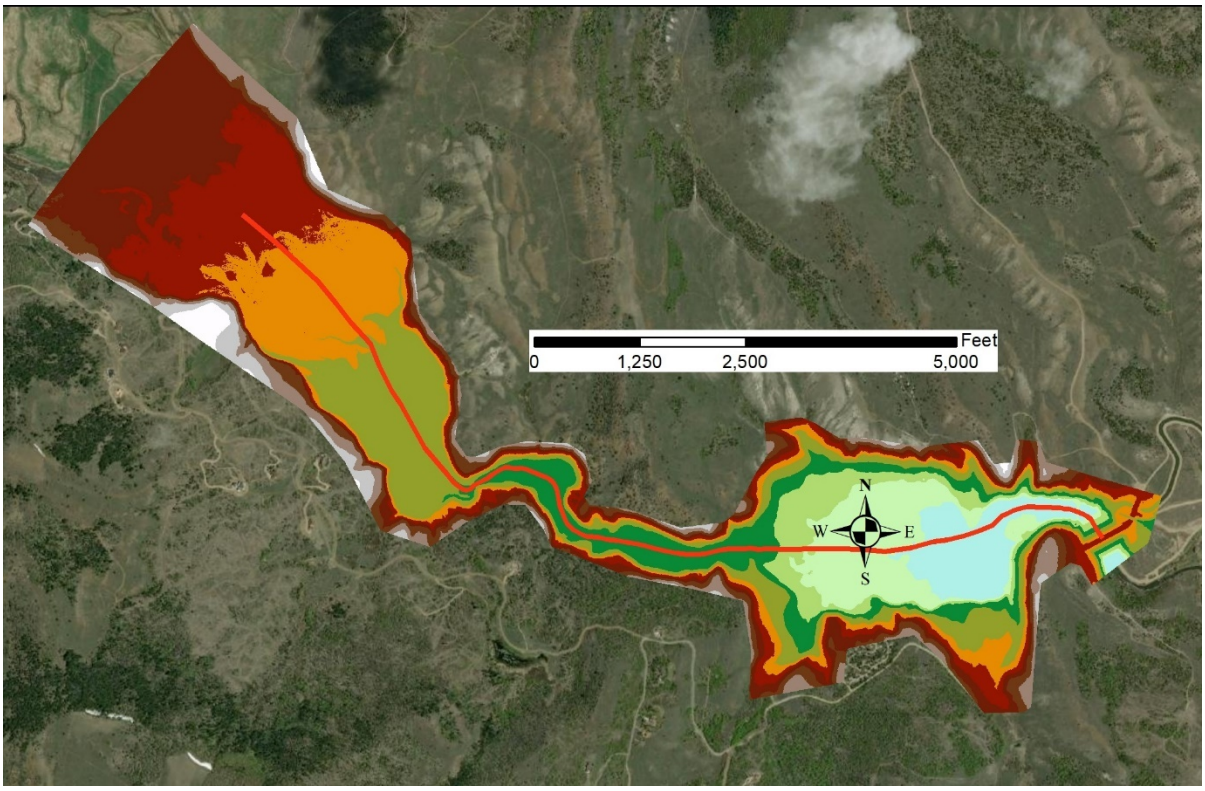

Figure 13.—Reservoir surface elevation map and alignment of longitudinal profile – the profile begins and ends at elevation 8140 ft (RPVD).

An analysis of reservoir bed elevation change from the 2020 to 2021 surveys has been performed by Javernick (2021). This comparison was difficult due to the two very different coverages of the surveys and the difference in sonar devices used. The most reliable portion of this analysis indicated between 0.5 and 1 ft of increased bed elevation in the delta region of the reservoir (station > 4,000 on figure 14).

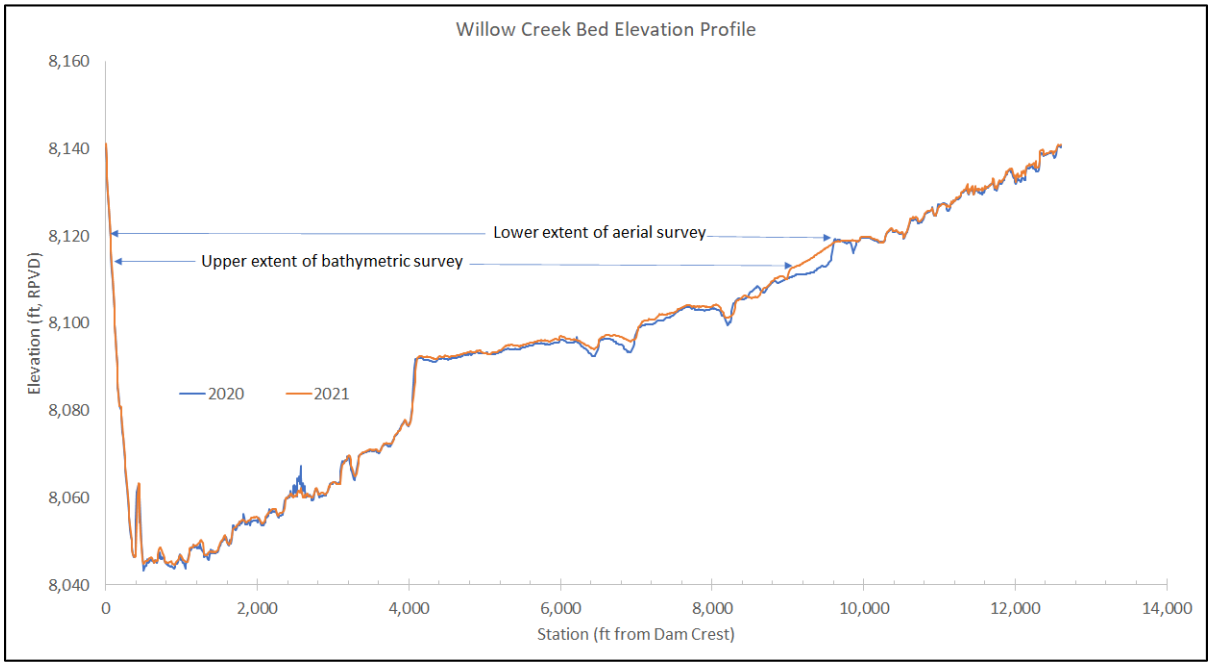

Figure 14.—Longitudinal profile of Willow Creek Reservoir bottom from the dam upstream through the delta.
Note the anomaly in the 2020 profile at station 2,550. Between stations 9,000 and 9,650 it was necessary to interpolate the digital surface between the bathymetry and the above-water topography. This region was surveyed through ice in February 2021 to complete the 2020 survey.

8.0 Sedimentation Trends

The sedimentation trends discussed in the 2020 survey report (Hilldale and Bradley 2021) remain valid after the 2021 survey. The changes in reservoir capacity from the 2020 survey to the 2021 survey indicate a very slight increase in reservoir capacity, which is primarily due to interpolation error in the 2020 bathymetric survey data throughout the largest portion of the reservoir. Interpolation was necessary due to the limited coverage of the 2020 bathymetric survey. Evaluating a trend from 2020 to 2021 will not yield meaningful results under these conditions, although trend evaluation is expected to be more meaningful in coming years as repeat surveys continue. The differences seen in reservoir capacity from 2020 to 2021 are small enough that they are within the error of the surveys.

9.0 Conclusions and Recommendations

9.1 Survey Methods and Data Analysis

The 2021 bathymetric survey, combined with 2021 photogrammetry data of the above-water topography, has been used to produce an accurate digital surface of the reservoir bottom. The bathymetric and above-water topographic data did not overlap and required interpolation at the margins of the reservoir and through a large portion of the delta, where there was approximately 650 ft (horizontal distance along reservoir axis) between the bathymetric and topographic surveys.

Reservoir surface areas were computed from this digital surface at 1-foot vertical intervals to determine the 2021 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 to sedimentation and the differences in survey methods. The latest surface area and storage capacity curves compare reasonably well with the original curves and with curves from the 2020 survey; however, there was a slight increase in capacity when comparing the 2020 and 2021 surveys. The capacity increase in dead pool (below elevation 8077 ft) volume is 7 percent. The increase in the volume of the surcharge pool (below 8132 ft) volume is 2 percent. Using a multibeam transducer and obtaining full coverage for the 2021 survey produced a more accurate and precise digital surface of the reservoir bottom than past surveys using other methods.

9.2 Sedimentation Progression and Location

Since the 1956 survey (65 years), sedimentation has filled in 5 percent of the original storage capacity as measured at the spillway crest (elevation 8130 ft). The 2021 reservoir survey indicates that most of this sedimentation is located in the delta, which extends through the narrow portion of the reservoir downstream to station 4,000 (see figure 14). Sedimentation has also deposited near the dam in the lowest portions of the reservoir, and 82.4 percent of the original dead storage capacity remains as of 2021. The lowest dam outlet (8077 ft) may not be as reliable after the dead storage has filled with sediment because the future deposition of logs and sediment may accumulate on the trash rack.

9.3 Recommendation for Next Survey

Over the next three years (2022–2024) Willow Creek Reservoir will be surveyed. This frequency of survey is due to the East Troublesome Fire in 2020. Additionally, sediment samples will be collected in 2022–2024 in the same locations as indicated earlier in this report (see figure 10 and table 5). Reclamation's Science and Technology Program has funded these future surveys and the sediment sampling through a competitive research grant program. In the final year of research funding (2024), sediment cores (up to 8 ft deep) are planned to be collected in the delta area.

10.0 Acknowledgments

The funding for this bathymetric survey was provided by Reclamation's Science and Technology Program. The funding for report writing was provided by the Asset Management Division. Dr. Luke Javernick (River Science, Cañon City, Colorado) collected the above-water survey data (drone photogrammetry) and processed the combined bathymetry and topography to create a final digital elevation model (DEM). Dr. Javernick also produced the DEM of difference showing aggradation since the 2020 survey. The Northern Colorado Water Conservation District funded Dr. Javernick's work on this project.

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Appendix A

Hydrographic Survey Equipment and Methods

The 2021 bathymetric survey was conducted from August 16 to 17, 2021. The final day (August 18) was spent collecting sediment samples and demobilizing the equipment. During surveying August 16 (evening) and August 17 (morning and early afternoon) reservoir water surface elevations varied from 8118.51 to 8118.78 feet Reclamation Project Vertical Datum (RPVD).

The survey was conducted along a series of predetermined cross section, longitudinal, and radial survey lines. The survey lines were spaced closely enough so there would be overlapping coverage from the multibeam depth sounder, except for the shallowest portion of the upper delta.

The 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 a multibeam echo sounder (Norbit iWBMSh), which consisted of the following equipment:

- Variable-frequency transducer with integrated motion reference unit
- Near-surface sound velocity probe
- Two Global Positioning System (GPS) receivers to measure the boat position and heading
- An external GPS radio to communicate with a base station in real time
- Processor box for synchronization of all depth, sound velocity, position, heading, and motion sensor data

Figure A-1.—Wooldridge boat with real-time kinetic Global Positioning System (RTK-GPS) and multibeam depth sounder system (Odom MB-1 sonar transducer shown).

The Norbit multibeam transducer has a curved array and emits up to 512 beams (user selectable); it surveyed a swath width of 160 degrees during the 2021 survey. 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 measured by the sonar.

Real-time kinetic Global Positioning System (RTK-GPS) survey instruments were used to continuously measure the position of the survey boat and to measure other ground control points and water surface elevation. The GPS base station and receiver were set up on a tripod over a new point overlooking the reservoir (figure 2, main report). 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 ultra high frequency antenna (figure A-2). The base station was powered by a 12-volt battery.

Figure A-2.—The RTK-GPS base station setup used during the survey of Willow Creek Reservoir in Colorado.

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 centimeters (cm) horizontally and ±3 cm vertically for stationary points and within ±15 cm for the moving survey boat.

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 (NAD83) coordinates and North American Vertical Datum 1988 (NAVD88) elevations in the State Plane Colorado North projection in units of U.S. survey feet. Elevations from the spillway crest obtained from design drawings and RTK-GPS measurements were used to convert the vertical reference measurements to RPVD.

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 post-processing. Final processing of the bathymetric data resulted a raster mesh with 3-foot square cells. For each raster mesh cell, the reservoir bottom elevation is assigned 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

The above-water topography was acquired from August 31 through September 2, 2021, by River Science (Javernick 2021). The data were acquired via drone and captured 3,573 images at a resolution of 1.13 inches per pixel (i.e., ground sample distance) (Javernick 2021). The area covered by the aerial survey, flown September 2, 2021, is shown on figure B-1).

Dr. Javernick was tasked with combining the bathymetry and topography to create a digital elevation model (DEM) (Javernick 2021). This DEM was used by the Bureau of Reclamation to determine the area and capacity table for the 2021 survey. For more information regarding the aerial data collection, surface development, and geomorphic change detection, see Javernick (2021).

Figure B-1.—Willow Creek Reservoir aerial survey extents for the 2021 topography. This figure is taken from Javernick (2021).

Appendix C

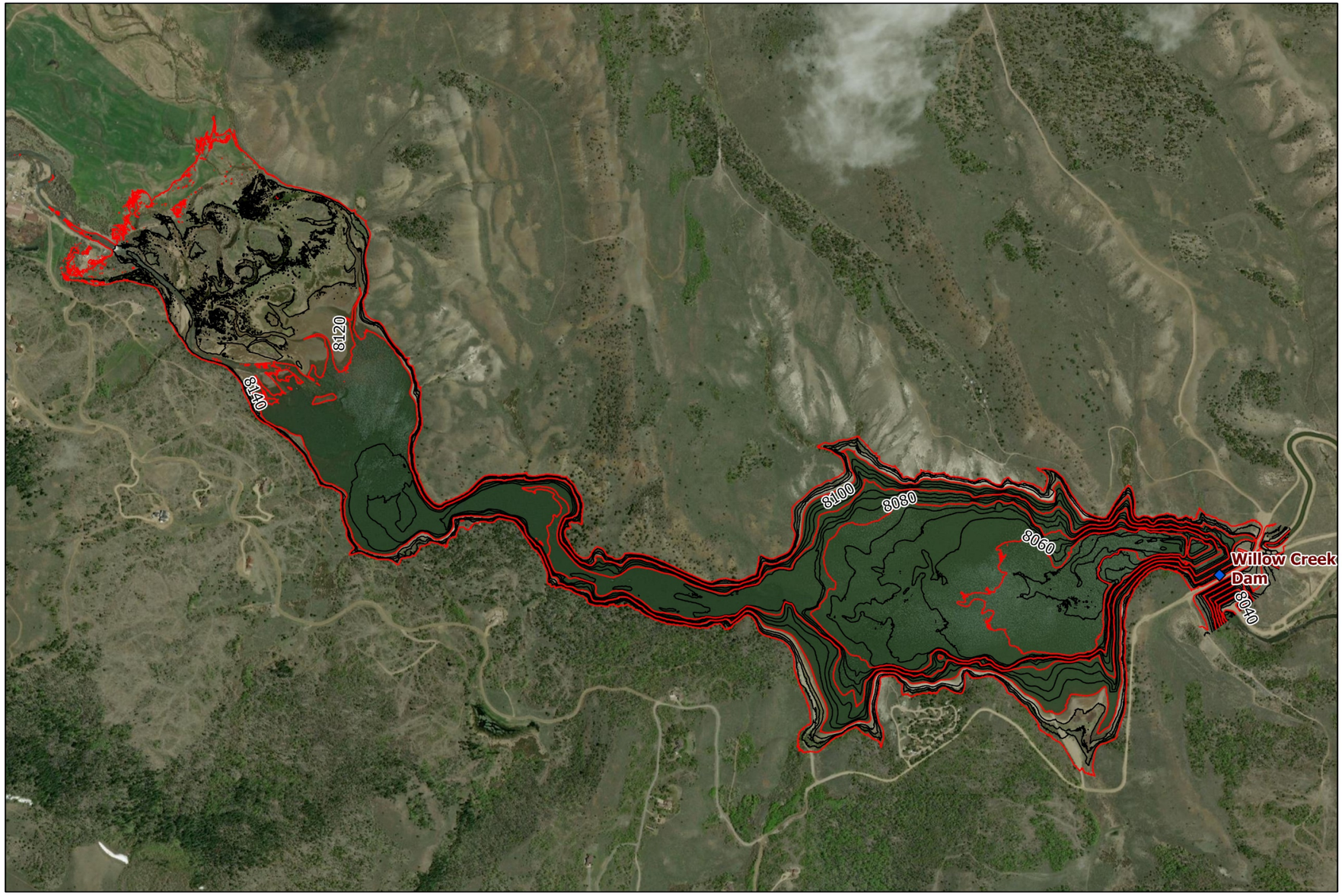
Computation of Reservoir Surface Area, Storage Capacity, and Sedimentation Volume

A digital surface of the reservoir bottom was generated by Javernick (2021) using the bathymetric data points (easting, northing, and elevation) processed by the Bureau of Reclamation combined with the above-water topography obtained via drone photogrammetry. Horizontal surface area and reservoir capacity were determined from the combined surface, computed at 1-foot (ft) increments over the complete range of reservoir elevations (8044 to 8140 ft, Reclamation Project Vertical Datum [RPVD]). This process was performed using functions within ArcGIS and an in-house tool (Bradley 2021) to provide formatted output at 1-, 0.1-, and 0.01-ft increments.

Reservoir surface areas and capacities were computed at 1-ft increments, using an ArcGIS tool (ACAP Toolset 2.0) based on the Esri surface volume function for the complete range of reservoir elevations (8044 to 8140 ft, RPVD). The tool interpolates the reservoir surface areas and capacities to 0.1 and 0.01-ft increments between each 1-ft interval following the method of Reclamation's AreaCAPacity (ACAP) Program Version 2.0 (Bradley 2021). Reservoir and area capacity information are available in the Willow Creek Reservoir (CO) 2021 Area and Capacity Tables report (Hilldale 2022) found at https://www.usbr.gov/tsc/techreferences/reservoir.html).

Appendix D

Contour Maps



Willow Creek Reservoir Colorado Elevation Contour Map

Overview Map

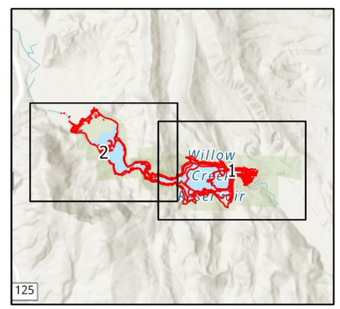
Map Prepared By:
Geographic Applications & Analysis Group
Bureau of Reclamation
Technical Service Center - 01/10/22

Horizontal: NAVD88, State Plane CO North, US feet
Vertical: Reclamation Project Vertical Datum (RPVD)
RPVD = NAVD88 - 6.48 ft
5 ft contour interval
Bathymetry from 2021 reservoir survey
Above Water Survey from 2021 Drone Photogrammetry

N

Scale 1:11,000

0 500 1,000 Feet



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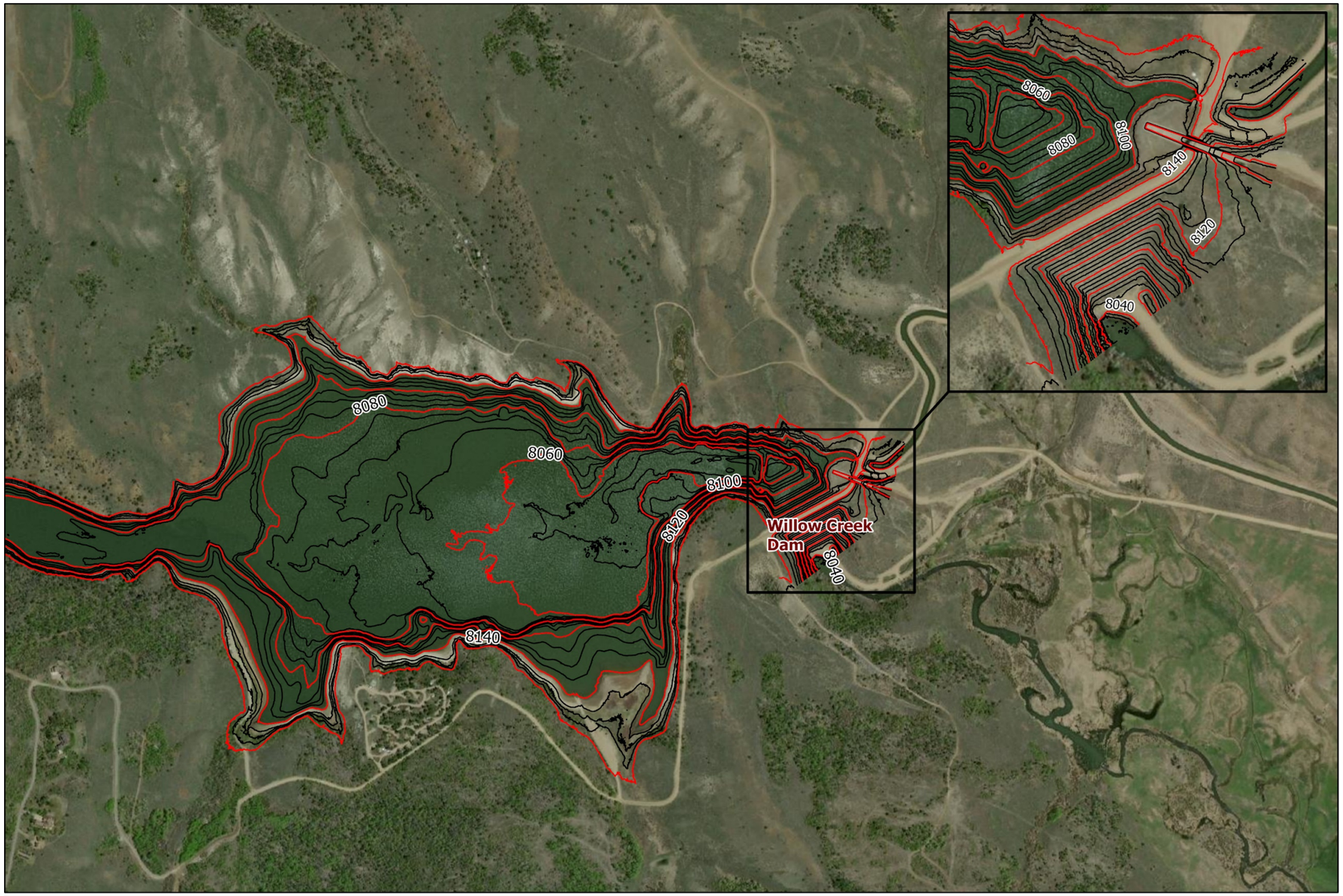
BUREAU OF RECLAMATION



Willow Creek Reservoir Colorado Elevation Contour Map

Sheet 1

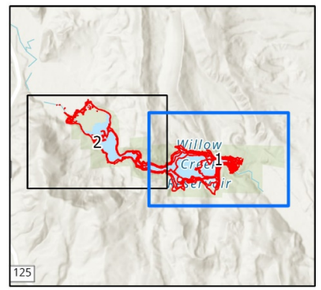
Map Prepared By:
Geographic Applications & Analysis Group
Bureau of Reclamation
Technical Service Center - 01/10/22

Horizontal: NAVD88, State Plane CO North, US feet
Vertical: Reclamation Project Vertical Datum (RPVD)
RPVD = NAVD88 - 6.48 ft
5 ft contour interval
Bathymetry from 2021 reservoir survey
Above Water Survey from 2021 Drone Photogrammetry

N

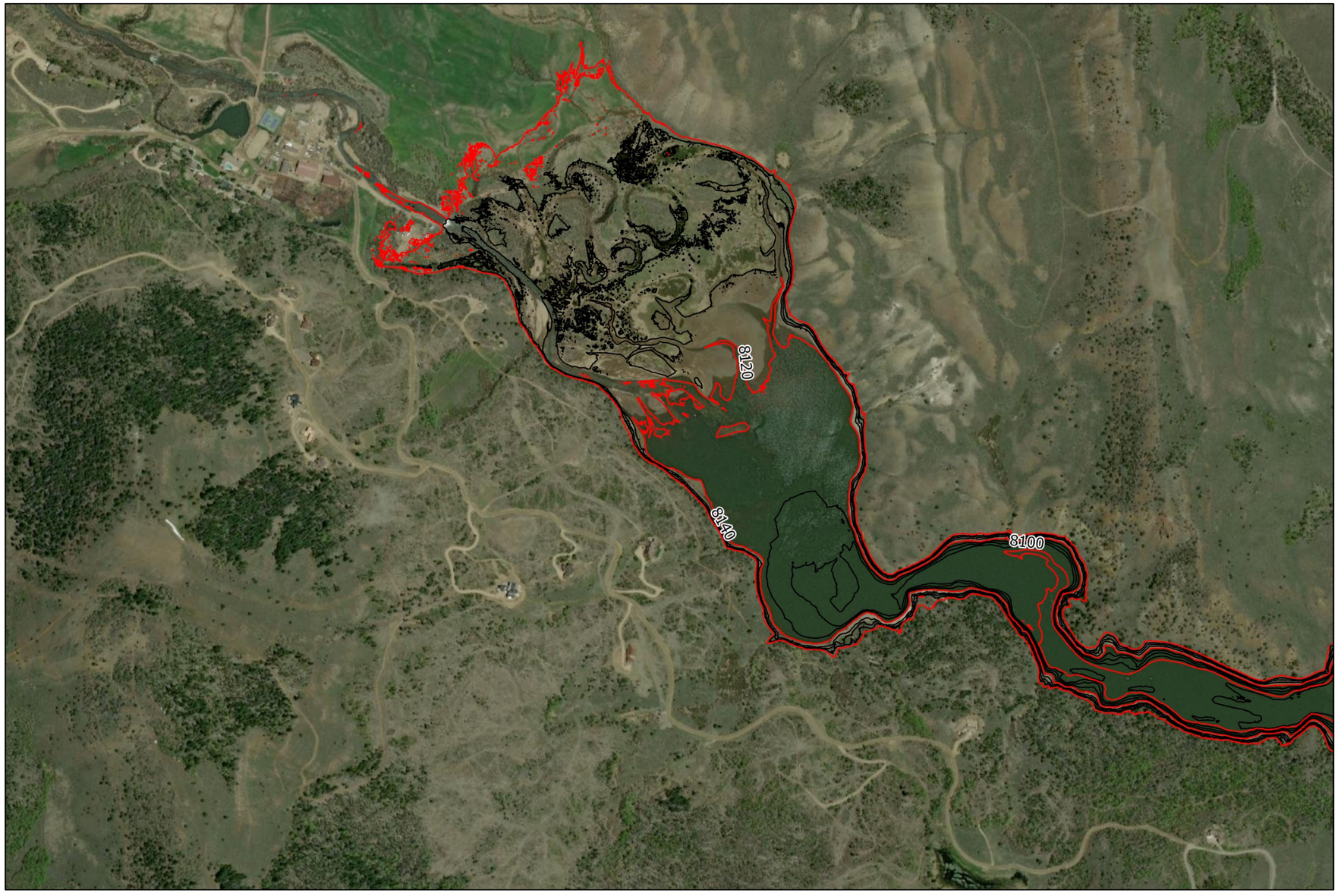
Scale 1:8,000

0 500 1,000 Feet



Maxar, Microsoft, Esri, NASA, NGA, USGS, FEMA, Grand County, CO, Esri, HERE, Garmin, SafeGraph, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, USDA, Maxar

BUREAU OF RECLAMATION



Willow Creek Reservoir Colorado Elevation Contour Map

Sheet 2

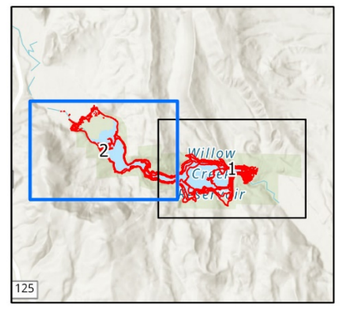
Map Prepared By:
Geographic Applications & Analysis Group
Bureau of Reclamation
Technical Service Center - 01/10/22

Horizontal: NAVD88, State Plane CO North, US feet
Vertical: Reclamation Project Vertical Datum (RPVD)
RPVD = NAVD88 - 6.48 ft
5 ft contour interval
Bathymetry from 2021 reservoir survey
Above Water Survey from 2021 Drone Photogrammetry

N

Scale 1:8,000

0 500 1,000 Feet



Maxar, Microsoft, Esri, NASA, NGA, USGS, FEMA, Grand County, CO, Esri, HERE, Garmin, SafeGraph, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, USDA, Maxar

BUREAU OF RECLAMATION