BUREAU OF RECLAMATION

Technical Report No. ENV-2021-074

Willow Creek Reservoir (CO) 2020 Sedimentation Survey

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

U.S. Department of the Interior **April 2021**

Mission Statements

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Acknowledgements

The authors would like to acknowledge the participation of Dr. Luke Javernick (River Science, Canon City, Colorado). Dr. Javernick collected above water data using structure from motion with photographs taken from an unmanned aerial vehicle. He also collected bathymetry in addition to that collected by Reclamation personnel and aided with bathymetry measurements through the ice. River Science also produced the final mapping product.
Kent Collins and Travis Hardee (Sedimentation and River Hydraulics Group, Technical Service Center [TSC], Bureau of Reclamation) assisted with data collection. Northern Water provided the boat used for the November survey and personnel to assist with the February survey through ice. The authors would like to acknowledge the constructive comments noted by the peer reviewers.

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13. SUPPLEMENTARY NOTES **This survey was conducted as a joint effort between Reclamation, Northern Water, and River Science.**					
14. SHORT ABSTRACT **The 2020 bathymetric survey of Willow Creek Reservoir (CO) was combined with above water survey data collected with a drone and processed using structure-from-motion (River Science 2021) to produce a combined digital surface of the reservoir. The above water data were collected in November 2020. Analysis of this survey indicates that at the top of the conservation pool (elevation 8,130 feet, RPVD) the reservoir has a surface area of 308 acres and a storage capacity of 9,801 acre-feet. Since the original filling in 1953, the reservoir is estimated to have lost 752 acre-feet of storage capacity (7.1%) due to sedimentation. The dead storage pool volume has reduced to 77 percent of the original dead storage volume. The sedimentation level at the dam is at 8,035 feet (RPVD), which is 100% of the height between the original reservoir bottom and the top elevation of the dead storage pool. This indicates minimal sedimentation directly in upstream of the dam.**					
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Technical Service Center, Denver, Colorado
Sedimentation and River Hydraulics Group, 86-68240

Technical Report No. ENV-2021-074

Willow Creek Reservoir Colorado (CO) 2020 Sedimentation Survey

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Acronyms and Abbreviations

%	percent
ADCP	Acoustic Doppler Current Profiler
CBT	Colorado-Big Thompson
cfs	cubic feet per second
CO	Colorado
ft	foot or feet
GIS	Geographic Information System
GPS	Global Positioning System
HUC	Hydrologic Unit Code
mi^2	square miles
NAD83	North American Datum, established 1983
NAVD88	North American Vertical Datum, established 1988
NGS	National Geodetic Survey
NID	National Inventory of Dams
NRCS	Natural Resources Conservation Service
OPUS	Online Positioning User Service
Reclamation	Bureau of Reclamation
RPVD	Reclamation Project Vertical Datum
RSI	Reservoir Sedimentation Information
RTK	Real-Time Kinematic
SfM	Structure from Motion
SONAR	Sound Navigation And Ranging
TSC	Technical Service Center
UAV	Unmanned aerial vehicle (drone)
USGS	U.S. Geological Survey

Executive Summary

Willow Creek Dam and Reservoir are on Willow Creek approximately 3 miles east of Lake Granby, which lies between the towns of Grand Lake and Granby, Colorado. This location is in the Rocky Mountains, 60 miles northwest of Denver, Colorado. Willow Creek Reservoir is operated in conjunction with the Colorado-Big Thompson (CBT) project, which carries water from the western slope of the Rockies to the Front Range. The survey included the full extent of the reservoir with limited resolution due to time constraints.

A bathymetric survey of Willow Creek Reservoir was conducted in November 2020 and February 2021 with these primary objectives:

1. Estimate reservoir sedimentation volume since the original reservoir filling began in 1953,

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

3. Obtain an updated map of Willow Creek Reservoir for reservoir routing purposes, and,

4. Obtain an updated survey for comparison to future surveys to track sedimentation following the East Troublesome Fire that burned 91 percent of the watershed.

The bathymetric survey was conducted from a boat using an acoustic Doppler current profiler (ADCP) and a single beam depth sounder that was interfaced with real-time kinematic (RTK) global positioning system (GPS) instruments (for navigation and positioning) to map the reservoir bottom. The 2021 bathymetric survey of Willow Creek Reservoir was combined with aerial data collected in November 2020 using an unmanned aerial vehicle (UAV, or drone) to produce a combined digital surface of the reservoir bottom. Due to the rapid response to survey this reservoir ahead of it freezing over, a multibeam transducer was not able to be utilized for this survey. The TSC boat was being repaired and there was no time to properly outfit the vessel of opportunity (provided by Northern Water) to accommodate the multibeam transducer.

This survey was conducted over two separate trips between November 17 – 22, 2020 and February 2 – 4, 2021. The reservoir water surface elevation ranged between 8,119.03 and 8,119.15 feet (Reclamation Project Vertical Datum, or RPVD) during the November bathymetric survey, which is just under 11 feet below the top of the conservation pool elevation of 8,130 feet (RPVD). The ice elevation during the February survey was approximately 8,118.9 feet (RPVD). The above-water topographic data were measured on November 21 and 22, 2020.

Analysis of the combined data sets indicate the following results:

- At reservoir water surface elevation 8,119.00 feet RPVD, which is 6.48 feet below NAVD88 [North American Vertical Datum, established 1988] (GEOID18), the reservoir surface area was 222 acres with a storage capacity of 6,871 acre-feet.

- At the top of the surcharge pool elevation (8,132.0 feet, RPVD), the reservoir has a surface area of 326 acres and a storage capacity of 10,436 acre-feet. Since the original filling of the reservoir in 1953, the reservoir is estimated to have lost 741 acre-feet of storage capacity (7.1 percent) due to sedimentation. This volume represents a sediment yield rate of 0.1 acre-feet per square mile per year (acre-feet/mi^2/year), which is considered a very low sedimentation rate as defined in Reclamation's Sedimentation Manual (Bureau of Reclamation 2006).

- By 2021, the dead storage pool volume had reduced to 77 percent of the original dead storage volume. However, accumulated sediment has not reached the dam. Measured bed elevations near the dam were as much as 2 feet below the stated original riverbed elevation of 8,037 feet (RPVD). This disparity may be due to construction activities when the dam was built or differences in surveying techniques.

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 Cr. Res. (CO)**	Region	MB&ART
Owner	Area Office Manager	Area Office	Eastern CO
Stream	Willow Creek	Vertical Datum	RPVD
County	Grand	Top of Dam (ft)	8,140
State	CO	Spillway Crest (ft)	8,130
Lat (deg min sec)	40 08 50.00	Power Penstock Elevation (ft)	N/A
Long (deg min sec)	105 56 31.24	Low Level outlet (ft)	8,077
HUC4	1401	Hydraulic Height (ft)	95.0
HUC8	14010001	Total Drainage Area (mi^2)	133
NID ID	CO01670	Date storage began	1953
Dam Purpose	Storage, C-BT operations	Date for normal operations	1953

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

Original Design

Storage Allocation	**Elevation (feet, RPVD)**	**Surface area (acres)**	**Capacity (acre-feet)**	**Gross Capacity (acre-feet)**
SURCHARGE	8,132	321	11,177	624
FLOOD CONTROL	'-------	'-------	'-------	'-------
MULTIPLE USE	'-------	'-------	'-------	'-------
CONSERVATION	8,130	303	10,553	3,329
INACTIVE	8,117	212	7,224	5,738
DEAD	8,077	100	1,486	1,486

Survey Summary

Survey Date	**Type of Survey**	**No. of Range lines or Contour Intervals**	**Contributing Sediment Drainage Area (mi^2)**	**Period Sedimentation Volume (acre-feet)**	**Lowest Reservoir Elevation (feet)**	**Remaining Portion of Dead Storage (%)**
1956	Unknown	N/A	133	0	8,037	100
2021	Bathymetric	N/A	133	752	8,035	77

Notes

The 2021 survey noted several survey points below 8,037 feet (RPVD), the streambed elevation at the time of the original survey. This is likely due to construction activities near the dam after the survey or perhaps survey methods.

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1. Introduction

Willow Creek Dam and Reservoir are on Willow Creek about 3 miles east of Lake Granby and 60 miles northwest of Denver, Colorado (Figure 1). Willow Creek Dam and Reservoir are operated by Northern Colorado Water Conservancy District (Northern Water) as part of the Colorado – Big Thompson Project, which provides supplemental water for irrigation of about 720,000 acres of land, municipal, and industrial use, hydroelectric power, and water-oriented recreation (Bureau of Reclamation, 1981).

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 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, with special concern for increased sedimentation due to the 2020 East Troublesome Fire, Northern Water requested River Science (Canon City, Colorado) conduct a bathymetric and above water survey of the reservoir. Northern Water and Reclamation's Missouri Basin Region requested that the Technical Service Center's (TSC) Sedimentation and River Hydraulics Group (86-68240) provide assistance as needed to complete this survey ahead of icing over for the winter. Survey efforts were delayed due to limited access during the fire. The survey included the extent of the reservoir with limited resolution due to time constraints. The recent survey was conducted from November 17 – 22, 2020 and February 2 – 4, 2021. During the November 2020 survey the delta portion of the reservoir was covered in ice too thick to obtain a Sound Navigation And Ranging (SONAR) survey. The survey crew returned to the reservoir in February to obtain reservoir bottom elevations using a weighted survey tape lowered to the reservoir bottom through holes bored through the ice. Figure 2 shows an image of Willow Creek Reservoir. Specific details of the surveys are provided in Section 3, Appendix A, and Appendix B of this report. Appendices C and D contain historical and current maps, respectively. The survey was conducted with these primary objectives:

1. Estimate reservoir sedimentation volume since the original reservoir filling began in 1953,
2. Determine new reservoir surface area and storage capacity tables for the full elevation range of dam and reservoir operations,
3. Provide an updated, accurate map of the reservoir for flood routing, and
4. Make the newly updated map available for future comparisons of sedimentation volume, anticipating increased sedimentation following the East Troublesome wildfire.

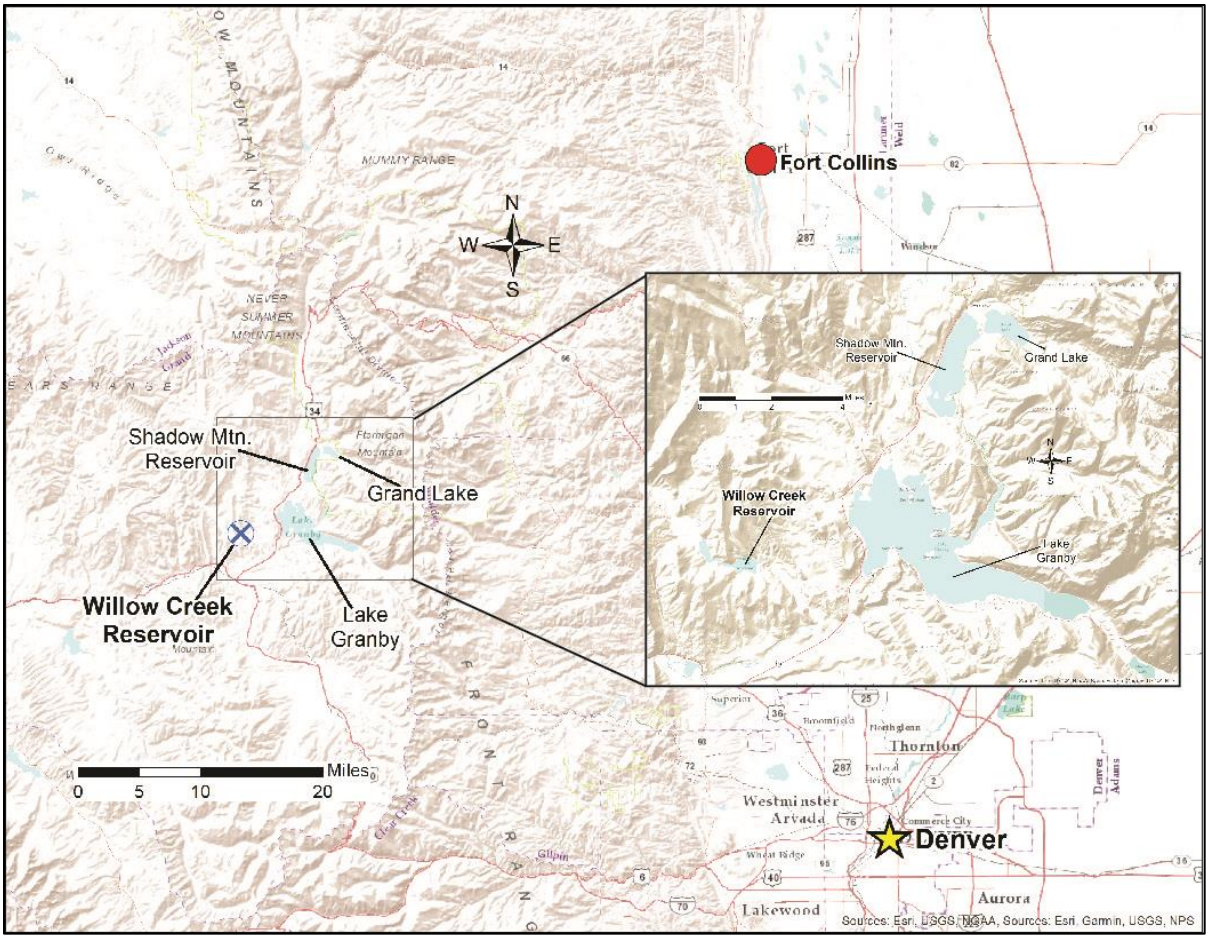

Figure 1. Location map of Willow Creek Reservoir and Dam, located 60 miles northwest of Denver, Colorado.

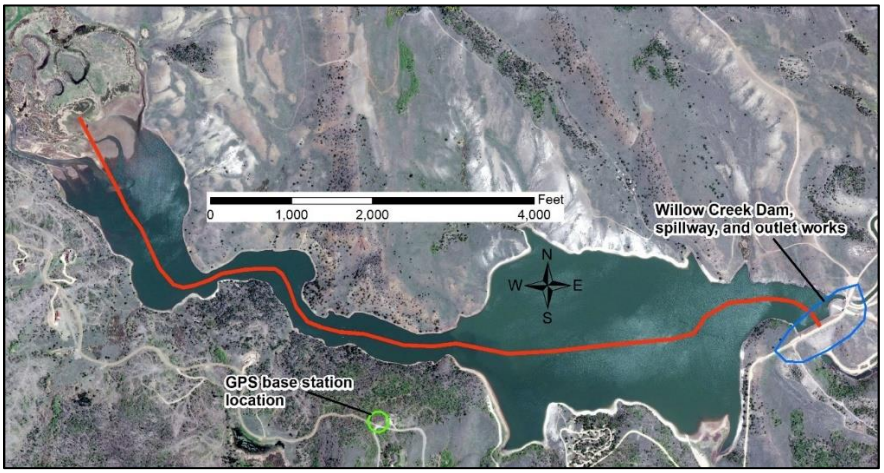

Figure 2 Aerial photograph of Willow Creek Reservoir showing the centerline profile and GPS base location.

2. Watershed Description

2.1 Location and Drainage

The watershed upstream of the Willow Creek Dam has a total contributing drainage area of 133.4 square miles (mi^2). Basin elevation ranges from 12,300 feet (ft) in the headwaters to 8,130 ft 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 (Figure 3).

Table 1. Willow Creek watershed characteristics from US 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 in
Mean Basin Elevation	9,514 ft
Maximum Elevation	12,300 ft
Minimum Elevation (at top of conservation pool)	8,130 ft
Percent of Impervious Area determined from NLCD 2001 Impervious dataset	2.8 %
Percent of drainage area covered by forest	54.6 %

Figure 3. The watershed above Willow Creek Dam has a total drainage area of 133 mi^2 and a sediment-contributing drainage area of 133 mi^2 (U.S. Geological Survey, 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 rests 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 the 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 (Figure 4, Table 2) (Horton, 2017).

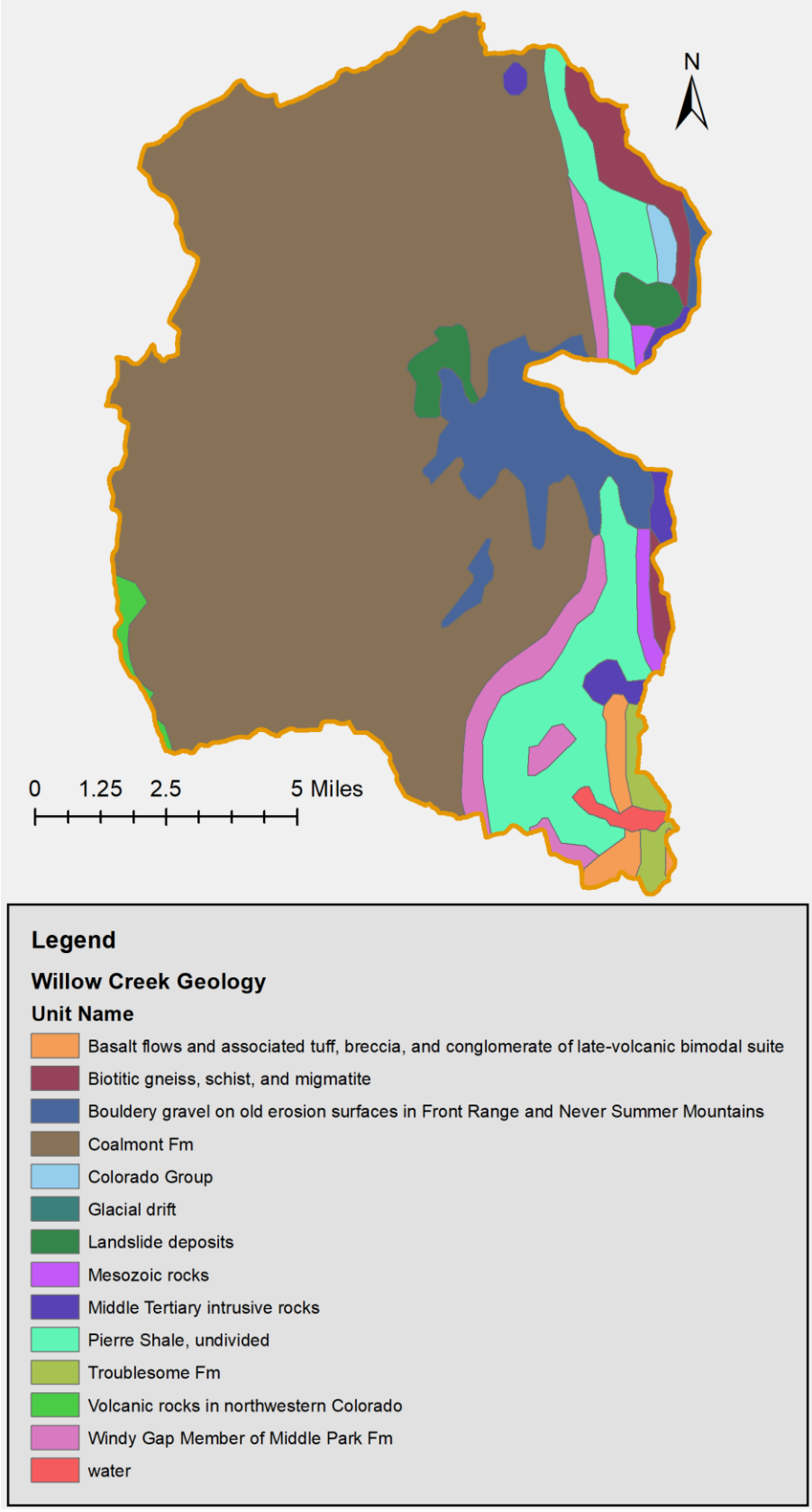

Figure 4. Surface geology of the Willow Creek watershed (Horton, 2017).

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%

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. 91 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. Willow Creek watershed is ungauged upstream of the reservoir, USGS 09021000 is immediately downstream of the dam. StreamStats (U.S. Geological Survey 2021) estimates that mean annual flow in Willow Creek is 87.7 cubic feet per second (cfs), 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 8,130 ft) in 2021 is 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 The East Troublesome Fire, 2020

The East Troublesome wildfire originated about 15 miles west of Willow Creek Reservoir on approximately Oct. 14, 2020 and ultimately burned approximately 91 percent of the Willow Creek Watershed (Figure 5). This proportion was determined in Arc GIS (ESRI, Redlands, California) by intersecting the Willow Creek watershed polygon (StreamStats, USGS) and the East Troublesome fire polygon (https://services.arcgis.com/yzB9WM8W0BO3Ql7d/arcgis/rest/services/East_Troublesome/FeatureServer, sourced from Northern Water) to obtain a watershed burn polygon. Only the northern-most portion of the watershed remained unburned. Within a week of initiation, the fire was spreading rapidly, expanding at a maximum rate of 87,093 acres between the afternoons of October 21 and October 22. The rapid spread was driven by high winds and fueled by beetle-killed trees. An early winter snowstorm during October 24-26 dramatically slowed the spread of the fire and the it was declared contained on November 30, 2020. Ultimately, the East Troublesome Fire burned a total area of 193,812 acres, making it the second largest fire in Colorado history (source: https://inciweb.nwcg.gov/incident/7242/).

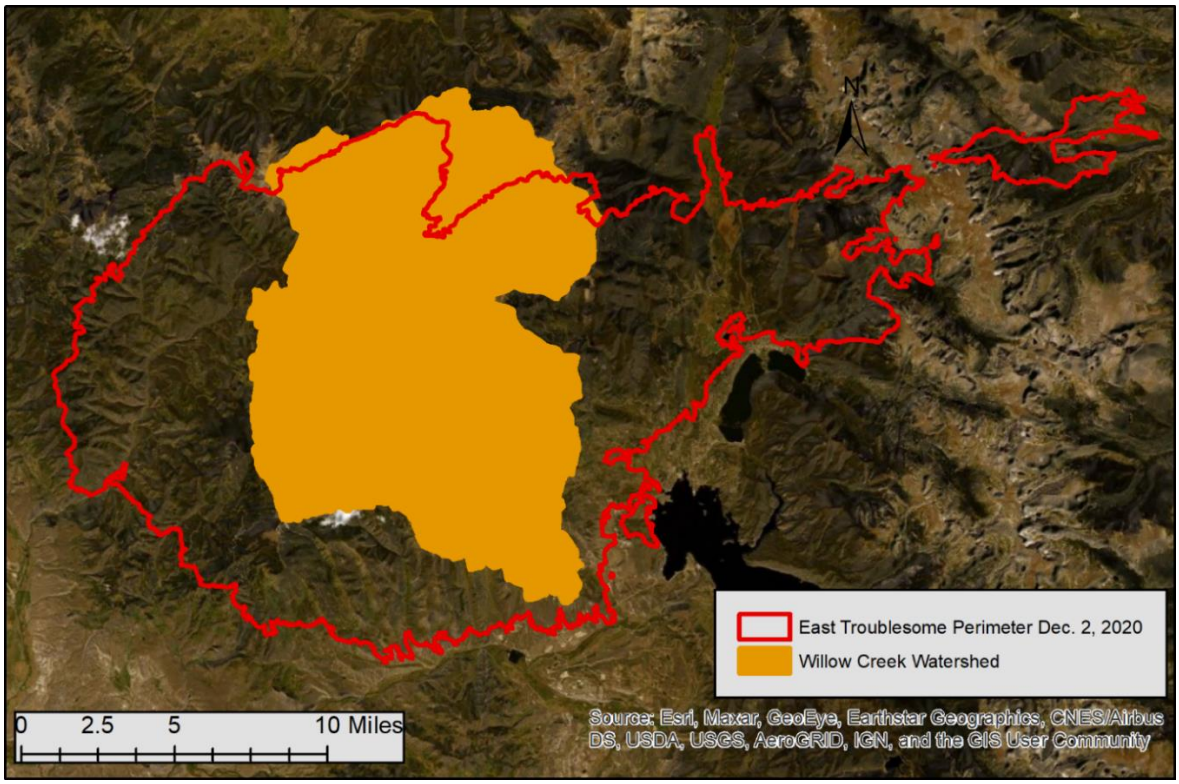

Figure 5. The East Troublesome Fire burned 91 percent of the Willow Creek Watershed in October and November, 2020.

2.6 Dam Operations and Reservoir Characteristics

Willow Creek Reservoir provides 3,353 acre-feet of operating capacity (active conservation) between elevations 8,117 and 8,130 ft (RPVD). Water from Willow Creek Reservoir is diverted via 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.

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 began storing water in that same year. Historic records of water level began 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 in Figure 6. 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 (8,117 to 8,130 ft, RPVD). Historic water elevation records 1953 to present are shown in Figure 7..

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

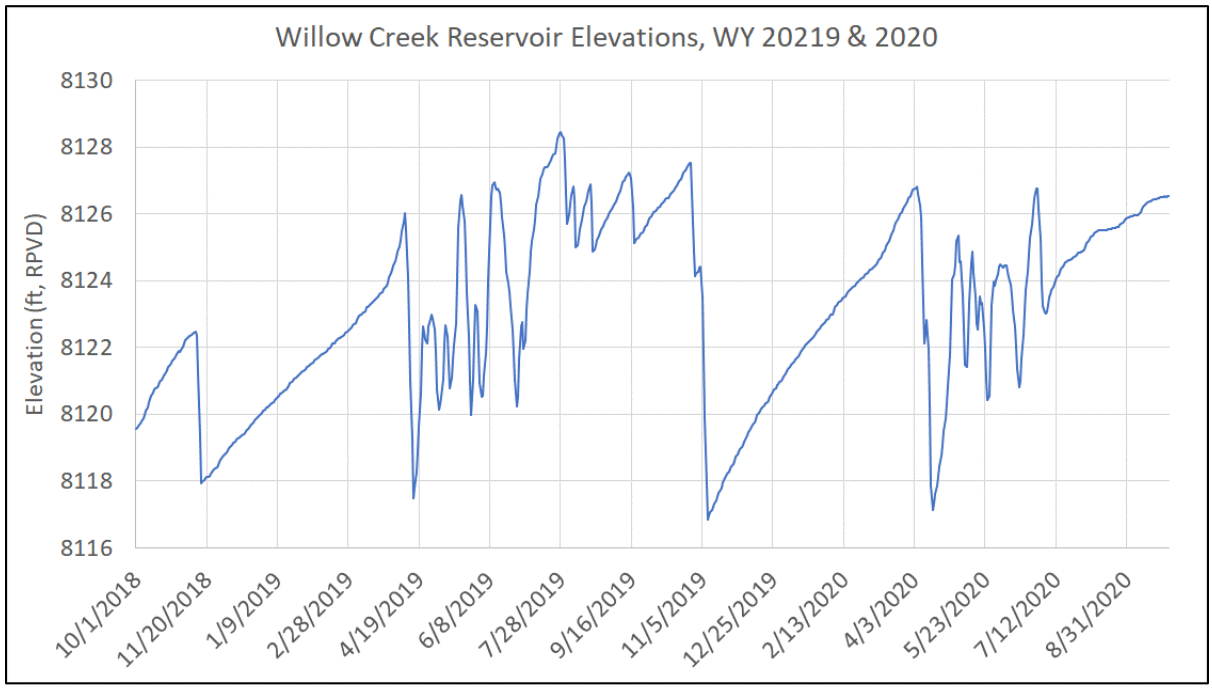

Figure 6. Plot of Willow Creek Reservoir elevations for water years 2019 & 2020, demonstrating the multiple fill cycles per year.

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 (reference Figure 2).

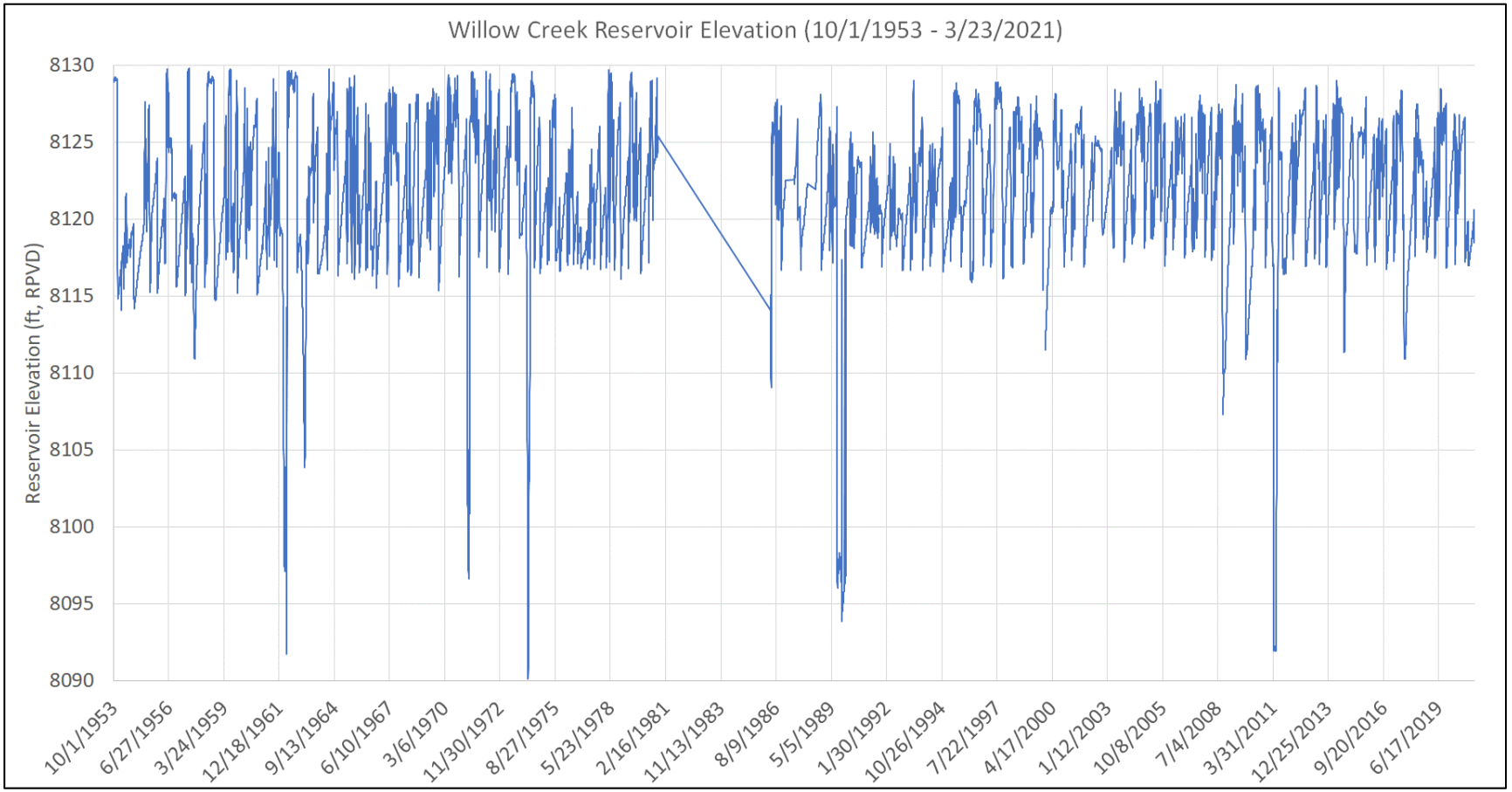

Figure 7. Historic Willow Creek Reservoir water surface elevations (RPVD). Spillway elevation is 8,130 ft, top of dead pool elevation is 8,077 ft. Data web source: https://www.usbr.gov/gp/hydromet/hydromet_arcread.html.

3. Reservoir Survey Methods and Extent

3.1 Survey Methods

A complete bathymetric survey was conducted during November 2020 and February 2021. The November 2020 survey utilized an Acoustic Doppler Current Profiler (ADCP) and a single beam transducer from a boat to continuously measure reservoir bottom elevation, November 17 and 18, 2020. Additional bathymetry data were collected by River Science using a single beam transducer on November 20, 2020. The horizontal position of the moving boat was continually tracked using RTK GPS during the SONAR survey. Due to ice cover in the delta portion of the reservoir (approximately 2,000 ft), boat access was not possible. Therefore, it was necessary to survey the remaining delta portion of the reservoir on a return trip in February 2021.

Because the reservoir completely ices over in the winter, the February 2021 survey was accomplished by boring holes through the ice and lowering a weighted survey tape through the water column to the reservoir bottom to obtain a depth to the top of the ice. The top of each ice hole was surveyed with RTK GPS. The reservoir bottom elevation was obtained by subtracting the depth measured with the survey tape from the elevation obtained with the RTK GPS survey. A map of the bathymetric data points collected by River Science and Reclamation is presented in Figure 8. This survey took place between February 2 – 4, 2021. Additional details about the bathymetric survey can be found in Appendix A.

On November 21 and 22, 2020 above water data were collected with an unmanned aerial vehicle (UAV, or drone) equipped with a camera. These images were used to obtain ground elevations using structure from motion (SfM). These data were collected by River Science; the accuracy report released by River Science can be found in Appendix B.

Surface areas at 1-foot contour intervals were computed using Geographic Information System (GIS) software and the computer program the was used to produce the reservoir surface area and capacity tables at 0.01-foot increments.

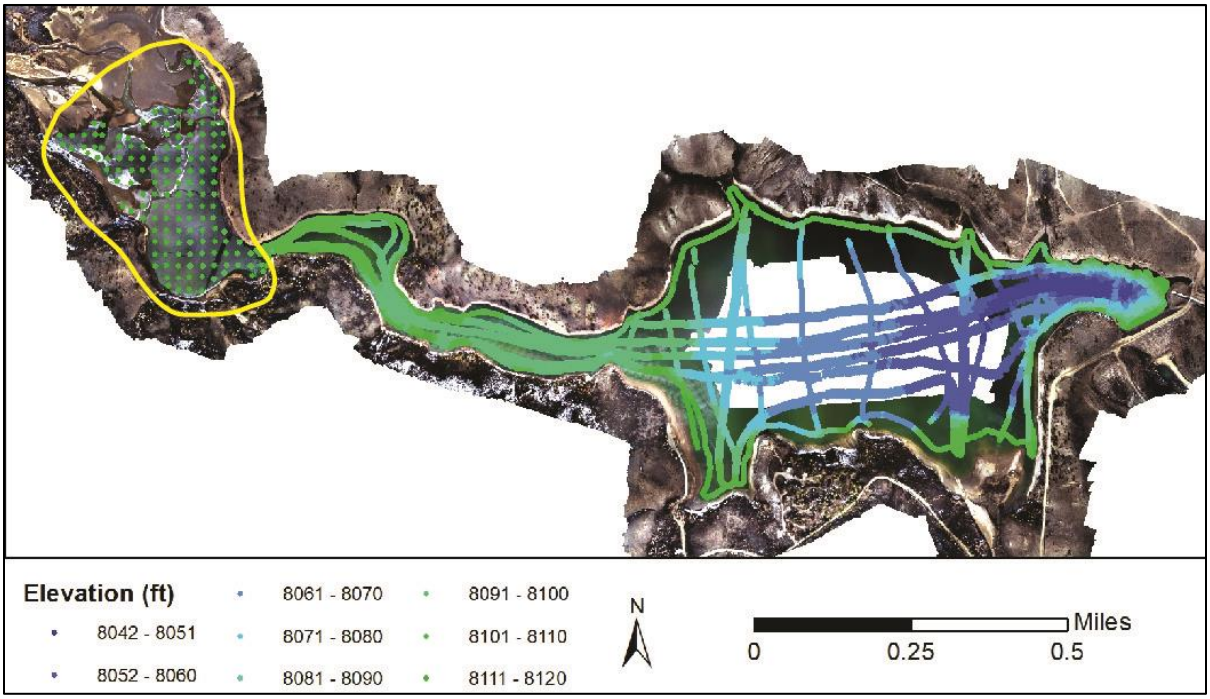

Figure 8. Map of bathymetric survey data coverage. The yellow shape indicates data collected through ice using RTK GPS and a weighted survey tape at a spacing of 100 ft. Bathymetric data collection with SONAR were accomplished by River Science and Reclamation. Above water survey data is coincident with the location of images that are outside of the reservoir. (Image credit: River Science, used with permission.)

3.2 Survey Control, Datum, and Monuments

For the November 2020 and February 2021 survey, all bathymetry and GPS control measurements were collected in North American Datum 1983 (NAD83) State Plane (horizontal) coordinates, Colorado North, US survey feet and North American Vertical Datum 1988 (NAVD88), Geoid 18, US survey feet elevations. During processing, all bathymetry and GPS measurements were converted to Reclamation Project Vertical Datum (RPVD) for Willow Creek Reservoir and Dam. The RPVD was determined to be 6.48 feet lower than NAVD88 (Geoid 18). The photogrammetry data were similarly shifted.

The GPS base station receiver was set up over a temporary monument located at a high point along the southern shore (Figure 9 and Figure 10). This location was used for both the November 2020 and February 2021 surveys.

State plane and elevation coordinates for the GPS base station were computed using the Online Positioning User Service (OPUS) developed by the National Geodetic Survey (NGS) (www.ngs.noaa.gov/OPUS/). The relationship between NAVD88 and RPVD at Willow Creek Reservoir was determined from RTK GPS measurements on the dam crest, spillway, and water surface elevations.

Figure 9. Photograph of GPS base stations used by River Science and Reclamation during the November 2020 survey.

Figure 10. Photograph of GPS base stations used by River Science and Reclamation during the February 2021 survey.

4. 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 2020). An abbreviated area and capacity table is shown in Table 3. Plots of the 2020 area and capacity curves are presented in Figure 11. For the 2020 survey, area and capacity curves are based on the 2020/2021 bathymetric (below-water) survey up to 8,119 feet elevation (RPVD), while curves above this elevation are based on November 2020 drone photogrammetry. A comparison of these curves indicates that largest reduction in surface area and storage capacity occurs between elevations 8,075 and 8,100 feet (RPVD).

The actual surface areas and storage-capacity volumes for above-water elevations may be different than the areas measured in 1953 because of delta sedimentation, shoreline erosion, or use of older methods.

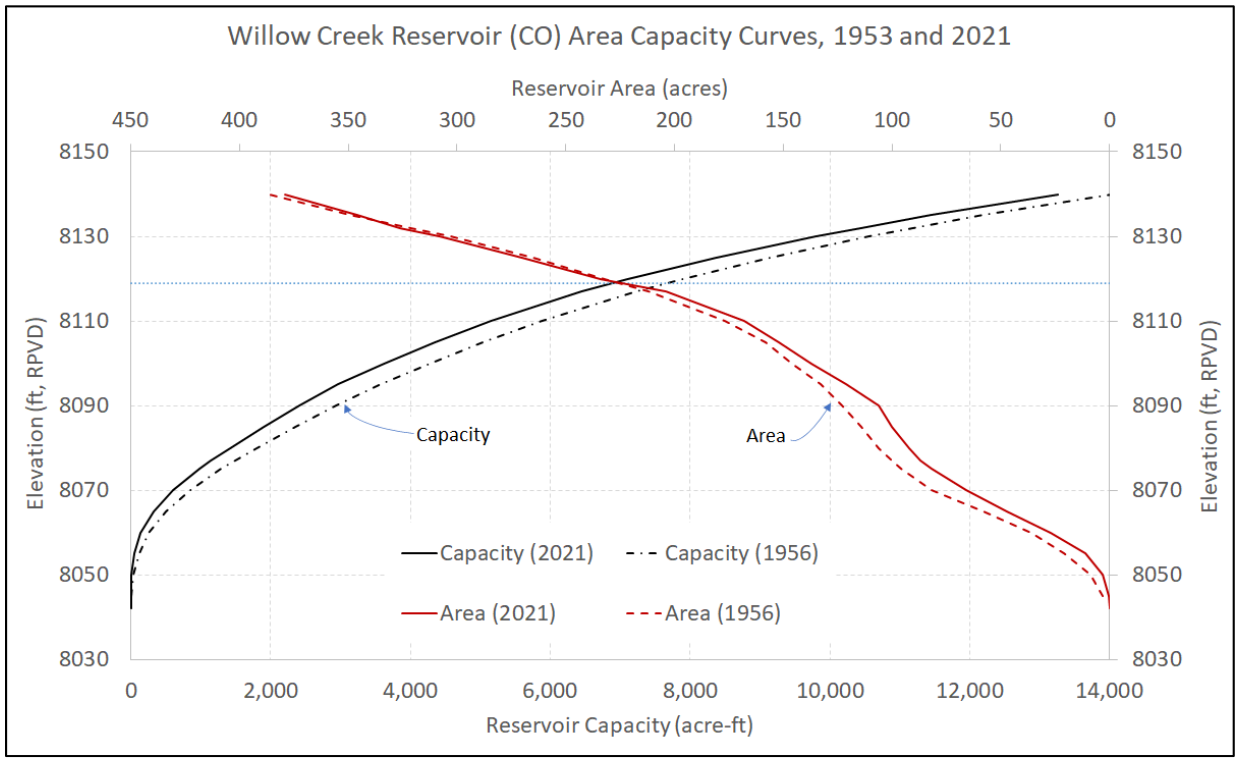

Figure 11. Plot of Willow Creek Reservoir surface area and storage capacity versus elevation (RPVD). Bathymetry and above-water data were collected in November 2020 and February 2021. Dashed blue line is at elevation 8,119 ft (RPVD), the reservoir elevation at the time of the bathymetric survey.

At reservoir water surface elevation 8,115 feet (RPVD), which is 4 feet below the water surface at the time of survey, the reservoir surface area was 194 acres with a storage capacity of 6,050 acre-feet. At maximum pool elevation (dam crest, 8,140 feet, RPVD), the reservoir has a surface area of 379 acres and a storage capacity of 13,257 acre-feet. A digital version of the original survey is not available for mapping the depth and location of accumulated sediment.

Table 3. Historical summary of reservoir surface area and storage capacity data.

	Reservoir Surface Area (acres)		**Reservoir Storage Capacity (acre-ft)**		**Sedimentation Volume (acre-ft)**
Elevation (ft)	**1956**	**2021**	**1956**	**2021**	**1956 to 2021**
8,042	----	0	----	0	----
8,045	3	0.5	12	0.4	11.6
8,050	9	3.4	42	9.6	32.4
8,055	21	11	117	43	74
8,060	36	27	260	141	119
8,065	58	47	495	323	172
8,070	82	66	843	601	243
8,075	96	82	1,290	975	315
8,077[1]	100	87	1,486	1,144	342
8,080	106	92	1,795	1,414	381
8,085	114	100	2,345	1,894	451
8,090	123	106	2,937	2,407	530
8,095	133	121	3,577	2,970	607
8,100	146	137	4,275	3,618	657
8,105	158	152	5,035	4,345	690
8,110	177	168	5,873	5,144	729
8,112.38[2]	186	181	6,311	5,559	752
8,117[3]	212	204	7,224	6,448	776
8,120	232	234	7,891	7,100	791
8,125	265	270	9,133	8,360	773
8,130[4]	303	308	10,553	9,801	752
8,132[5]	321	326	11,177	10,436	741
8,135	349	346	12,185	11,446	739
8,140[6]	386	379	14,020	13,257	763

[1]Top of dead storage

[2]Canal Invert

[3]Top of inactive storage

[4]Top of active conservation storage

[5]top of surcharge storage

[6]top of dam crest

5. Sedimentation Observations

Willow Creek Reservoir has lost 741 acre-feet, 7.1 percent of the storage, at the top of the conservation pool (8,130 ft, RPVD). Figure 2 shows an image of the reservoir and the profile used to plot bottom elevations, shown in Figure 12. The profile indicates a delta face located at station 4,300 ft, which is coincident with the downstream end of the narrow portion of the reservoir. The delta face drops approximately 18 vertical feet over a longitudinal distance of 190 ft. The capacity curves shown in Figure 11 and the profile shown in Figure 12 both indicate the greatest accumulation of sediment occurs between elevations 8,075 and 8,100 ft (RPVD). In the profile, this location of greatest aggradation is between stations 4,300 and 7,000 ft.

The reservoir is typically drawn down to reservoir elevations 8,116 to 8,118 ft (RPVD) in recent decades. This elevation corresponds to an approximate station of 10,200 in Figure 12, which is upstream of the narrow portion of the reservoir. However, the incoming fine sediment is apparently being transported through much of the narrow portion of the reservoir and deposited between stations 4,300 ft (elevation 8,092 ft RVPD) and 8,000 ft (elevation 8,102 RVPD).

Although reservoir sediment accumulates at all reservoir elevations, it appears as though little sediment has deposited downstream of station 3,000 ft. The pre-dam maps (shown in Appendix C) have coarse contour intervals (25 ft) and do not show contours below elevation 8,050 ft (RPVD). Observations during the survey indicated small vertical variations of the reservoir bottom elevations, which is not consistent with sediment deposits. This is particularly true downstream of station 2,000 ft (Figure 12). The top of the dead pool is at elevation 8,077 ft (RPVD), which is coincident with a reservoir station of approximately 4,130 ft. The dead pool has accumulated 342 acre-feet, likely limited to locations between stations 3,000 and 4,000 ft. The accumulation in the dead pool is nearly half of the overall sedimentation in the reservoir.

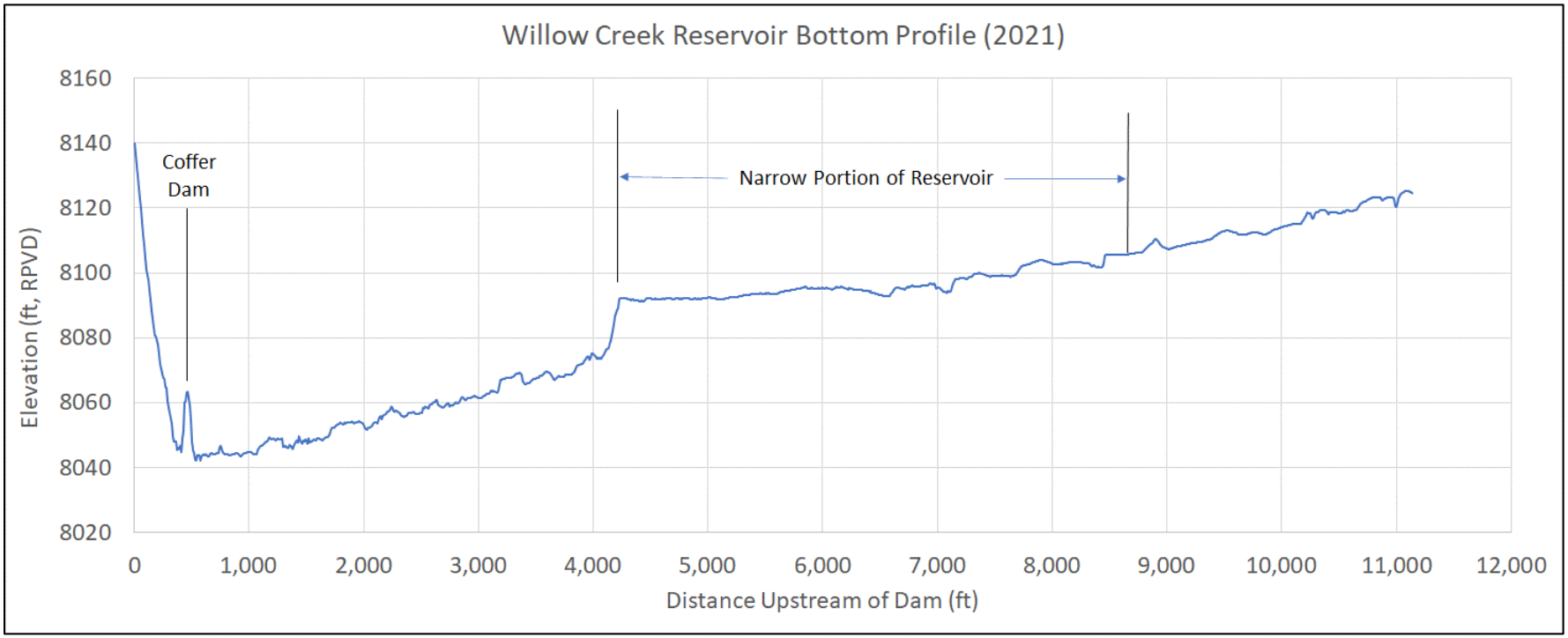

Figure 12. Profile of Willow Creek Reservoir bottom. Stationing begins at the dam.

6. Conclusions and Recommendations

As a result of the East Troublesome Fire, increased sedimentation is likely in the coming years due to limited ground cover, resulting in the increased probability of excess storm runoff and potential debris flows within the Willow Creek watershed. The watershed is large and runoff from bare hillslopes may take many years to reach the reservoir. Fine sediment and ash are likely to be transported into the reservoir sooner than coarser material.

6.1 Survey Methods and Data Analysis

The 2020/2021 bathymetric survey, combined with November 2020 photogrammetry data of the above-water topography, has been used to produce an accurate digital surface of the reservoir bottom, albeit with limited resolution. There was no overlap of the above- and below-water surveys. Due to time constraints, the coverage of the reservoir was less than would normally be obtained. Refer to Figure 8 for data coverage. The resolution of the survey is limited in the middle portion of the reservoir where only sparse cross sections and several profile lines were able to be surveyed.

Reservoir surface areas were computed from this digital surface at 1-foot 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, but also the differences in survey methods. The latest surface area and storage capacity curves compare as anticipated with the original curves, showing the decrease in reservoir storage due to sedimentation. Additional information on the survey methods and processes are shown in Appendix A.

6.2 Recommendation for Next Survey

The probability of an increased sediment load is due to the 2020 East Troublesome fire. The increased likelihood of excess runoff will last approximately 5 years or more and will decrease over time as new vegetation begins to take root in the watershed. In an effort to accelerate vegetation growth in the burned portion of the watershed, Northern Water, and perhaps other agencies, are planning aerial reseeding campaigns beginning in the spring/summer of 2021.

It is recommended that repeat surveys are performed annually through 2025 so that sedimentation can be documented within the reservoir following a fire that resulted in 91 percent of the watershed being burned. The winter 2020/2021 survey can serve as the pre-fire survey, as no storm runoff occurred during or after the East Troublesome fire that would have resulted in sediment being transported into Willow Creek Reservoir. Future surveys can be compared to this survey to accurately document sedimentation following a significant wildland fire event in the watershed. Electronic maps can be generated that show depth and location of sediment deposition.

Funding has been secured to survey Willow Creek Reservoir in 2021. The bathymetry survey will be funded by Reclamation's Dam Safety Program. The above-water survey is expected to be funded by Northern Water and will be performed by River Science using a drone similar to the previous above water surface effort. Every effort will be made to perform the aerial (above-water) survey when the reservoir is as low as feasible. Similarly, the bathymetric survey of the reservoir will be surveyed when the reservoir is high.

Future aerial surveys with a drone should consider performing repeat surveys of the Willow Creek channel well upstream of the reservoir when stream flows are minimal. These data would show the presence of recent deposits within the channel resulting from the East Troublesome Fire. These deposits are likely to be transported to the reservoir over a period of years to decades, depending on hydrology. Tracking these deposits and how they move over time could provide a rough prediction of when the sediment might reach the reservoir. The aerial photography of the river channel may only need orthorectification and not necessarily need to have tight elevation control, which might be less expensive. Qualitative observations of sediment deposits can serve the purpose of predicting the timing of sediment reaching the reservoir if repeat surveys are performed. However, quantitative data using photogrammetry can provide the volume of excess sediment in the Willow Creek channel. The increase of sediment in the Willow Creek channel upstream of the reservoir is expected to occur due to the East Troublesome Fire.

Future bathymetric surveys should be performed using a multibeam SONAR to improve coverage of the reservoir bottom. This will improve resolution and accuracy of the reservoir map.

References

Horton, J.D., 2017. The State Geologic Map Compilation (SGMC) geodatabase of the conterminous United States (ver. 1.1, August 2017): U.S. Geological Survey data release, https://doi.org/10.5066/F7WH2N65. Accessed 03/25/2021.

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River Science, 2021. "Willow Creek Reservoir Elevation Model", accuracy report provided to Northern Water from River Science, 425 Main St., Ste. #10, Canon City, Colorado.

US Geological Survey, StreamStats, available online at: https://streamstats.usgs.gov/ss/ Accessed 03/25/2021.

Appendix A — Hydrographic Survey Equipment and Methods

The 2021 bathymetric survey was conducted in two phases. The first phase was conducted using SONAR deployed from a boat from November 17 to 20 2020 by Reclamation. During this period, reservoir water surface elevations varied from 8,119.1 to 8,119.3 ft (RPVD). During the first phase of the survey it was necessary to break-up ice in some locations of the upper reservoir. However, in the upper most portion of the reservoir, in the delta, the ice was too thick to break up and a SONAR survey was not able to be completed. Additional bathymetry data were collected on November 20 by River Science.

From February 2 to 4, 2021 the survey team (Reclamation, River Science, and Northern Water) returned to the reservoir to complete the survey in the delta. This survey was accomplished by boring holes through the ice at predetermined grid locations that were spaced at 100 ft. This survey grid can be seen in Figure 8. After each hole was drilled through the ice a weighted survey tape was lowered to the reservoir bottom to measure a depth to the top of the ice. An RTK GPS point was surveyed at the top of the ice hole to provide horizontal position and elevation. The reservoir bottom elevation was obtained by subtracting the measured depth from the RTK elevation. Ice thickness was approximately 1.5 ft thick, as noted at periodic locations during the survey.

The November SONAR survey was conducted along a series of cross section, longitudinal, radial, and shoreline survey lines. Near the dam, the survey lines were spaced closely enough so there would be overlapping coverage from the depth sounder or close enough that liner interpolation of single-beam depth data between survey lines would be adequate.

The SONAR survey employed a 20 ft pontoon boat belonging to Northern Water. This boat was powered with an outboard motor. Reservoir depths were measured using a SonTek ADCP functioning as a depth sounder, using Hypack 2020 for data collection and data processing. The ADCP was mounted to the starboard bow of the boat and used to collect bathymetry on November 18th and 19th by Reclamation personnel. In addition to the ADCP, a single beam SONAR device (SonarMite) was mounted to the port bow of the boat. On November 20th, River Science collected additional SONAR data using only the SonarMite.

The ADCP transducer has 9 beams, 8 on the outer perimeter of the device at 25 degrees from nadir (vertical) and one central beam at nadir. The ADCP emits 5 beams per ping. The central nadir beam always pings, along with 4 of the 8 outer beams, selected by SonTek software and typically dependent on depth. The beams are capable of projecting a swath width up to 0.84*depth (with the ADCP rotated 22.5 degrees to optimize the footprint).

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 data from the depth sounders.

The Ohmex SonarMite is a single beam SONAR device that utilizes an interface box to communicate directly with the Trimble survey controller via Bluetooth to calculate and store reservoir bottom elevations. A GPS receiver is mounted in line vertically with the transducer and communicates continuously with the base station for continuous position correction.

RTK GPS survey instruments were used to continuously measure 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 2 and Figure 9). 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 antenna (Figure 9 and Figure 10). The base station was powered by a 12-volt battery.

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 (ground and ice survey) and within ±20 cm for the moving survey boat.

During the SONAR survey on November 18 and 19, a laptop computer was connected to the GPS rover receiver and ADCP echo sounder system mounted to the boat. 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 from the ADCP to map the reservoir bathymetry in the Colorado North State Plane System (NAD83(2011) and NAVD88 (GEOID 18). This task was accomplished by Reclamation personnel. Trimble Business Center (TBC) software was used to process bathymetry data from the SonarMite by Reclamation and River Science personnel. Sound velocity corrections were applied to data collected by both devices. 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.

Final processing of the bathymetric data resulted in 163 data points during the survey through the ice, 14,908 points using the SonarMite, and 35,001 points using the ADCP. A total of 50,072 bathymetry points were used in the development of the reservoir surface.

On November 22nd aerial data using a drone was collected around the reservoir, including the delta. These data were collected and processed by River Science. There were 3,340 pictures collected at an image resolution of 1.13 inches per pixel. More information on the above-water data are contained in Appendix B. The above and below water surveys were combined to create a final reservoir map in raster format with 1-ft pixels.

Appendix B — Above Water Survey Methods, "Willow Creek Reservoir Elevation Model," River Science, February 11, 2021

February 11, 2021

RE: Digital Elevation Model Accuracy Report

Dear Joe Donnelly,

Please review the following accuracy report for the Willow Creek Reservoir.

TASK 1 – SURVEY

Subtask 1A – Survey certification

The land survey took place from November 16-20, 2020. Land survey points were collected using Trimble R10, RTK-GPS units. River Science created a site benchmark on the southern hillside that was perched above the reservoir for optimal radio frequency. Static GPS observations were later processed by the NGS OPUS solution. Full details of these solutions can be found in Appendix A: Initial Survey OPUS Solution, and Appendix B: Secondary Survey OPUS Solution. This benchmark was used as the Base location for the remaining survey that was conducted in NAD83 (2011) State Plane Coordinates, Colorado North Zone (0501), US survey feet, NAVD88 (Geoid18).

The dam crest was first surveyed and found to be an elevation of approximately 8147.6 feet (NAVD88). All areas shown in Figure 1 were then surveyed to the pre-determined extents. In total, 368 ground control points (GCPs) were placed in a distributed pattern and another 419 ground truthing elevation points were surveyed.

Figure 1: Willow Creek Reservoir survey extents outlined in blue.

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Willow Creek Reservoir Elevation Model

Subtask 2A – Bathymetric Survey

The bathymetric survey was conducted in partnership Bureau of Reclamation's (hereafter Reclamation) Sediment and River Hydraulic's Group (Rob Hilldale, Kent Collins, and Travis Hardee). The survey was conducted using River Science's Trimble RTK-GPS equipment with a Sonarmite single beam echo-sounder and Reclamation's Trimble RTK-GPS equipment with a multi-beam echo-sounder. Echo-sounders were mounted off the bow of Northern Water's pontoon boat and data was collected with the boat slowly (idle speeds) navigating the longitudinal profile, transecting, and circling the reservoirs perimeter. Reclamation's depth data was corrected for sound velocity on-site, and River Science's depth data was post-processed by Reclamation (Kent Collins) using 9 velocity measurements that indicated the velocity was an average of 1419.8 m/s as opposed to the default setting of 1500 m/s. Final review of overlapping data showed that the multi- beam and single-beam depth data compared very well (typically ≤0.5 feet) at the deepest depths of the lake.

Due to cold weather, the last ~1,500 feet of the reservoir's delta had iced over and was too thick to break up and survey with the boat. During later discussions, Northern Water requested that additional surveying be conducted once the ice was safe to access. During the week of February 1st, 2021, River Science and Reclamation drilled 163 holes in the ice and measured the depth using a weighed line and recorded the location with RTK-GPS. These survey points were spaced on a 100-foot grid that were pre-determined using GIS and followed closely in the field. Final datasets comprised of 14,908 single-beam points and 35,001 multi- beam points in the main body of the reservoir, and 163 points in the delta.

Subtask 3A – Survey Certification

The land survey conducted by River Science was independently surveyed by John Kratz, PLS, Red Rock Land Surveys, Inc. Mr. Kratz found all methods and elevations to be accurate, and provided a letter to certify the elevations. Full details of his methods, findings, and certification can be found in Appendix C.

TASK 2 – AERIAL IMAGERY ACQUISITION

Drone imagery was acquired on November 21st and 22nd and captured 3,340 pictures at an image resolution of 1.13 inch per pixel (i.e. ground sample distance, GSD). These were cloudy days, but image quality and clarity were improved using a polarized ND4 filter. All images had high side and forward overlap (80% and 80%, respectively).

TASK 3 – DEM GENERATION

The initial elevation model was processed in PhotoScan using all images and GCPs to perform a non-linear transformation. GCP residual errors are calculated by differencing the surveyed and estimated xyz values. Residual errors generated in PhotoScan during the transformation were x=0.038 ft, y= 0.037 ft, and z=0.022 ft.

The resulting point cloud for Willow Creek consisted of 1.01 billion points. These points were processed into the first digital surface model (DSM) (Figure 2B). Processing the DSM into a bare-Earth digital elevation model (DEM) (Figure 2C) was accomplished by using algorithms that find and remove steep-sided peaks using a specified moving window and slope threshold. As shown in Figures 2B and 2C, the processed bare-Earth DEM successfully removed vegetation and off-terrain objects (e.g. cars, buildings, and fences) from the DSM. At this time, the DEM was also modified to remove bridges (shown in Figure 2C). As requested by Northern Water and Reclamation, the final DEM was shifted from NAVD88 to Reclamation Project Vertical Datum (RPVD), US survey feet. Under the direction of Reclamation, River Science shifted the datum to RPVD by lowering the elevations by 6.48 feet.

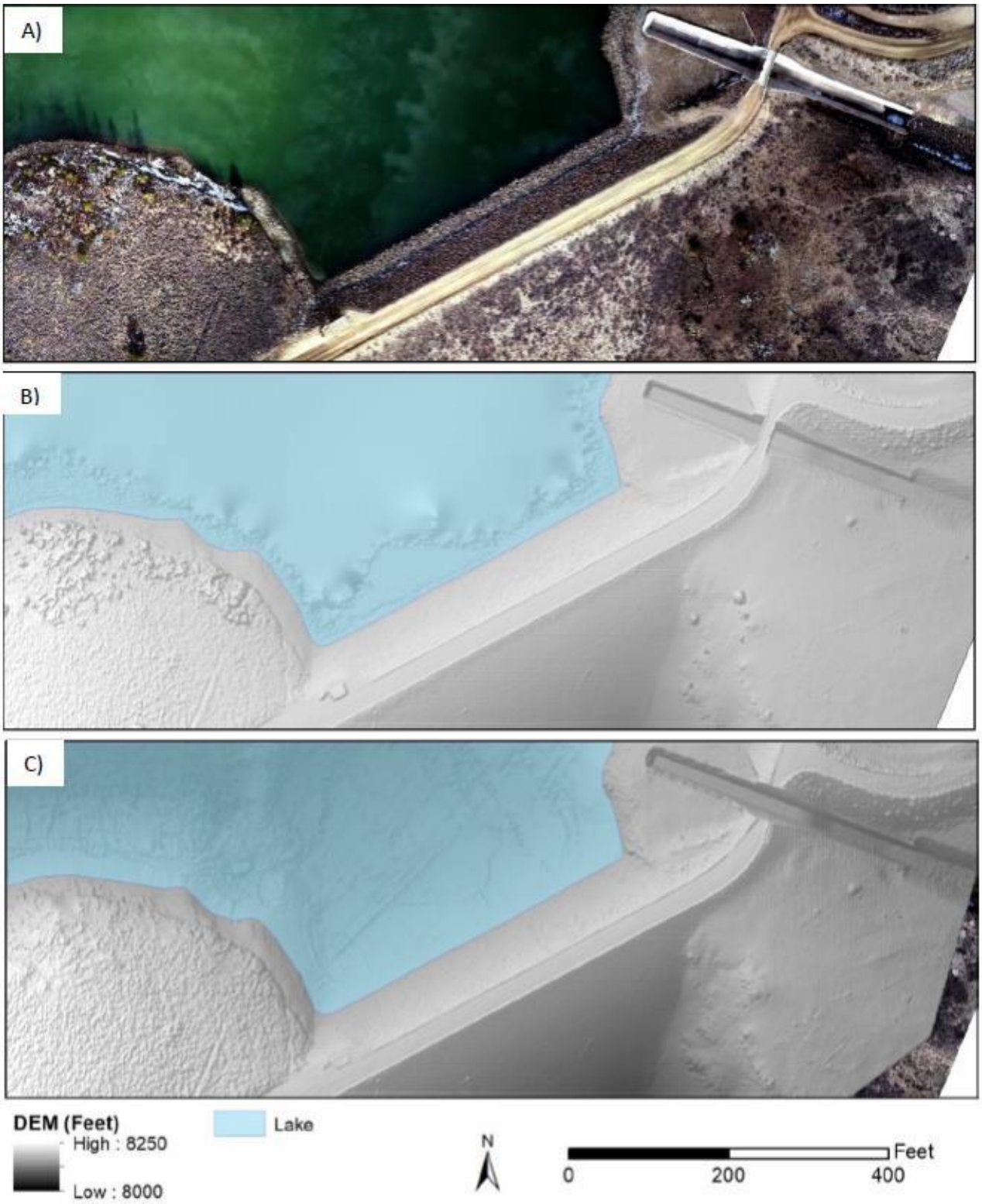

Figure 2: Example of the generated: A) orthoimagery at 0.5 foot resolution, B) digital surface model (DSM) (i.e. vegetation and bridge included), and C) bare-Earth digital elevation model (DEM).

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Willow Creek Reservoir Elevation Model

To assess the elevation accuracy away from the GCPs' influence, the ground truthing elevations were subtracted from the DEM elevations. These residual errors, were then used to calculate the following relevant statistics: i) mean errors (ME) for the accuracy, ii) standard deviation (STD) for the precision, iii) the mean absolute error (MAE), and iv) the root mean squared error (RMSE). The resulting accuracies are shown below in Table 1.

The results (Table 1) show a ME of 0.02 ft (accuracy) and a standard deviation (STD) of 0.20 ft (precision). ME statistics are near zero, indicating the DEM produced a highly accurate surface. ME is shown to be positive 0.02 feet, which indicates that the modeled surface was on average slightly above the surveyed surface. The low STD errors indicate that good precisions across the entire DEM was achieved. The RMSE was 0.06 m which was well below the scope of works claim of achieving a RMSE less than or equal to 0.1 m in non-vegetated areas.

Table 1: Residual error statistics for the Willow Creek Reservoir final digital elevation model (DEM)

	ME	MAE	STD	RMSE
Feet	0.02	0.17	0.20	0.20
Inches	0.28	2.02	2.43	2.45
Meters	0.01	0.05	0.06	0.06
Centimeters	0.72	5.12	6.18	6.22

As depicted in Figure 3, the bathymetric mapping performed with the boat achieved closely spaced longitudinal profile, transects, and the lake's perimeter (limited to depths ≥3 feet). The frozen lake survey achieved a semi-uniform grid spacing of 100 feet that covered the missing areas.

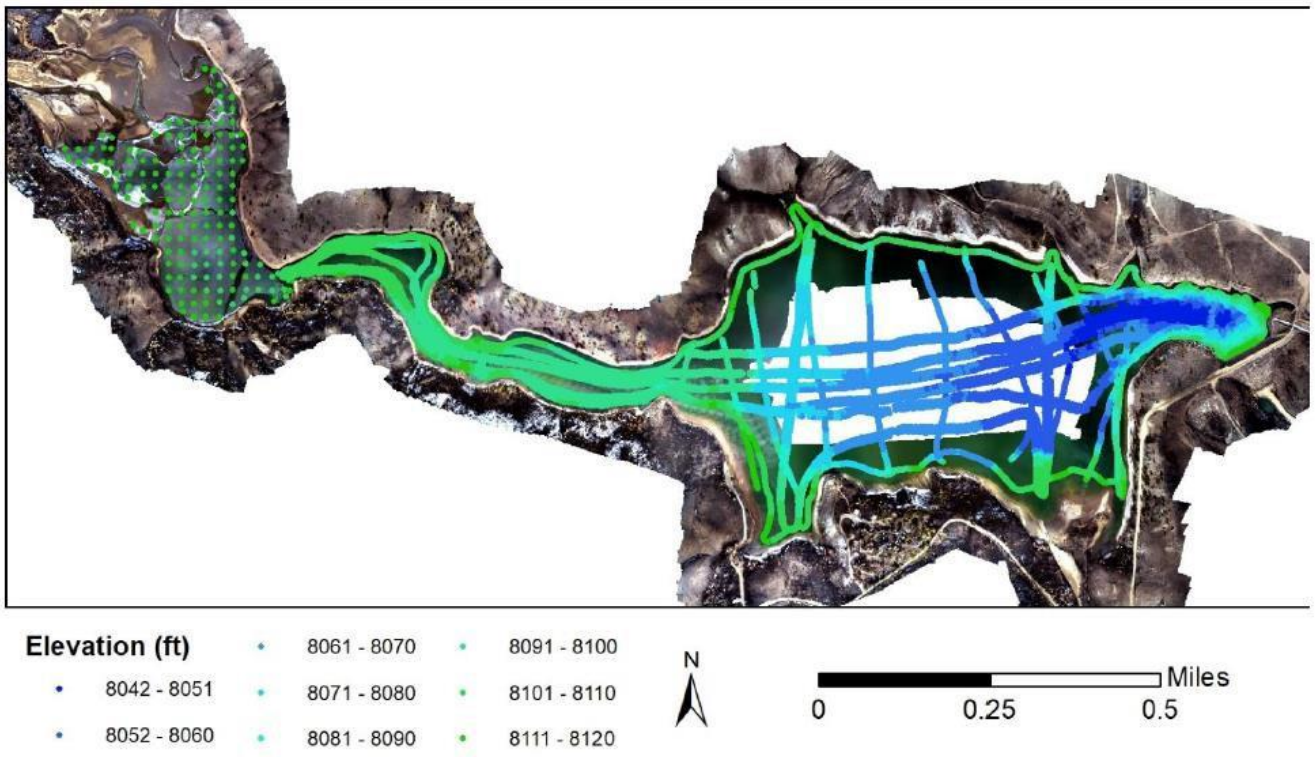

Figure 3: Bathymetric survey data shown as lakebed elevations using a color map.

To create a continuous lakebed surface that joins all the bathymetric data to the land surface DEM, a Triangular Irregular Network (TIN) was used to interpolate between the elevation points using a Delaunay Constraint. As shown in Figure 3 with color-coded depths, the lake has a simple geometry with shallow depths at the inlet, through the narrow section, and deeper depths toward the dam and center of the wide section of the lake. Delaunay triangulations were used so that the resulting triangulations are likely to contain fewer long, skinny triangles. This result is desirable for surface analysis. Following the TIN's generation, the triangulations were reviewed. One area was manually modified (shown in Figure 4) as the Delaunay priority of shortest triangles created an artifact outcropping. This area was simply modified by creating a breakline between the transects at similar elevations which produced a more typical lake depth profile.

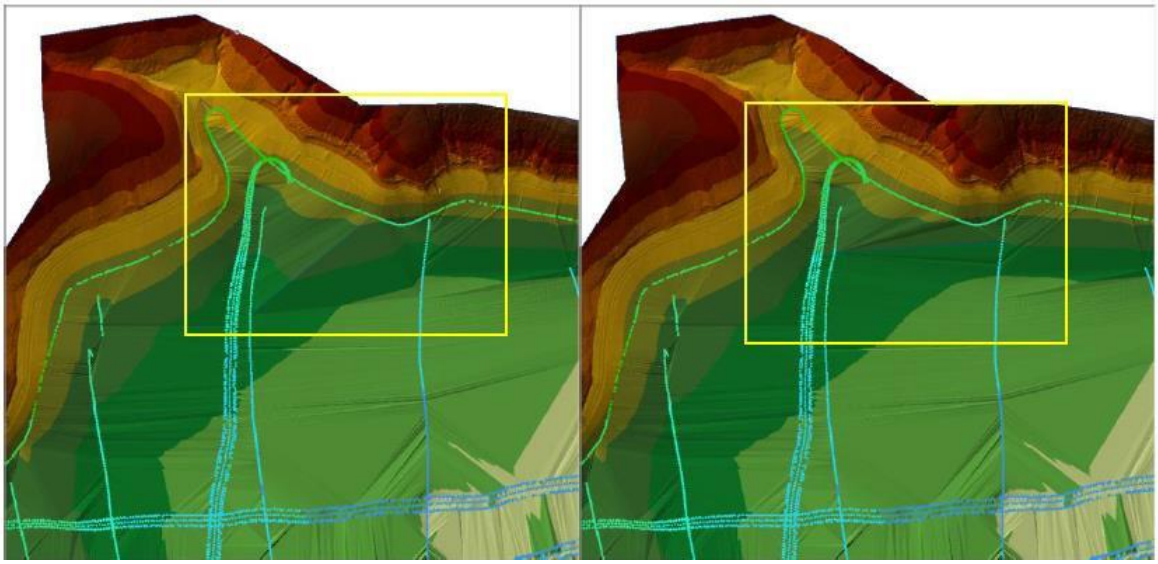

Figure 4: Resulting TIN surface of the bathymetric data. The generated TIN produced triangulations based on Delaunay Constraints to produce smaller triangles. As shown on the left image, these favored smaller triangles produced an artifact outcropping that was later modified (right) to follow a more typical lake shore depth profile.

Some limited areas of small coves were not measured with the bathymetric survey due to depth constraints of the boat and echo-sounder. Photogrammetry is not often used to map inundated areas as the water creates several challenges (i.e. varying color at different camera angles, reflective surface, refraction with depth, etc.). However, it has been shown to map shallow, clear, and still waters with relatively good accuracy. Due to reflection and refraction, waters are often underpredicted. Based on this evidence, it was reasoned that the photogrammetry's DEM in the shallow cove areas could provide improved depth data compared to the interpolated surface. Therefore, anywhere the photogrammetry's inundated areas were deeper than the interpolated surface, the photogrammetry's elevation was given priority.

Figures 5-8 show detailed hillshades of the final DEM (i.e. merged land and lake bed surfaces) with ground truthing residual error results. As the lake bed TIN creates a surface of triangularly interpolated surfaces between closely spaced elevations that vary, it can create subtle artifacts of peaks, troughs, and diamond shapes (where the transects cross perpendicularly). These can be smoothed, but River Science elected to leave the raw bathymetric data instead of over-processing the final result.

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Willow Creek Reservoir Elevation Model

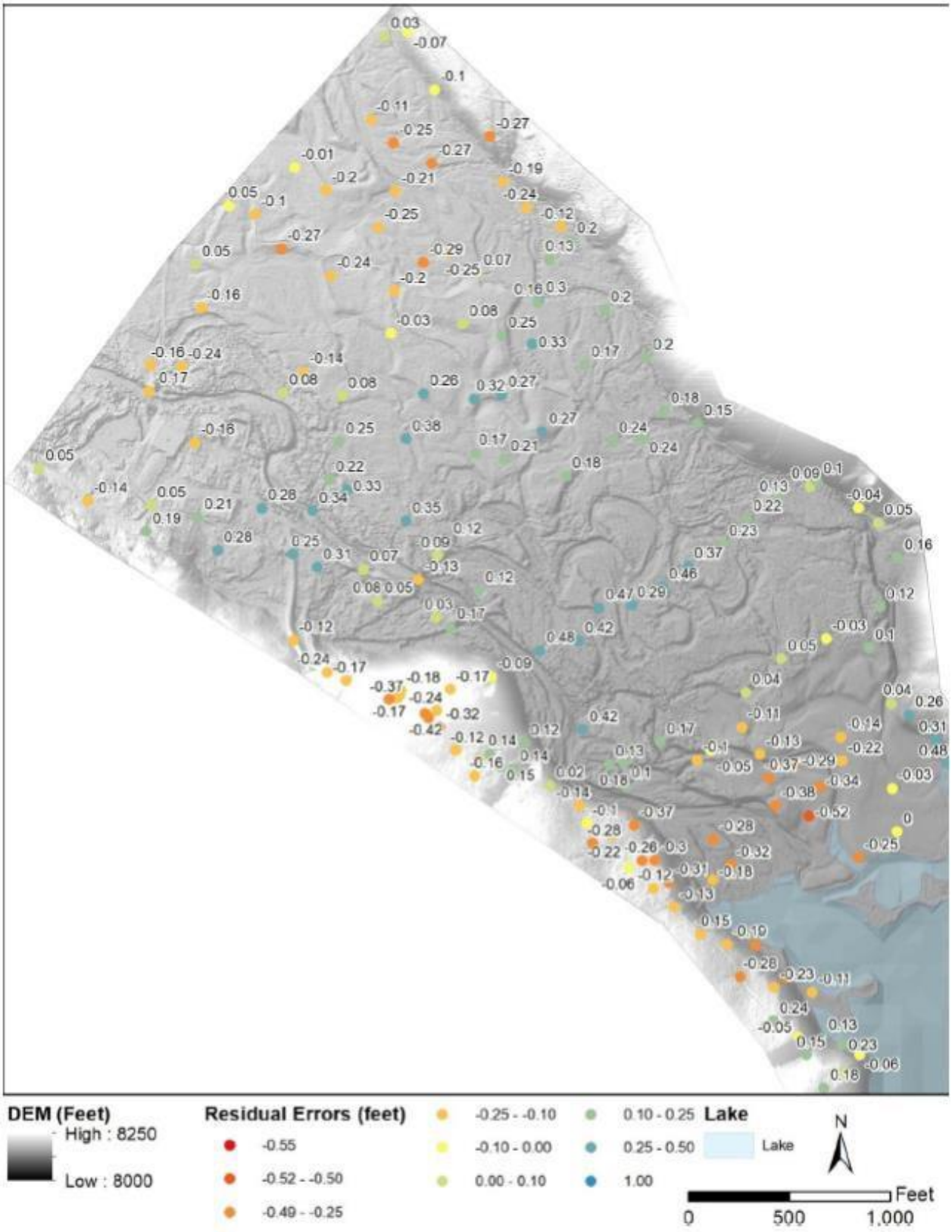

Figure 5: Ground truthing residual errors for western floodplain and delta of Willow Creek Reservoir.

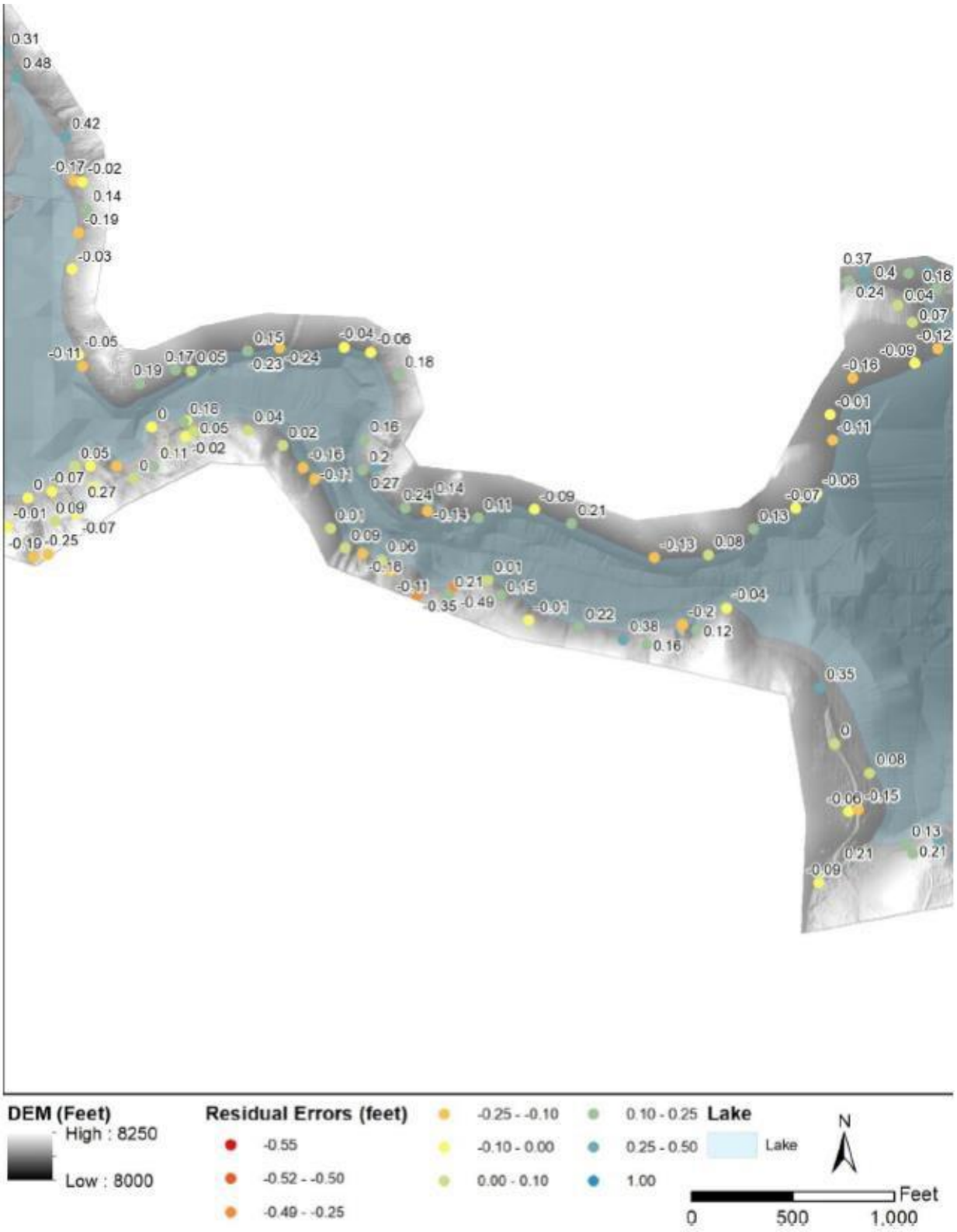

Figure 6: Ground truthing residual errors for delta and narrows of Willow Creek Reservoir.

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Willow Creek Reservoir Elevation Model

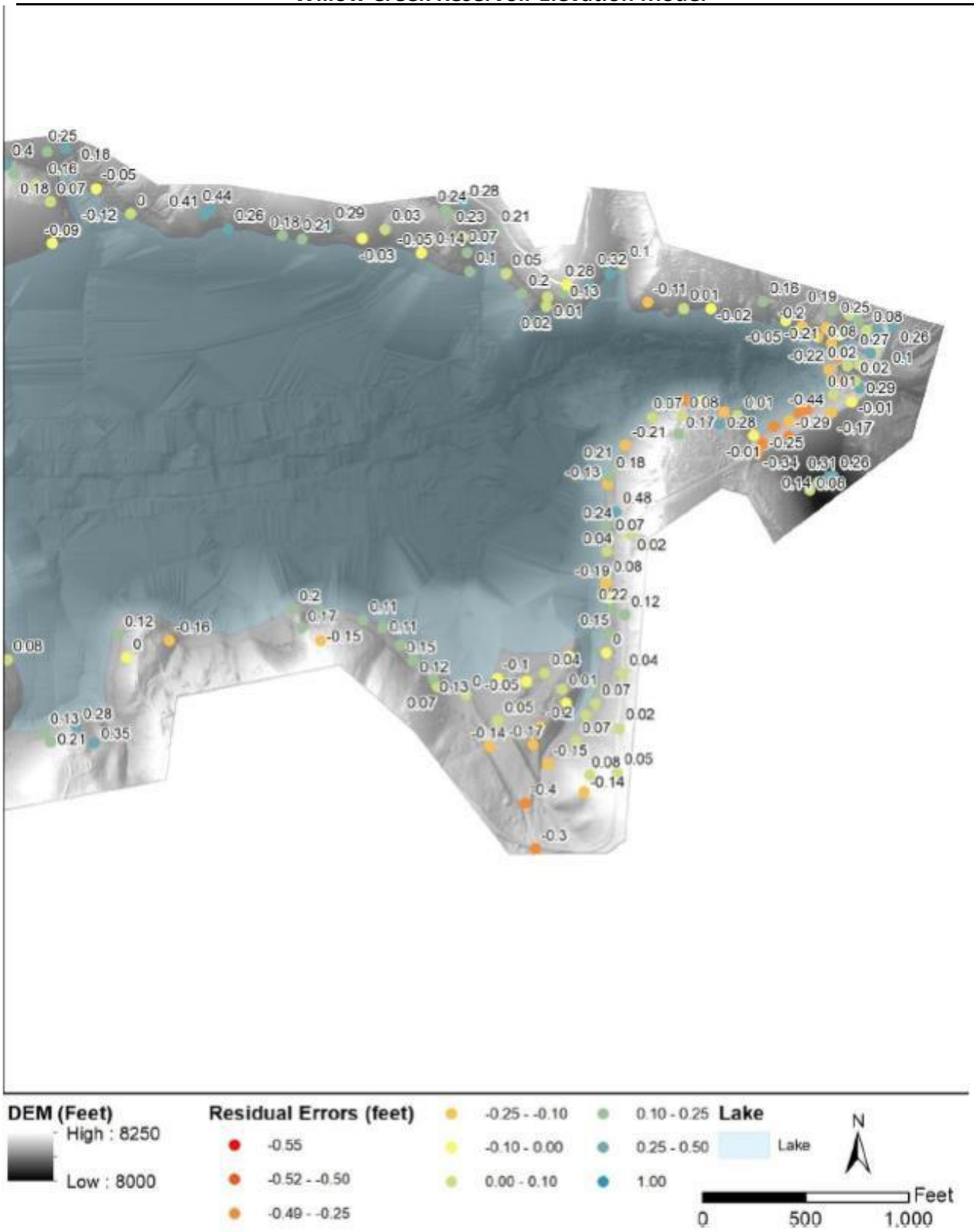

Figure 7: Ground truthing residual errors for eastern half of Willow Creek Reservoir.

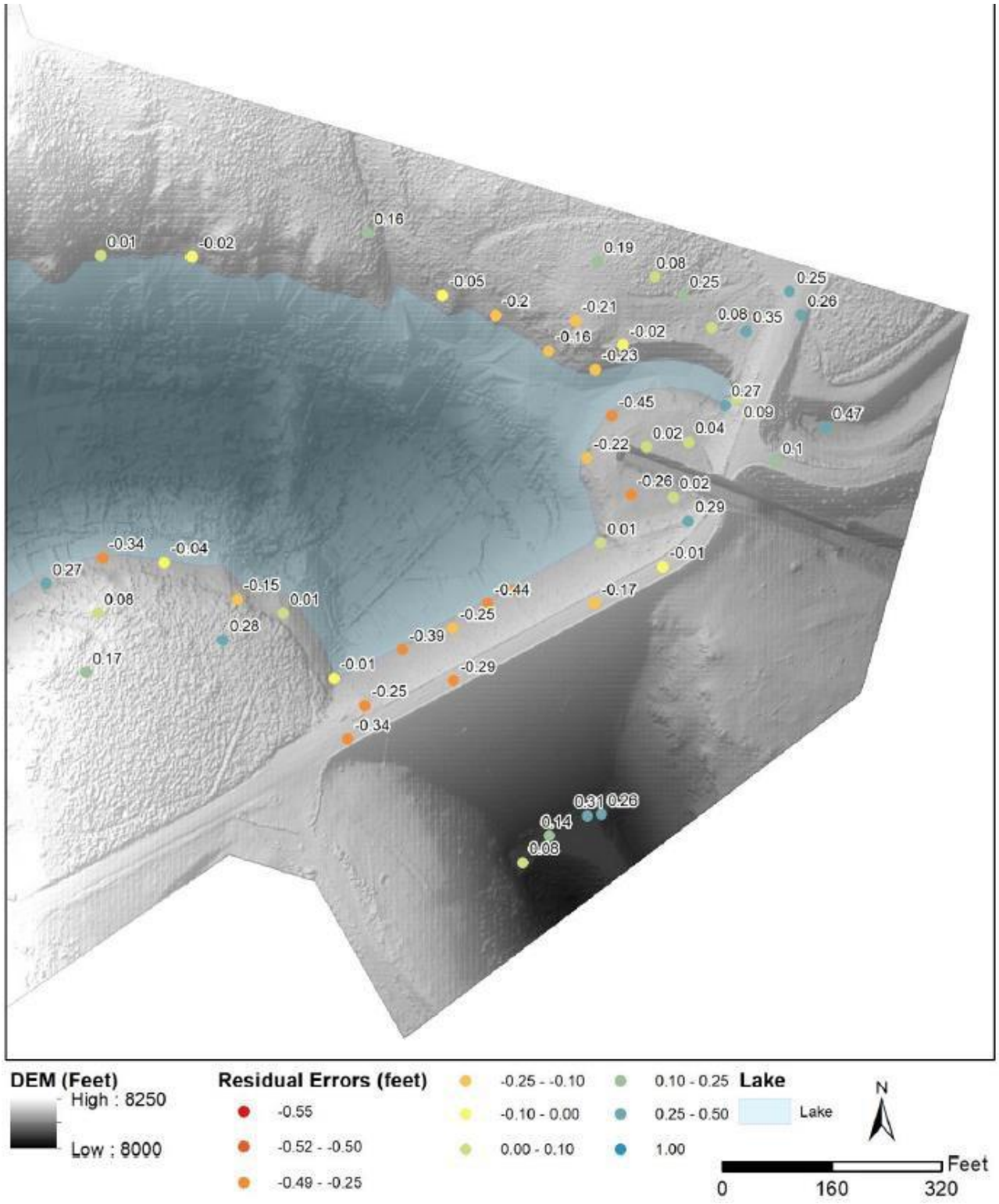

Figure 8: Detailed view of the ground truthing residual errors for Willow Creek Reservoir dam.

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Willow Creek Reservoir Elevation Model

Appendix A

INITIAL SURVEY OPUS SOLUTION (BLUE FONT)

FILE: 13403230.20o OP1606498696929

NGS OPUS SOLUTION REPORT
==========

All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: https://www.ngs.noaa.gov/OPUS/about.jsp#accuracy

USER: lukejavernick@gmail.com DATE: November 27, 2020
RINEX FILE: 1340323p.20o TIME: 17:40:27 UTC

SOFTWARE: page5 2008.25 master54.pl
160321 START: 2020/11/18 15:12:00
EPHEMERIS: igr21323.eph [rapid] STOP: 2020/11/18 20:10:00
NAV FILE: brdc3230.20n OBS USED: 11161 / 12419 : 90%
ANT NAME: TRMR10 NONE # FIXED AMB: 79 / 87 : 91%
ARP HEIGHT: 1.3398 OVERALL RMS: 0.021(m)

REF FRAME: NAD_83(2011)(EPOCH:2010.0000) ITRF2014 (EPOCH:2020.8818)

X: -1343154.602(m) 0.012(m) -1343155.528(m) 0.012(m)
Y: -4696056.098(m) 0.033(m) -4696054.789(m) 0.033(m)
Z: 4091859.095(m) 0.025(m) 4091858.968(m) 0.025(m)

LAT: 40 8 38.25830 0.013(m) 40 8 38.27612 0.013(m)
E LON: 254 2 18.74184 0.010(m) 254 2 18.68903 0.010(m)
W LON: 105 57 41.25816 0.010(m) 105 57 41.31097 0.010(m)
EL HGT: 2545.895(m) 0.038(m) 2545.046(m) 0.038(m)
ORTHO HGT: 2558.467(m) 0.071(m) [NAVD88 (Computed using GEOID18)]

UTM COORDINATES STATE PLANE COORDINATES
UTM (Zone 13) SPC (0501 CO N)
Northing (Y) [meters] 4444178.677 394906.992
Easting (X) [meters] 418101.963 875080.612

Convergence [degrees] -0.61989722 -0.29816389
Point Scale 0.99968257 0.99995857
Combined Factor 0.99928347 0.99955936

US NATIONAL GRID DESIGNATOR: 13TDE1810144178(NAD 83)

BASE STATIONS USED
PID DESIGNATION LATITUDE LONGITUDE DISTANCE(m)
DQ7576 TMG2 TABLE MOUNTAIN 2 CORS ARP N400747.834 W1051358.999 62122.6
DG7429 P041 MARSHALL FIELD CORS ARP N395658.150 W1051139.316 68966.4
AI2151 DSRC BOULDER CORS ARP N395929.130 W1051539.675 62134.5

NEAREST NGS PUBLISHED CONTROL POINT
LL0824 N 361 N400839.000 W1055952.000 3094.8

BASE STATION INFORMATION

STATION NAME: tmg2 a 1 (Table Mountain 2; Table Mountain, Colorado USA)
MONUMENT: NO DOMES NUMBER
XYZ -1283434.6975 -4713071.9754 4090105.0067 MON @ 2010.0000 (M)
XYZ -0.0149 0.0000 -0.0048 VEL (M/YR)
NEU -0.0000 0.0000 0.0083 MON TO ARP (M)
NEU 0.0005 0.0008 0.0854 ARP TO L1 PHASE CENTER (M)
NEU 0.0002 0.0001 0.1150 ARP TO L2 PHASE CENTER (M)
XYZ -0.1621 0.0000 -0.0522 VEL TIMES 10.8825 YRS
XYZ -0.0017 -0.0061 0.0053 MON TO ARP
XYZ -0.0163 -0.0629 0.0555 ARP TO L1 PHASE CENTER
XYZ -1283434.8776 -4713072.0444 4090105.0152 L1 PHS CEN @ 2020.8818
XYZ 0.0000 -0.0001 -0.0001 + XYZ ADJUSTMENTS
XYZ -1283434.8776 -4713072.0445 4090105.0151 NEW L1 PHS CEN @ 2020.8818
XYZ -1283434.8613 -4713071.9816 4090104.9597 NEW ARP @ 2020.8818
XYZ -1283434.8596 -4713071.9755 4090104.9543 NEW MON @ 2020.8818
LLH 40 7 47.85317 254 46 0.94852 1669.2122 NEW L1 PHS CEN @ 2020.8818
LLH 40 7 47.85316 254 46 0.94848 1669.1268 NEW ARP @ 2020.8818
LLH 40 7 47.85316 254 46 0.94848 1669.1185 NEW MON @ 2020.8818

STATION NAME: p041 a 5 (MARSHALL FIELD; Boulder, Colorado, U.S.A.)
MONUMENT: NO DOMES NUMBER

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XYZ -1283634.2357 -4726427.8874 4074798.0138 MON @ 2010.0000 (M)
XYZ -0.0150 0.0007 -0.0054 VEL (M/YR)
NEU -0.0000 0.0000 0.0083 MON TO ARP (M)
NEU 0.0013 0.0009 0.0848 ARP TO L1 PHASE CENTER (M)
NEU 0.0010 -0.0003 0.1181 ARP TO L2 PHASE CENTER (M)
XYZ -0.1632 0.0081 -0.0584 VEL TIMES 10.8825 YRS
XYZ -0.0017 -0.0061 0.0053 MON TO ARP
XYZ -0.0160 -0.0622 0.0555 ARP TO L1 PHASE CENTER
XYZ -1283634.4165 -4726427.9476 4074798.0162 L1 PHS CEN @ 2020.8818
XYZ 0.0000 -0.0000 -0.0000 + XYZ ADJUSTMENTS
XYZ -1283634.4165 -4726427.9476 4074798.0162 NEW L1 PHS CEN @ 2020.8818
XYZ -1283634.4006 -4726427.8854 4074797.9607 NEW ARP @ 2020.8818
XYZ -1283634.3989 -4726427.8793 4074797.9554 NEW MON @ 2020.8818
LLH 39 56 58.16820 254 48 20.63124 1728.9301 NEW L1 PHS CEN @ 2020.8818
LLH 39 56 58.16816 254 48 20.63121 1728.8452 NEW ARP @ 2020.8818
LLH 39 56 58.16816 254 48 20.63121 1728.8369 NEW MON @ 2020.8818

STATION NAME: dsrc a 2 (Boulder; Boulder, Colorado USA) MONUMENT:
NO DOMES NUMBER
XYZ -1288338.7942 -4721988.5441 4078321.0958 MON @ 2010.0000 (M)
XYZ -0.0147 0.0014 -0.0061 VEL (M/YR)
NEU 0.0000 0.0000 0.0000 MON TO ARP (M)
NEU 0.0011 -0.0000 0.0649 ARP TO L1 PHASE CENTER (M)
NEU 0.0001 0.0007 0.0580 ARP TO L2 PHASE CENTER (M)
XYZ -0.1595 0.0151 -0.0662 VEL TIMES 10.8825 YRS
XYZ 0.0000 0.0000 0.0000 MON TO ARP
XYZ -0.0129 -0.0473 0.0426 ARP TO L1 PHASE CENTER
XYZ -1288338.9666 -4721988.5762 4078321.0721 L1 PHS CEN @ 2020.8818
XYZ 0.0000 -0.0000 -0.0000 + XYZ ADJUSTMENTS
XYZ -1288338.9666 -4721988.5762 4078321.0721 NEW L1 PHS CEN @ 2020.8818
XYZ -1288338.9537 -4721988.5290 4078321.0296 NEW ARP @ 2020.8818
XYZ -1288338.9537 -4721988.5290 4078321.0296 NEW MON @ 2020.8818
LLH 39 59 29.14836 254 44 20.27271 1656.3307 NEW L1 PHS CEN @ 2020.8818
LLH 39 59 29.14833 254 44 20.27272 1656.2658 NEW ARP @ 2020.8818
LLH 39 59 29.14833 254 44 20.27272 1656.2658 NEW MON @ 2020.8818

REMOTE STATION INFORMATION STATION

NAME: 1340 1
MONUMENT: NO DOMES NUMBER
XYZ -1343155.4982 -4696054.2688 4091858.5250 MON @ 2020.8815 (M)
NEU 0.0009 0.0006 1.3398 MON TO ARP (M)

```
  NEU       -0.0009       -0.0006        0.1284 ARP TO L1 PHASE CENTER (M)
  NEU       -0.0027       -0.0064        0.1197 ARP TO L2 PHASE CENTER (M)
  XYZ     -0.2809         -0.9843     0.8645 MON TO ARP
  XYZ     -0.0278         -0.0947     0.0821 ARP TO L1 PHASE CENTER
XYZ -1343155.8068 -4696055.3479 4091859.4716 L1 PHS CEN @ 2020.8818 BASELINE

NAME: tmg2 1340
  XYZ     -0.0255         -0.5264     0.4539 + XYZ ADJUSTMENTS
  XYZ -1343155.8323  -4696055.8743   4091859.9255 NEW L1 PHS CEN @ 2020.8818
  XYZ -1343155.8045  -4696055.7796   4091859.8434 NEW ARP @ 2020.8818
  XYZ -1343155.5237  -4696054.7952   4091858.9789 NEW MON @ 2020.8818
  LLH 40 8 38.27629   254 2 18.68928    2546.5247 NEW L1 PHS CEN @ 2020.8818
  LLH 40 8 38.27632 254 2 18.68931      2546.3964 NEW ARP @ 2020.8818
  LLH 40 8 38.27629 254 2 18.68928      2545.0565 NEW MON @ 2020.8818

  BASELINE NAME: p041 1340
  XYZ     -0.0376         -0.5340     0.4461 + XYZ ADJUSTMENTS
  XYZ -1343155.8445  -4696055.8819   4091859.9176 NEW L1 PHS CEN @ 2020.8818
  XYZ -1343155.8167  -4696055.7872   4091859.8356 NEW ARP @ 2020.8818
  XYZ -1343155.5358  -4696054.8028   4091858.9711 NEW MON @ 2020.8818
  LLH 40 8 38.27588   254 2 18.68887    2546.5278 NEW L1 PHS CEN @ 2020.8818
  LLH 40 8 38.27591 254 2 18.68890      2546.3995 NEW ARP @ 2020.8818
  LLH 40 8 38.27588 254 2 18.68887      2545.0596 NEW MON @ 2020.8818

  BASELINE NAME: dsrc 1340
  XYZ     -0.0264         -0.5013     0.4287 + XYZ ADJUSTMENTS
  XYZ -1343155.8332  -4696055.8491   4091859.9002 NEW L1 PHS CEN @ 2020.8818
  XYZ -1343155.8054  -4696055.7544   4091859.8182 NEW ARP @ 2020.8818
  XYZ -1343155.5246  -4696054.7701   4091858.9537 NEW MON @ 2020.8818
  LLH 40 8 38.27617   254 2 18.68895    2546.4901 NEW L1 PHS CEN @ 2020.8818
  LLH 40 8 38.27620   254 2 18.68898    2546.3618 NEW ARP @ 2020.8818
  LLH 40 8 38.27617   254 2 18.68895    2545.0219 NEW MON @ 2020.8818

G-FILES Axx20201118

201118
B202011181511  2011182010 1 page5 v2008.25IGS       132 1 2 27NGS  20201127IFDDPX
IITRF2014_2118          IGS  20200809
C00090004 597206640 12 -170171802 36 -17540246 26 X3230A1340X3230ATMG2
D 1 2 4460418 1 3 -5107396 2 3 -9024897
Axx20201118 201118
```

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```
B202011181511  2011182010 1 page5 v2008.25IGS       132 1 2 27NGS  20201127IFDDPX
IITRF2014_2118          IGS  20200809
C00090005 595211370 11 -303730765 28 -170610157 23 X3230A1340X3230AP041
D 1 2 6519496 1 3 -7361334 2 3 -8993466

Axx20201118 201118
B202011181511  2011182010 1 page5 v2008.25IGS       132 1 2 27NGS  20201127IFDDPX
IITRF2014_2118          IGS  20200809
C00090003 548165709 12 -259337589 31 -135379241 27 X3230A1340X3230ADSRC
D 1 2 6684949 1 3 -7472904 2 3 -8991024

POST-FIT RMS BY SATELLITE VS. BASELINE OVERALL 01    03

                     04    08    10    11    13    15
  tmg2-1340|  0.021  0.022  0.023    ... 0.025  0.031.............0.024
           18    20    22    23    24    25    26    27    29
     tmg2-1340| 0.021 0.021 0.021 0.019 0.019 0.034 0.029 0.018 ...
           31    32
  tmg2-1340| 0.019 0.020

OVERALL              01    03    04    08    10    13    15    18
     p041-1340| 0.020 0.018 0.024 ... 0.027 0.026 ... 0.029 0.017
           20    22    23    24    25    26    27    29    31
  p041-1340|  0.019  0.016  0.018  0.019  0.032  0.020  0.019.......0.018
          32
 p041-1340| 0.014

OVERALL              01    03    04    08    10    11    13    15
  dsrc-1340|  0.021  0.023  0.019    ... 0.028  0.024 .............0.029
           18    20    22    23    24    25    26    27    29
    dsrc-1340| 0.021 0.019 0.019 0.021 0.022 0.024 0.044 0.019 ...
           31    32
 dsrc-1340| 0.022 0.017

OBS BY SATELLITE VS. BASELINE

OVERALL              01    03    04    08    10    11    13    15
tmg2-1340|   3801    283    106    ...    241       47..... 170
           18    20    22    23    24    25    26    27    29
  tmg2-1340|  294 419 205 435 318 169              39 283 ...
  31             32
  tmg2-1340|  303 489
```

```
OVERALL              01    03    04    08    10    13    15    18
   p041-1340| 3793 280 104 ... 251            37 ... 170 294
            20   22     23    24    25    26    27 29       31
   p041-1340| 419 216 452 328 167            22 275 ... 298
            32
   p041-1340| 480
  OVERALL           01    03   04    08    1011       13  15
  dsrc-1340| 3567   266       90 ...  217      43 ...      ...  158
  18              20    22    23    24    25    26    27    29
   dsrc-1340|   294  410 220 399 292          99       43 274 ...
            31    32
   dsrc-1340|   307  455
```

ITRF position of 1340 as determined by individual baselines X

	Y	Z
tmg2	-1343155.524	-4696054.795	4091858.979
p041	-1343155.536	-4696054.803	4091858.971
dsrc	-1343155.525	-4696054.770	4091858.954

Residuals of position determined by individual baselines from the final position

	X	Y	Z	East	North	Up
tmg2	0.004	-0.006	0.011	0.006	0.006	0.010
p041	-0.008	-0.013	0.003	-0.004	-0.007	0.014
dsrc	0.003	0.019	-0.014	-0.002	0.002	-0.024

Covariance Matrix for the xyz OPUS Position (meters^2).

0.0000008622	0.0000001675	-0.0000001487
0.0000001675	0.0000064067	-0.0000004916
-0.0000001487	-0.0000004916	0.0000051222

Covariance Matrix for the enu OPUS Position (meters^2).

0.0000011929	-0.0000008560	0.0000010096
-0.0000008560	0.0000050100	-0.0000003795
0.0000010096	-0.0000003795	0.0000061883

Horizontal network accuracy = 0.00460 meters.
Vertical network accuracy = 0.00488 meters.

Derivation of NAD 83 vector components

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Position of reference station ARP in NAD_83(2011)(EPOCH:2010.0000).

	Xa(m)	Ya(m)	Za(m)	
TMG2	-1283433.93580	-4713073.29306	4090105.08635	2010.00
P041	-1283633.47490	-4726429.20751	4074798.09569	2010.00
DSRC	-1288338.03130	-4721989.85735	4078321.17171	2010.00

Position of reference station monument in NAD_83(2011)(EPOCH:2010.0000).

	Xr(m)	Yr(m)	Zr(m)	
TMG2	-1283433.93410	-4713073.28696	4090105.08105	2010.00
P041	-1283633.47320	-4726429.20141	4074798.09039	2010.00
DSRC	-1288338.03130	-4721989.85735	4078321.17171	2010.00

Velocity of reference station monument in NAD_83(2011)(EPOCH:2010.0000).

	Vx (m/yr)	Vy (m/yr)	Vz (m/yr)
TMG2	0.00217	0.00074	-0.00030
P041	0.00202	0.00144	-0.00089
DSRC	0.00233	0.00214	-0.00158

Vectors from unknown station monument to reference station monument in NAD_83(2011)(EPOCH:2010.0000).

	Xr-X= DX(m)	Yr-Y= DY(m)	Zr-Z= DZ(m)	
TMG2	59720.66790	-17017.18896	-1754.01395	2010.00
P041	59521.12880	-30373.10341	-17061.00461	2010.00
DSRC	54816.57070	-25933.75935	-13537.92329	2010.00

STATE PLANE COORDINATES - U.S. Survey Foot SPC
(0501 CO N)

Northing (Y) [feet]	1295624.023
Easting (X) [feet]	2870993.641
Convergence [degrees]	-0.29816389
Point Scale	0.99995857
Combined Factor	0.99955936

APPENDIX B

SECONDARY QUALITY CONTROL SURVEY OPUS SOLUTION (BLUE FONT)

FILE: 13403250.20o OP1606498575492

NGS OPUS SOLUTION REPORT
==========

All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: https://www.ngs.noaa.gov/OPUS/about.jsp#accuracy

USER: lukejavernick@gmail.com DATE: November 27, 2020
RINEX FILE: 1340325o.20o TIME: 17:38:15 UTC

SOFTWARE: page5 2008.25 master91.pl
160321 START: 2020/11/20 14:43:00
EPHEMERIS: igr21325.eph [rapid] STOP: 2020/11/20 20:10:00
NAV FILE: brdc3250.20n OBS USED: 13530 / 15036 : 90%
ANT NAME: TRMR10 NONE # FIXED AMB: 62 / 67 : 93%
ARP HEIGHT: 1.3398 OVERALL RMS: 0.020(m)

REF FRAME: NAD_83(2011)(EPOCH:2010.0000) ITRF2014 (EPOCH:2020.8872)

X:	-1343154.611(m)	0.013(m)	-1343155.537(m)	0.013(m)
Y:	-4696056.108(m)	0.001(m)	-4696054.799(m)	0.001(m)
Z:	4091859.093(m)	0.017(m)	4091858.966(m)	0.017(m)

LAT:	40 8 38.25798	0.014(m)	40 8 38.27584	0.014(m)
E LON:	254 2 18.74159	0.013(m)	254 2 18.68878	0.013(m)
W LON:	105 57 41.25841	0.013(m)	105 57 41.31122	0.013(m)
EL HGT:	2545.903(m)	0.010(m)	2545.054(m)	0.010(m)
ORTHO HGT:	2558.475(m)	0.055(m)	[NAVD88 (Computed using GEOID18)]	

UTM COORDINATES		STATE PLANE COORDINATES
UTM (Zone 13)		SPC (0501 CO N)
Northing (Y) [meters]	4444178.667	394906.982
Easting (X) [meters]	418101.956	875080.606
Convergence [degrees]	-0.61989722	-0.29816389
Point Scale	0.99968257	0.99995857
Combined Factor	0.99928347	0.99955936

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Willow Creek Reservoir Elevation Model

US NATIONAL GRID DESIGNATOR: 13TDE1810144178(NAD 83)

BASE STATIONS USED

PID	DESIGNATION	LATITUDE	LONGITUDE	DISTANCE(m)
NIST				61894.9
DG7429	P041 MARSHALL FIELD CORS ARP	N395658.150	W1051139.316	68966.4
DQ7574	COBK BRECKENRIDGE CO CORS ARP	N393146.861	W1060251.646	68631.3

NEAREST NGS PUBLISHED CONTROL POINT

LL0824	N 361	N400839.000	W1055952.000	3094.8

BASE STATION INFORMATION

STATION NAME: nist a 2 (Boulder, Colorado, UNI; Boulder, Colorado USA)
MONUMENT: 49507M002

XYZ	-1288398.3776	-4721696.9281	4078625.3913	MON @ 2010.0000 (M)
XYZ	-0.0153	0.0004	-0.0048	VEL (M/YR)
NEU	0.0000	0.0000	0.0000	MON TO ARP (M)
NEU	0.0006	0.0020	0.0656	ARP TO L1 PHASE CENTER (M)
NEU	-0.0006	0.0008	0.0642	ARP TO L2 PHASE CENTER (M)
XYZ	-0.1661	0.0044	-0.0522	VEL TIMES 10.8879 YRS
XYZ	0.0000	0.0000	0.0000	MON TO ARP
XYZ	-0.0112	-0.0487	0.0427	ARP TO L1 PHASE CENTER
XYZ	-1288398.5549	-4721696.9723	4078625.3817	L1 PHS CEN @ 2020.8872
XYZ	0.0000	-0.0000	-0.0000	+ XYZ ADJUSTMENTS
XYZ	-1288398.5549	-4721696.9723	4078625.3817	NEW L1 PHS CEN @ 2020.8872
XYZ	-1288398.5437	-4721696.9237	4078625.3390	NEW ARP @ 2020.8872
XYZ	-1288398.5437	-4721696.9237	4078625.3390	NEW MON @ 2020.8872
LLH	39 59 42.23906	254 44 14.61525	1648.4017	NEW L1 PHS CEN @ 2020.8872
LLH	39 59 42.23904	254 44 14.61517	1648.3361	NEW ARP @ 2020.8872
LLH	39 59 42.23904	254 44 14.61517	1648.3361	NEW MON @ 2020.8872

STATION NAME: p041 a 5 (MARSHALL FIELD; Boulder, Colorado, U.S.A.)
MONUMENT: NO DOMES NUMBER

XYZ	-1283634.2357	-4726427.8874	4074798.0138	MON @ 2010.0000 (M)
XYZ	-0.0150	0.0007	-0.0054	VEL (M/YR)
NEU	-0.0000	0.0000	0.0083	MON TO ARP (M)
NEU	0.0013	0.0009	0.0848	ARP TO L1 PHASE CENTER (M)
NEU	0.0010	-0.0003	0.1181	ARP TO L2 PHASE CENTER (M)
XYZ	-0.1632	0.0081	-0.0584	VEL TIMES 10.8879 YRS
XYZ	-0.0017	-0.0061	0.0053	MON TO ARP
XYZ	-0.0160	-0.0622	0.0555	ARP TO L1 PHASE CENTER

```
  XYZ  -1283634.4166 -4726427.9476 4074798.0161 L1 PHS CEN @ 2020.8872
  XYZ        0.0000       -0.0000       -0.0000 + XYZ ADJUSTMENTS
  XYZ  -1283634.4166 -4726427.9476   4074798.0161 NEW L1 PHS CEN @ 2020.8872
  XYZ  -1283634.4006 -4726427.8854   4074797.9607 NEW ARP @ 2020.8872
  XYZ  -1283634.3990 -4726427.8793   4074797.9553 NEW MON @ 2020.8872
  LLH  39 56 58.16820 254 48 20.63124  1728.9301   NEW L1 PHS CEN @ 2020.8872
  LLH 39 56 58.16816 254 48 20.63120   1728.8452   NEW ARP @ 2020.8872
  LLH 39 56 58.16816 254 48 20.63120   1728.8369   NEW MON @ 2020.8872

STATION NAME: cobk  a       1 (Breckenridge CO; Breckenridge, Colorado  USA)
MONUMENT: NO DOMES NUMBER
XYZ -1362360.8045 -4736234.0080 4039638.0063 MON @ 2010.0000 (M)
   XYZ -0.0147            0.0001 -0.0050       VEL (M/YR)
   NEU 0.0000             0.0000 0.0000        MON TO ARP (M)
   NEU 0.0014            -0.0002 0.0880        ARP TO L1 PHASE CENTER (M)
   NEU 0.0006             0.0002 0.0812        ARP TO L2 PHASE CENTER (M)
   XYZ -0.1601            0.0011 -0.0544       VEL TIMES 10.8879 YRS
   XYZ 0.0000             0.0000 0.0000        MON TO ARP
   XYZ -0.0188           -0.0643 0.0571        ARP TO L1 PHASE CENTER
   XYZ -1362360.9833  -4736234.0712 4039638.0090 L1 PHS CEN @ 2020.8872
   XYZ 0.0002            0.0000         0.0000 + XYZ ADJUSTMENTS
   XYZ -1362360.9832  -4736234.0712   4039638.0090 NEW L1 PHS CEN @ 2020.8872
   XYZ -1362360.9644  -4736234.0069   4039637.9519 NEW ARP @ 2020.8872
   XYZ -1362360.9644  -4736234.0069   4039637.9519 NEW MON @ 2020.8872
   LLH  39 31 46.87955   253 57  8.30125 2814.8663    NEW L1 PHS CEN @ 2020.8872
  LLH 39 31 46.87951 253 57     8.30126 2814.7782    NEW ARP @ 2020.8872
  LLH 39 31 46.87951 253 57     8.30126 2814.7782    NEW MON @ 2020.8872

REMOTE STATION INFORMATION STATION

NAME: 1340                     1
MONUMENT: NO DOMES NUMBER
XYZ -1343155.4659 -4696054.2441 4091858.5456 MON @ 2020.8869 (M)
  NEU    0.0009          0.0007      1.3398 MON TO ARP (M)
  NEU    -0.0009         -0.0006     0.1284 ARP TO L1 PHASE CENTER (M)
  NEU    -0.0027         -0.0064     0.1197 ARP TO L2 PHASE CENTER (M)
  XYZ    -0.2809         -0.9843     0.8645 MON TO ARP
  XYZ    -0.0278         -0.0947     0.0821 ARP TO L1 PHASE CENTER
XYZ -1343155.7745 -4696055.3232 4091859.4922 L1 PHS CEN @ 2020.8872

BASELINE NAME: nist 1340
  XYZ       -0.0653       -0.5546      0.4202 + XYZ ADJUSTMENTS
  XYZ  -1343155.8399 -4696055.8778    4091859.9123 NEW L1 PHS CEN @ 2020.8872
  XYZ  -1343155.8121 -4696055.7830    4091859.8303 NEW ARP @ 2020.8872
  XYZ  -1343155.5312 -4696054.7987    4091858.9658 NEW MON @ 2020.8872
  LLH   40 8 38.27585  254 2 18.68901   2546.5204 NEW L1 PHS CEN @ 2020.8872
```

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```
LLH 40 8 38.27588 254 2 18.68904 2546.3920 NEW ARP @ 2020.8872
LLH 40 8 38.27585 254 2 18.68901 2545.0522 NEW MON @ 2020.8872

BASELINE NAME: p041 1340
  XYZ  -0.0697          -0.5559       0.4285 + XYZ ADJUSTMENTS
  XYZ -1343155.8443 -4696055.8790   4091859.9207  NEW L1 PHS CEN @ 2020.8872
  XYZ -1343155.8165 -4696055.7843   4091859.8386  NEW ARP @ 2020.8872
  XYZ -1343155.5356 -4696054.8000   4091858.9741  NEW MON @ 2020.8872
  LLH  40 8 38.27601  254  2 18.68885   2546.5276 NEW L1 PHS CEN @ 2020.8872
  LLH  40 8 38.27604  254  2 18.68888   2546.3993 NEW ARP @ 2020.8872
  LLH  40 8 38.27601  254  2 18.68885   2545.0594 NEW MON @ 2020.8872

  BASELINE NAME:    cobk 1340
  XYZ       -0.0786       -0.5550      0.4117 + XYZ ADJUSTMENTS
  XYZ -1343155.8531 -4696055.8782   4091859.9039  NEW L1 PHS CEN @ 2020.8872
  XYZ -1343155.8253 -4696055.7835   4091859.8218  NEW ARP @ 2020.8872
  XYZ -1343155.5445 -4696054.7991   4091858.9573  NEW MON @ 2020.8872
  LLH  40 8 38.27556  254  2 18.68848   2546.5180 NEW L1 PHS CEN @ 2020.8872
  LLH  40 8 38.27559  254  2 18.68851   2546.3897 NEW ARP @ 2020.8872
  LLH  40 8 38.27556  254  2 18.68848   2545.0498 NEW MON @ 2020.8872

G-FILES Axx20201120 201120
B202011201443  2011202010 1 page5 v2008.25IGS       132 1 2 27NGS  20201127IFDDPX
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D 1 2 6562038 1 3 -7087936 2 3 -8936119

Axx20201120 201120
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Axx20201120 201120
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IITRF2014_2118          IGS 20200809
C00090001 -192054199      8 -401792078 25 -522210054 24 X3250A1340X3250ACOBK
D 1 2 8673229 1 3 -6853607 2 3 -7987361

POST-FIT RMS BY SATELLITE VS. BASELINE OVERALL     01

                        03    04    08    10    13    15    16
   nist-1340|  0.019 0.019 0.026   ... 0.031 0.014 0.035 0.020   ...
            18    20    21    22    23    24    25    26    27
```

```
nist-1340| 0.036 0.019 0.016 0.021 0.017 0.025 0.019 0.019 0.023
29                  31     32
nist-1340| 0.031 0.016  0.023

          OVERALL     01     03     04     08     10     13     15     16
   p041-1340|  0.019  0.022  0.024    ...  0.027  0.032  0.029  0.022    ...
              18     20     21     22     23     24     25     26     27
     p041-1340| 0.015 0.016 0.019 0.021 0.013 0.022 0.031 0.032 0.017
              29     31     32
   p041-1340| 0.020 0.023  0.014

          OVERALL     01     03     04     08     10     13     15     16
cobk-1340|  0.020  0.020  0.024       ...  0.027  0.025  0.022  0.017    ...
18                  20     21     22     23     24     25     26     27
cobk-1340| 0.013 0.022 0.020 0.020 0.016 0.022 0.033 0.046  0.019
29                  31     32
cobk-1340|       ... 0.019  0.016

                  OBS BY SATELLITE VS. BASELINE

          OVERALL     01    03     04     08    10    13     15      16
    nist-1340|  4451    296   101    ...    182   633   38     211     ...
  18                  20     21     22   23     24     25      26     27
  nist-1340|     70    459    414    229    479    374    148     20    308
              29     31     32
  nist-1340|     28    293    168
  OVERALL             01     03   04     08     10     13     15     16
   p041-1340|  4635 298       122...      197      78     60    212    ...
              18 20     21      22      23     24      25     26     27
   p041-1340|  336   467       418    237    497    368184        63  296
              29 31     32
   p041-1340|  44     295    463
  OVERALL           01      03     04     08      10     13     15     16
   cobk-1340|  4444 274       101...      176      75     30    210    ...
              18 20     21      22      23     24      25     26     27
   cobk-1340|  333   478       407    242    479    358157      42      306
              29 31     32
   cobk-1340|  ...      316    460


ITRF position of 1340 as determined by individual baselines X
                           Y            Z
nist      -1343155.531   -4696054.799    4091858.966
p041      -1343155.536   -4696054.800    4091858.974
cobk      -1343155.545   -4696054.799    4091858.957
```

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Willow Creek Reservoir Elevation Model

Residuals of position determined by individual baselines from the final position

	X	Y	Z	East	North	Up
nist	0.006	0.001	0.000	0.006	0.001	-0.002
p041	0.002	-0.001	0.008	0.002	0.006	0.006
cobk	-0.007	0.000	-0.008	-0.007	-0.008	-0.004

Covariance Matrix for the xyz OPUS Position (meters^2).

0.0000005022	0.0000000980	-0.0000000837
0.0000000980	0.0000036400	-0.0000002758
-0.0000000837	-0.0000002758	0.0000028889

Covariance Matrix for the enu OPUS Position (meters^2).

0.0000006877	-0.0000004829	0.0000005692
-0.0000004829	0.0000028384	-0.0000002279
0.0000005692	-0.0000002279	0.0000035050

Horizontal network accuracy = 0.00346 meters.
Vertical network accuracy = 0.00367 meters.

Derivation of NAD 83 vector components

Position of reference station ARP in NAD_83(2011)(EPOCH:2010.0000).

	Xa(m)	Ya(m)	Za(m)	
NIST	0.00000	0.00000	0.00000	
P041	-1283633.47490	-4726429.20751	4074798.09569	2010.00
COBK	-1362360.04263	-4736235.32241	4039638.08422	2010.00

Position of reference station monument in NAD_83(2011)(EPOCH:2010.0000).

	Xr(m)	Yr(m)	Zr(m)	
NIST	0.00000	0.00000	0.00000	
P041	-1283633.47320	-4726429.20141	4074798.09039	2010.00
COBK	-1362360.04263	-4736235.32241	4039638.08422	2010.00

Velocity of reference station monument in NAD_83(2011)(EPOCH:2010.0000).

	Vx (m/yr)	Vy (m/yr)	Vz (m/yr)
NIST	0.00174	0.00114	-0.00028
P041	0.00202	0.00144	-0.00089
COBK	0.00220	0.00081	-0.00020

Vectors from unknown station monument to reference station monument in NAD_83(2011)(EPOCH:2010.0000).

	Xr-X= DX(m)	Yr-Y= DY(m)	Zr-Z= DZ(m)	
NIST	1343154.61100	4696056.10800	-4091859.09300	
P041	59521.13780	-30373.09341	-17061.00261	2010.00

COBK -19205.43163 -40179.21441 -52221.00878 2010.00

STATE PLANE COORDINATES - U.S. Survey Foot SPC
(0501 CO N)
Northing (Y) [feet] 1295623.990
Easting (X) [feet] 2870993.622
Convergence [degrees] -0.29816389
Point Scale 0.99995857
Combined Factor 0.99955936

River Science
425 Main Street, Ste 10
Canon City, CO 81212

Willow Creek Reservoir Elevation Model

APPENDIX C

Red Rock Land Surveys, Inc.
254 Pelage Ct. – Cañon City – CO - 81212
(303) 994-6300 jkratz@redrocklandsurveys.com

Attn: Luke Javernick
River Science
425 Main St. Ste. 10
Canon City, CO 81212

RE: Willow Creek Reservoir, Grand County, Colorado

Dear Mr. Javernick:

On November 18-20, 2020, Red Rock Land Surveys Inc. fulfilled your request to provide an independent check on the survey data and ground control used for generation of a Digital Elevation Model (DEM) by River Science at Willow Creek Reservoir. Verification was achieved in three primary ways:

1. Independent Survey of a sampling of the Ground Control Points (GCP's) set by River Science.
2. A survey of random field points for comparison with the DEM.
3. Observation of the methods River Science utilized for the establishment and survey of GCP's.

1. Red Rock created a Site Control Point on the near the reservoir dam, with the elevation established by static GPS observations, processed by the NGS OPUS online website. 94 percent of the 14962 observations were used by OPUS, yielding an Orthometric Height of 2497.262 meters +/- 0.058 meters. (NAVD 1988, Geoid 18). The Site Control Point was then used as a Base Point for GPS RTK observations of GCP's previously established by River Science throughout the subject area. 21 random GCP's were observed and compared with River Science data for the same. Comparison to data surveyed by River Science yielded horizontal ranges from 0.001-0.09' (X), 0.004-0.076' (Y) with averages of 0.027' and 0.0484', respectively. Vertical difference ranged from 0.009-0.149' with an average of 0.049'. These results are within the expected tolerances of the 2cm horizontal and 5cm vertical.

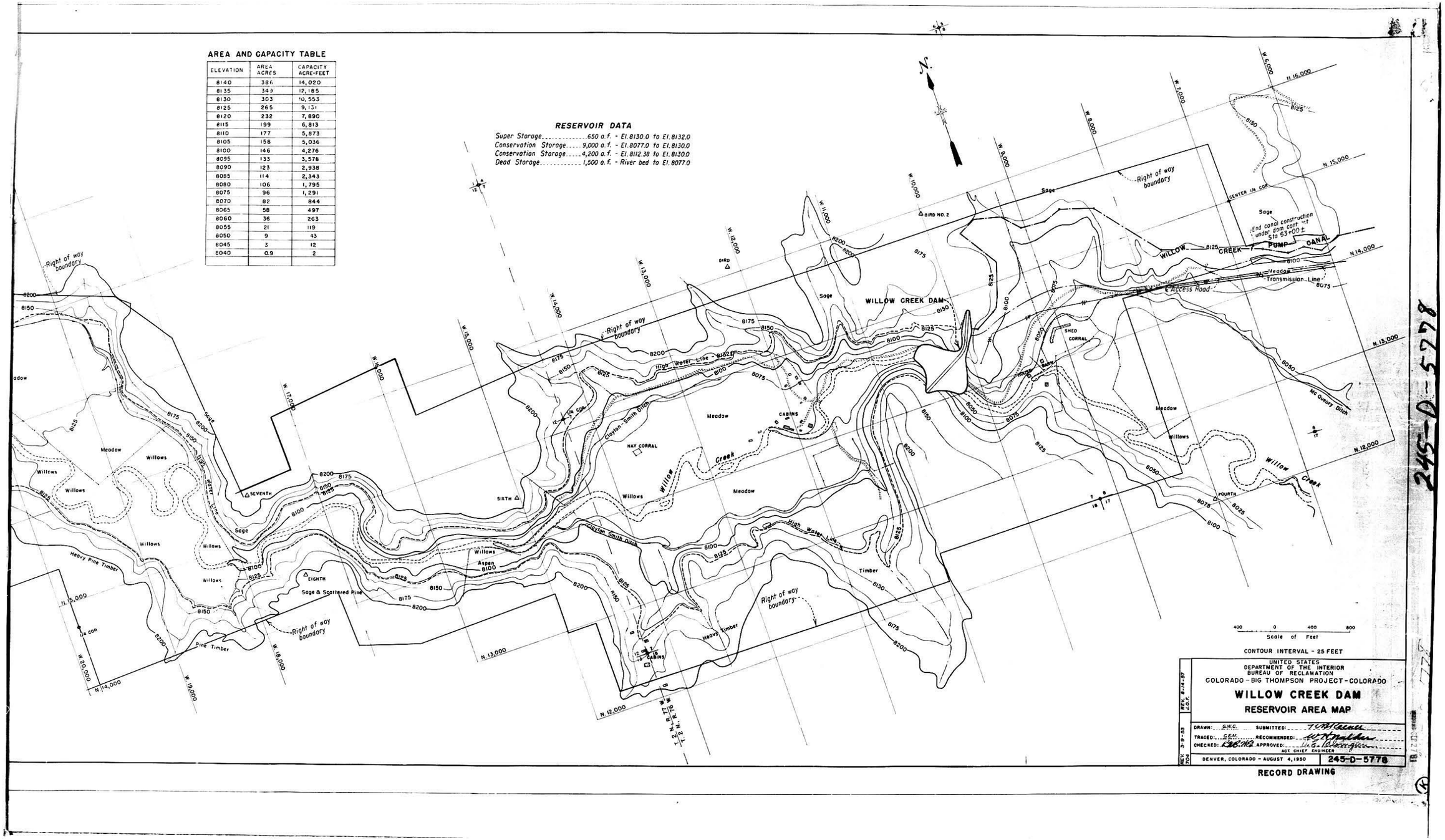
2. During the course of the surveying described above, Red Rock Land surveyed 218 independent ground points for comparison with the River Science DEM. Vertical differences were predominantly in the range of 0.0 to 0.2 feet.

3. Acting in my capacity as a Professional Land Surveyor, I observed and supervised the methods used by River Science in obtaining ground control data, including establishment of base points, RTK observations and OPUS solutions. All practices were within the normal standard of care, or better, for surveying in the State of Colorado.

I, John E. Kratz, a Registered Professional Land Surveyor in the State of Colorado, hereby certify the surveying described above was performed by me or under my direct supervision and checking and to the best of my professional knowledge and belief, the digital model generated by River Science is correct within the tolerances described within the Accuracy Report generated by River Science.

John E. Kratz
PLS No. 20142

Appendix C — Pre-Dam Reservoir Maps

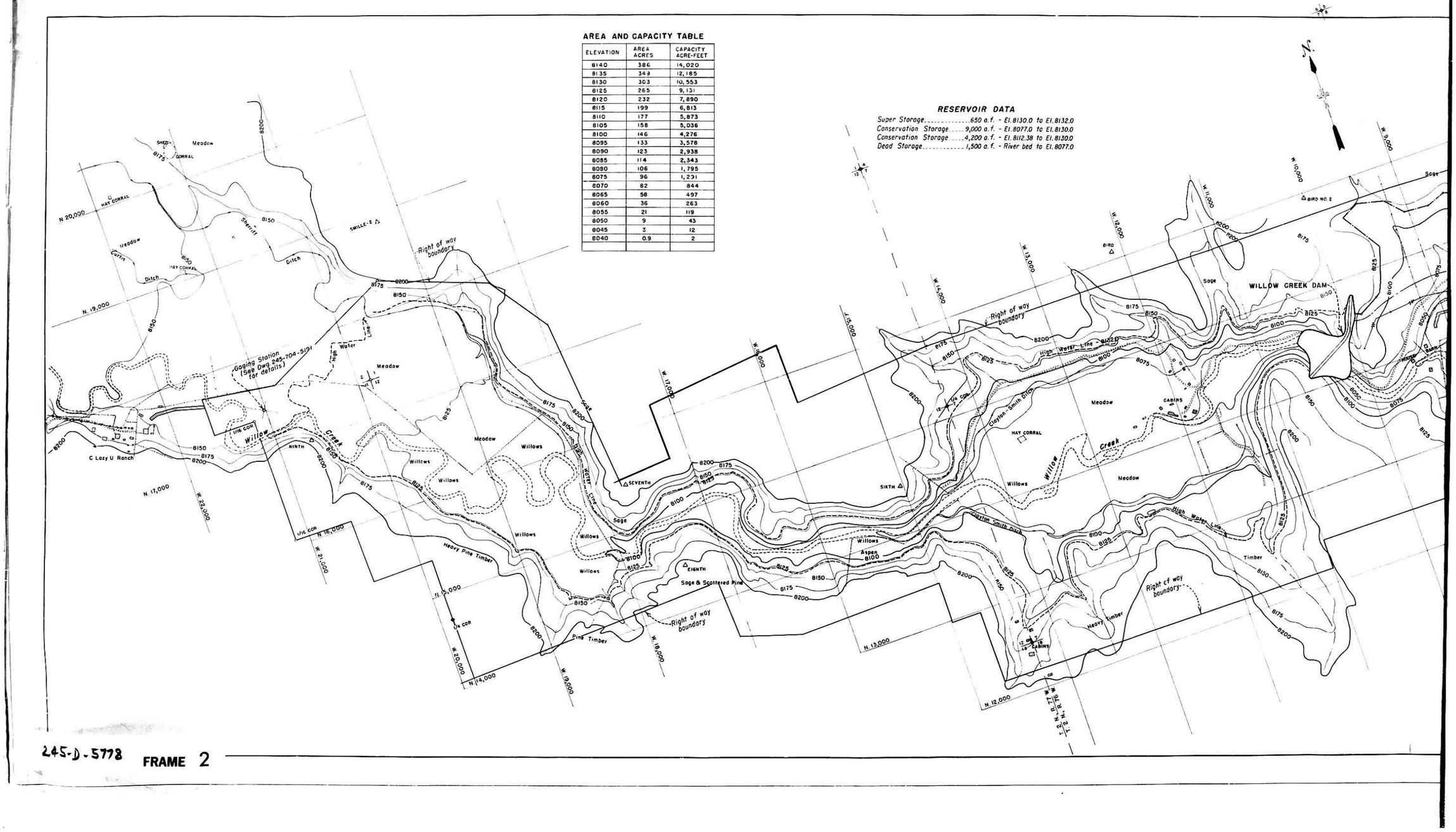

AREA AND CAPACITY TABLE
ELEVATION | AREA ACRES | CAPACITY ACRE-FEET
8140 | 386 | 14,020
8135 | 349 | 12,185
8130 | 303 | 10,553
8125 | 265 | 9,131
8120 | 232 | 7,890
8115 | 199 | 6,813
8110 | 177 | 5,873
8105 | 158 | 5,036
8100 | 146 | 4,276
8095 | 133 | 3,578
8090 | 123 | 2,938
8085 | 114 | 2,343
8080 | 106 | 1,795
8075 | 96 | 1,291
8070 | 82 | 844
8065 | 58 | 497
8060 | 36 | 263
8055 | 21 | 119
8050 | 9 | 43
8045 | 3 | 12
8040 | 0.9 | 2
RESERVOIR DATA
Super Storage.....650 a.f. - El. 8130.0 to El. 8132.0
Conservation Storage.....9,000 a.f. - El. 8077.0 to El. 8130.0
Conservation Storage.....4,200 a.f. - El. 8112.38 to El. 8130.0
Dead Storage.....1,500 a.f. - River bed to El. 8077.0
WILLOW CREEK DAM
WILLOW CREEK PUMP CANAL
BIRD NO. 2
SEVENTH
SIXTH
EIGHTH
CABINS
HAY CORRAL
SHED
CORRAL
BARN
Clayton-Smith Ditch
McCluskey Ditch
Willow Creek
Right of way boundary
High Water Line
Access Road
Transmission Line
Center 1/4 cor
End canal construction under dam cont'd Sta 63+00 ±
Sage
Meadow
Willows
Aspen
Timber
Heavy Timber
Heavy Pine Timber
Pine Timber
Sage & Scattered Pine
N. 16,000
N. 15,000
N. 14,000
N. 13,000
N. 12,000
W. 5,000
W. 8,000
W. 9,000
W. 10,000
W. 11,000
W. 12,000
W. 13,000
W. 14,000
W. 15,000
W. 17,000
W. 18,000
W. 19,000
W. 20,000
T. 1 N., R. 72 W., 6th P.M.
T. 1 S., R. 72 W., 6th P.M.
Scale of Feet
CONTOUR INTERVAL - 25 FEET
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO-BIG THOMPSON PROJECT-COLORADO
WILLOW CREEK DAM
RESERVOIR AREA MAP
DRAWN: G.W.C.
TRACED: G.E.M.
CHECKED: R.B.H.S.
SUBMITTED:
RECOMMENDED:
APPROVED:
ACT CHIEF ENGINEER
DENVER, COLORADO - AUGUST 4, 1950
245-D-5778
REV. 6-14-57
REV. 3-9-53
RECORD DRAWING
245-D-5278

AREA AND CAPACITY TABLE

ELEVATION	AREA ACRES	CAPACITY ACRE-FEET
8140	386	14,020
8135	349	12,185
8130	303	10,553
8125	265	9,131
8120	232	7,890
8115	199	6,813
8110	177	5,873
8105	158	5,036
8100	146	4,276
8095	133	3,578
8090	123	2,938
8085	114	2,343
8080	106	1,795
8075	96	1,231
8070	82	844
8065	58	497
8060	36	263
8055	21	119
8050	9	43
8045	3	12
8040	0.9	2

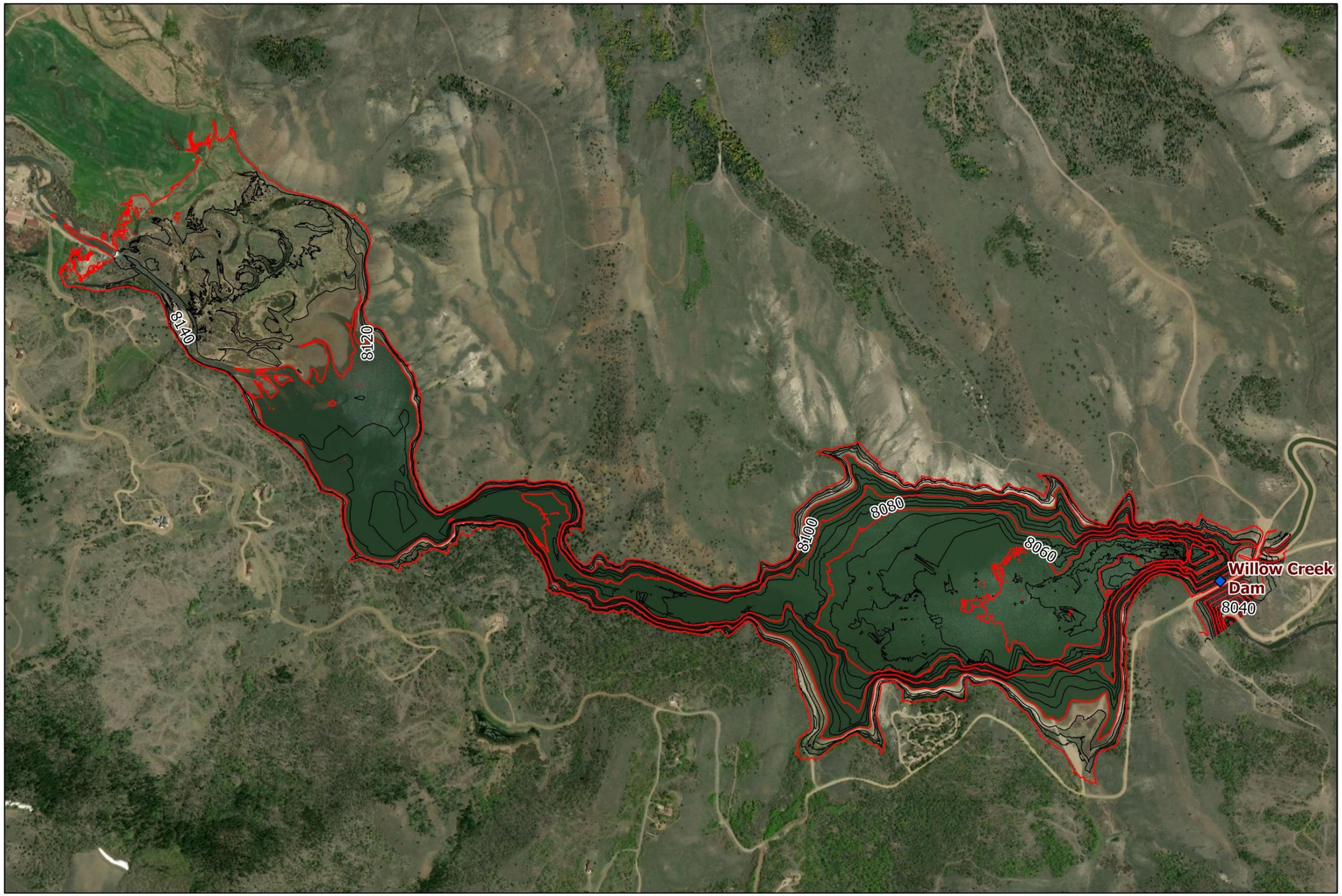
RESERVOIR DATA

Super Storage.....650 a.f. - El. 8130.0 to El. 8132.0
Conservation Storage.....9,000 a.f. - El. 8077.0 to El. 8130.0
Conservation Storage.....4,200 a.f. - El. 8112.38 to El. 8130.0
Dead Storage.....1,500 a.f. - River bed to El. 8077.0



245-D-5778 FRAME 2

Appendix D — 2020 Reservoir Maps



Willow Creek Reservoir Colorado Elevation Contour Map

Overview Map

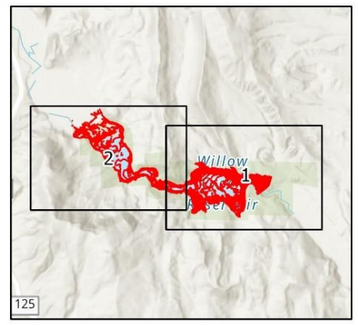
Map Prepared By:
Geographic Applications & Analysis Group
Bureau of Reclamation
Technical Service Center - 03/30/21

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 2020/2021 reservoir survey
Above Water Survey from 2020 Drone Photogrammetry

N

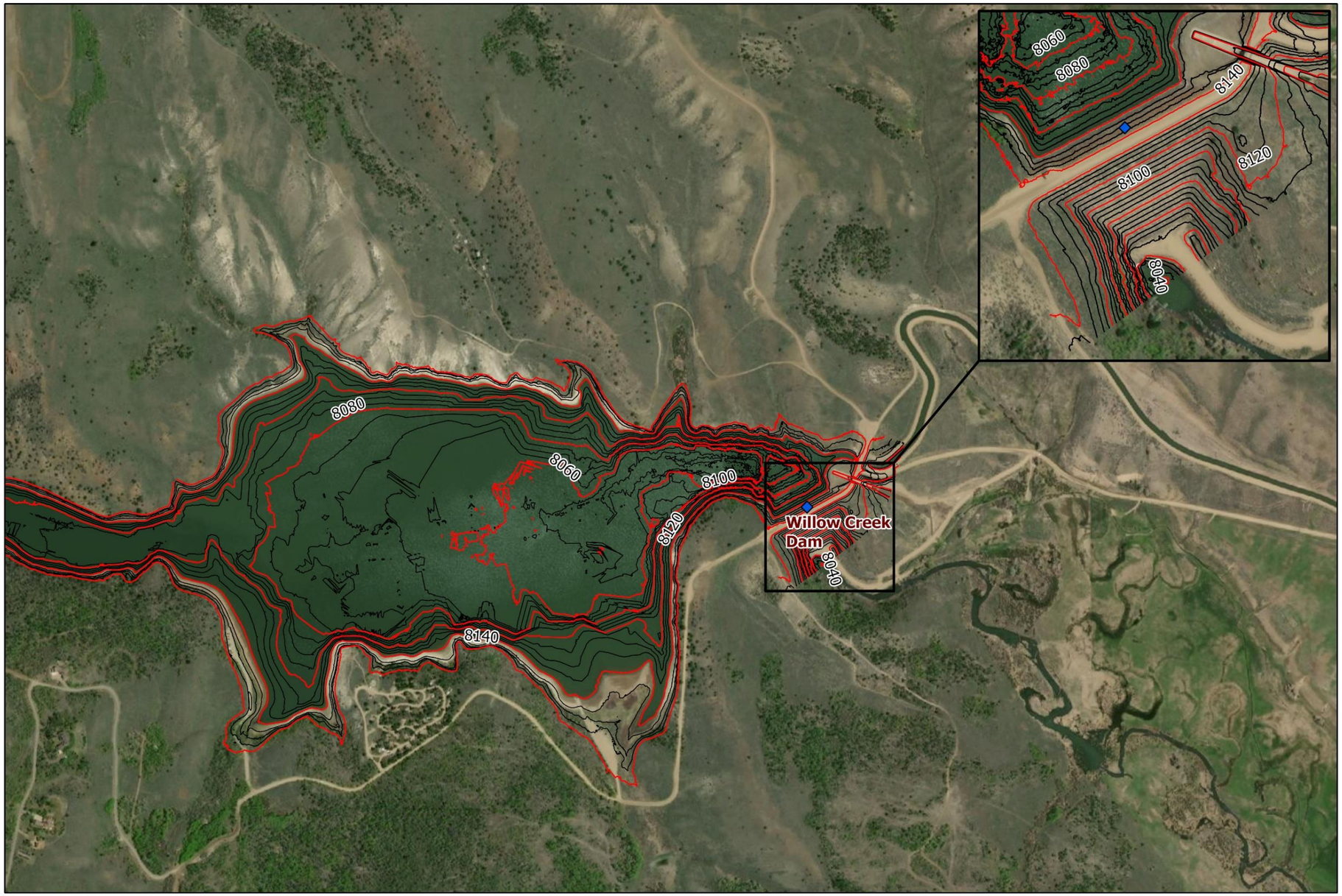
Scale 1:11,000

0 500 1,000 Feet



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

BUREAU OF RECLAMATION



Willow Creek Reservoir Colorado Elevation Contour Map

Sheet 1

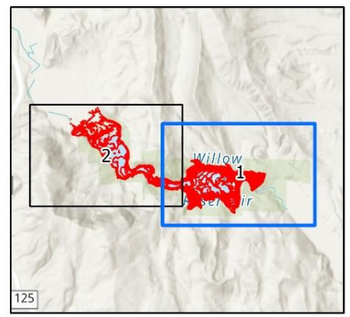
Map Prepared By:
Geographic Applications & Analysis Group
Bureau of Reclamation
Technical Service Center - 03/30/21

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 2020/2021 reservoir survey
Above Water Survey from 2020 Drone Photogrammetry

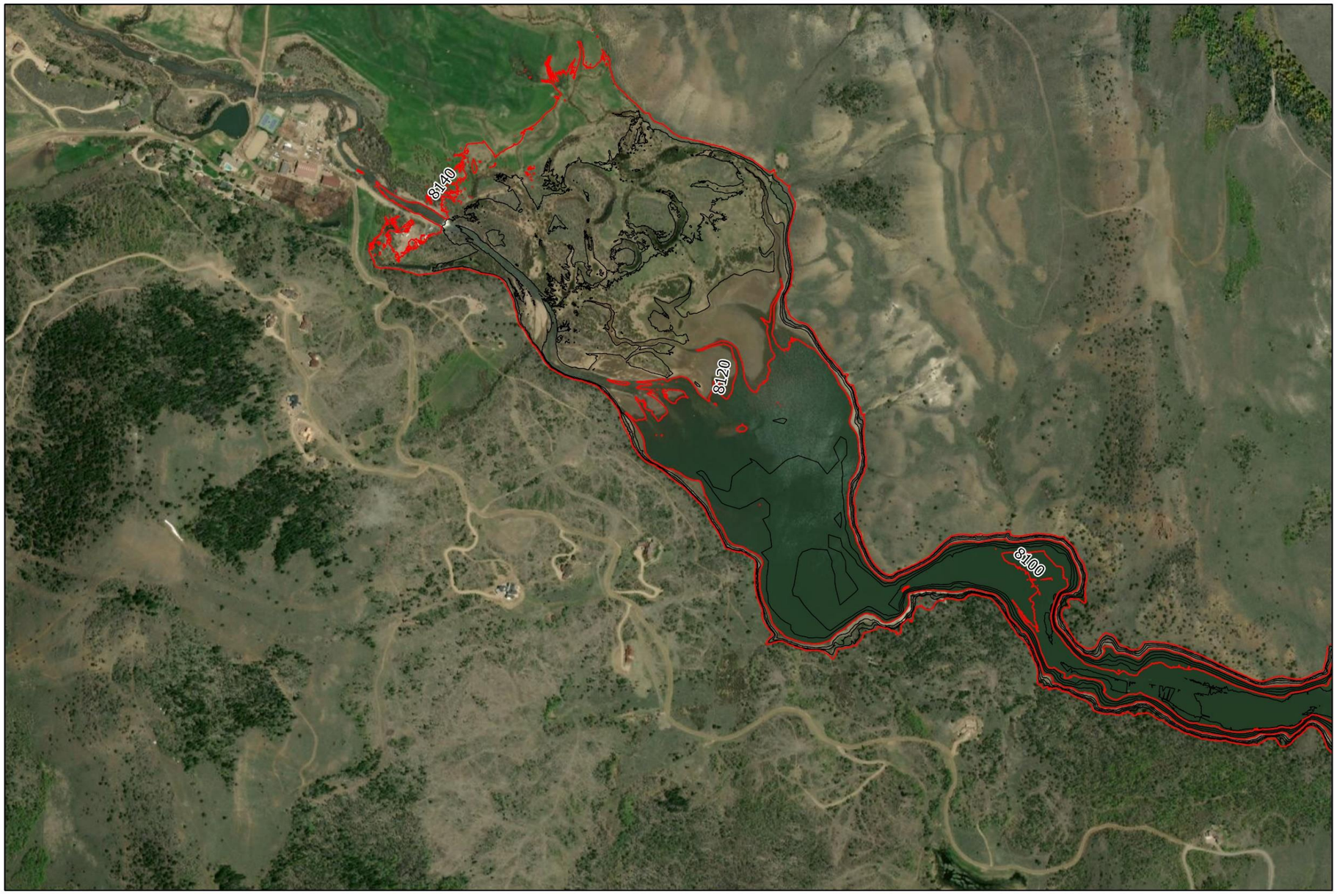
N

Scale 1:8,000

0 500 1,000 Feet



BUREAU OF RECLAMATION



Willow Creek Reservoir Colorado Elevation Contour Map

Sheet 2

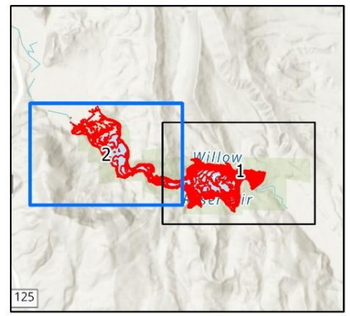
Map Prepared By:
Geographic Applications & Analysis Group
Bureau of Reclamation
Technical Service Center - 03/30/21

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 2020/2021 reservoir survey
Above Water Survey from 2020 Drone Photogrammetry

N

Scale 1:8,000

0 500 1,000 Feet



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

BUREAU OF RECLAMATION