CWTS report 2016-07, December 2016

NATIONAL DROUGHT RESILIENCE:
Improved Reservoir Sediment Surveys

Low water levels (67% storage capacity) at New Hogan Lake, California, in January 2014.

USACE
CLIMATE
PREPAREDNESS
AND RESILIENCE

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14. ABSTRACT

This report provides an update on the progress of USACE and Reclamation to provide an accurate, cost-efficient means for collecting reservoir sediment data in accordance with Goal 1, Task 4 of the NDRP Action Plan. It supplies information on drought impacts to reservoirs, the results of the NDRP reservoir survey by LiDAR in drought-lowered reservoirs, the cost and data quality advantages of a combined LiDAR – multi-beam SONAR approach, and examples that show the use of both of these technologies to assess sedimentation and remaining capacity at some of the nation's reservoirs. The report concludes with lessons learned to help guide subsequent deployment of these technologies at reservoirs across the Nation.

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EXECUTIVE SUMMARY

Reservoirs play a critical role in mitigating the effects of drought by providing water storage. Over time, sediment deposition reduces the amount of water that can be stored or managed at reservoirs. Most Federal reservoirs are designed to include a certain amount of sedimentation. Periodic sediment surveys provide critical information on sediment volume and the rate of sedimentation for comparison to the original designs. Ideally, the surveys are repeated on a regular basis because the location and rate of sediment deposits can change significantly over time due to large storm events, land development, land use change, and climate change-induced alterations in runoff. Historically, reservoir sediment information has been sporadic at reservoirs, in part because of the cost to obtain traditional sediment surveys in a constrained budget environment.

Based on available information, USACE staff suggested that drought-lowered reservoirs provided an opportunity to obtain more detailed reservoir survey information at a lower cost using airborne surveys compared to water-based bathymetric methods. The National Drought Resilience Partnership (NDRP), which was established in March 2016 to improve the security and economy of communities to threats from current and future drought through better coordination of Federal drought support provided an opportunity to act on this concept.

As an NDRP partner, the U.S. Army Corps of Engineers (USACE) took the lead for NDRP Action Plan Goal 1, Task 4, to improve and expand reservoir sediment surveys for reservoirs with water levels significantly lowered by drought. Working together with the Department of the Interior's Bureau of Reclamation (Reclamation), an interagency team developed a strategy and supporting technologies to enable rapid deployment and data collection using Light Detection and Ranging (LiDAR) technology. Because droughts tend to be regional phenomena, multiple reservoirs in an affected area are likely to be at exceptionally low water levels, which enables economies of scale through collection of data at multiple reservoirs during a single LiDAR mission. The team found that cost and field time are both minimized by using airborne LiDAR to collect topographic data when reservoir elevations are low. Data processing times are now smaller than before; the data can be shared through online databases, such as the USACE Geospatial Repository and Data Management System (GRiD); and the high resolution of the data set makes it useful for other purposes, including reallocation studies, project planning, and cultural resources management.

This report provides an update on the progress of USACE and Reclamation to provide an accurate, cost-efficient means for collecting reservoir sediment data in accordance with Goal 1, Task 4 of the NDRP Action Plan. It supplies information on drought impacts to reservoirs, the results of the NDRP reservoir survey by LiDAR in drought-lowered reservoirs, the cost and data quality advantages of a combined LiDAR – multi-beam SONAR approach, and examples that show the use of both of these technologies to assess sedimentation and remaining capacity at some of the nation's reservoirs. The report concludes with lessons learned to help guide subsequent deployment of these technologies at reservoirs across the Nation.

TABLE OF CONTENTS

Executive Summary ..... **i**
Introduction **1**
Current and Future Drought Impacts 4
Sedimentation Process 5
Sedimentation and Reservoir Capacity 6
National Drought Resilience: Improved Reservoir Sediment Surveys **9**
Reservoir Surveys Site Selection 11
Examples of NDRP Reservoir Survey Project LiDAR Data Collects 15
LiDAR Data Collection and Processing 17
Background 17
LiDAR Data Collection for the NDRP Reservoir Surveys Project 22
Post-Collection Data Processing and Archiving 23
Time Requirements for LiDAR Data Collection, Processing, and Archiving 30
Time to Determine Area of Interest 30
Time to Compute Flight Path 30
Time for Contracting Process 31
Time and Cost to Acquire Data 31
Time and Cost to Process Data 32
Time and Cost to Load to GRiD 32
Time and Cost to Extract DEM 32
Time and Cost to Run RIC 32
Time and Cost to Load to the RSI Data Portal 32
Data Collection Comparisons **33**
Case Study 1: Bear Creek Reservoir Single-Beam and Multi-Beam Sonar 33
Case Study 2: Bluestem Lake, Nebraska Combination of Multi-Beam SONAR and LiDAR 37
Case Study 3: Paonia Dam, Colorado Multi-Beam SONAR Volume Change 39
Case Study 4: Conchas Lake, New Mexico LiDAR Coupled with Multi-Beam Sonar for Reservoir Volume Calculations 42
Discussion and Conclusions **46**
Costs 47
Benefits of Reservoir LiDAR Surveys 49
Lessons Learned 50
Conclusions 51
References **52**

LIST OF FIGURES

Figure 1 Low water levels at USACE's Black Butte Lake, California, in 2013, with water levels typically reaching the top of the boat ramp in the distance, a difference of nearly 28 feet in elevation and 59,500 acre-feet of water. 3

Figure 2 Low water levels at USACE's Hensley Lake, California, in February 2015, showing large areas of exposed reservoir surface that could be reliably imaged using LiDAR. At high water level, the red floats mark the location of the submerged staff gauges, so that boaters do not collide with them. 3

Figure 3 Sediments entering a reservoir and depositing. (Original figure was from the COMET training courses, paid for by Reclamation and USACE). 5

Figure 4 Sediment migration over time in a reservoir illustrating reduce storage capacity with the potential to obstruct outlet works. (From Reclamation 2016). 6

Figure 5 General diagram showing the relationship between pools in a reservoir and the dam outlet. 7

Figure 6 Digital elevation model based on LiDAR data collected at Lake Isabella by the USACE in FY2015. 10

Figure 7 Low water levels in Lake Isabella in September 2014. 10

Figure 8 Location of reservoir survey project focus areas, highlighted in red. 11

Figure 9 Status of Drought in the US on October 26, 2016. 12

Figure 10 LiDAR data collected, in color and black greyscale, at Lake Isabella for the NDRP reservoir survey project in November 2016. 15

Figure 11 LiDAR data collected at Pine Flat Lake for the NDRP reservoir survey project in November 2016. 16

Figure 12 LiDAR data collected at Twitchell Reservoir for the NDRP reservoir survey project in November 2016. 16

Figure 13 Map of Oahe Reservoir showing the location of transects. 18

Figure 14 Sediment along Transect 1345.2 on Lake Oahe. Data from the original survey in 1968 is shown by the blue line, while the red line shows the data from the most recent survey in 1980. 19

Figure 15 Comparison between single- and multi-beam SONAR. 20

Figure 16 Topographic data being collected with airborne LiDAR in a drought-lowered reservoir. 21

Figure 17 Combination of multi-beam SONAR and LiDAR. 22

Figure 18 CAD model of the VQ-480i ALS system integrated onto the Partenavia P68 installation plates. 23

Figure 19 Screenshot of the LiDAR data collection area (red shaded squares) for the area of interest in GRiD. 26

Figure 20 Screenshot of a LiDAR DEM in the GRiD data portal. 26

Figure 21 View of the RIC software with a DEM of Whittier Narrows, near Los Angeles, California. 27

Figure 22 Example of the computational output from the RIC calculator. 27

Figure 23 Data selection screen in the Reservoir Sedimentation Information (RSI) Data Portal. 28

Figure 24 Elevation capacity curve for Prado Reservoir, California, as displayed by the Reservoir Sedimentation Information (RSI) Data Portal. The blue line represents the capacity of the reservoir at each water depth (elevation) in 1941, and the brown line represents capacity at each elevation in 2008. 29

Figure 25 LiDAR flight lines used to collect data at Twitchell Reservoir, California 30

Figure 26 Map showing (top) the bed map and the single-beam SONAR transects of Bear Creek Dam and (bottom) Bear Creek Reservoir DEM created by a combination of multi-beam SONAR and LiDAR. 34

Figure 27 Area capacity data from Bear Creek, Colorado, showing that changes in pool capacity over the last 36 years due to sedimentation have been small. (Purple line is essentially the same as the blue line). 35

Figure 28 Bankline recession observed at Bear Creek range line BC-08 shown by the magenta line between station 1500 and 1650. 36

Figure 29 Photo of Bluestem Lake, Nebraska, showing location of transects. 37

Figure 30 Bluestem Lake transect 7, showing the difference between the LiDAR DEM end area (purple dashed line) and the end area used in historic transect surveys (copied outer bank). 37

Figure 31 DEM based on multi-beam SONAR data collected in 2013 (top) and 2015 (bottom) at Paonia Dam, Colorado. 40

Figure 32 A map showing the elevation change based on subtracting the 2013 Multi-beam DEM from the 2015 Multi-beam DEM, Paonia Dam, Colorado. Negative values indicate erosion from 2013 and positive values indicate deposition since 2013. 41

Figure 33 Photo looking upstream from Paonia Dam, Colorado, in November 2014 showing the arrival of sediment at the outlet works intake and racked debris being cleared away by manual labor with the assistance of a 60-ft-long reach excavator. 42

Figure 34 Multi-beam SONAR data collection at Conchas Lake showing data collection instrumentation. Top: view of the boat exterior, with SONAR unit on the bow. Bottom: view of the boat interior. 43

Figure 35 Flight lines for LiDAR data collection at Conchas Lake, New Mexico. 44

Figure 36 Resulting fused digital elevation model, clipped to the extent of the pool at the elevation of the top of the dam. Historic structures inundated by Conchas Lake are visible just to the lower right of the promontory in the inset graphic. 45

Figure 37 Area-capacity graphs comparing the results of surveys at Conchas Lake, New Mexico. 46

LIST OF TABLES

Table 1 Status of USACE and Reclamation Reservoirs in the NDRP Reservoir Survey Project..... 13

Table 2 Data for USACE's Bear Creek Reservoir located near Denver, Colorado. Negative volume difference indicates a storage greater at that elevation using the single beam data than the multi-beam data for area-capacity calculations. 35

Table 3 Table of capacity differences at Bluestem Lake, Nebraska, by survey method..... 38

Table 4 LiDAR data collection costs at twenty-eight reservoirs in California and Arizona, fall 2016. 48

Table 5 Single-beam SONAR data collection costs at three reservoirs near Denver, Colorado, in August 2016. 49

Table 6 Multi-beam SONAR data collection costs at three reservoirs near Denver, Colorado, in August 2016. 49

INTRODUCTION

Drought causes major economic losses in the US, with estimated damages of over $220B since 1980 (NOAA, 2016). The water stored in Federal reservoirs can help to mitigate the effects of drought. However, all reservoirs capture sediment over time, which gradually reduces available storage for water supply, flood risk reduction, hydropower generation, or other purposes. Accurate information on current reservoir capacities is essential for planning and achieving these goals, as well as the planning and implementation of deviations from existing water control operational plans to alleviate critical drought impacts consistent with authorized dam purposes. Repeated topographic (above water) and bathymetric (below water) surveys are necessary to estimate how the water storage capacity of reservoirs changes as sediment enters from upstream and accumulates, how fast this sedimentation is occurring, and whether the sedimentation rate is changing or remaining constant. However, these surveys can incur substantial costs.

U.S. Army Corps of Engineers (USACE) staff suggested that recently developed survey technologies could be more accurate, efficient, and cost-effective for determining remaining reservoir capacities at federal reservoirs, particularly if deployed at reservoirs with water levels lowered due to drought (Figures 1 and 2). Increasing use of shared databases also encourages new ways of sharing these data among Federal agencies, and with state, local, and tribal governments, supporting more effective collaboration around drought mitigation efforts.

With the establishment of the National Drought Resilience Partnership (NDRP) in 2016, USACE saw an opportunity to test this concept. The NDRP was outlined in the 2013 President's Climate Action Plan and institutionalized in the Presidential Memorandum "Building National Capabilities for Long-Term Drought Resilience" released in March 2016. The NDRP builds on and strengthens the existing National Integrated Drought Information System, an interagency program led by the Department of Commerce. The objective of the NDRP is to reduce the vulnerability of communities to current and future drought through better coordination of Federal support for drought-related efforts. The memorandum charged Federal agencies to implement policies and take action to achieve six key drought resilience goals:

1. Improve sharing of information and data related to drought, water use and water availability, including data on snowpack, groundwater, streamflow and soil moisture, with State, regional, tribal and local officials with the goal of improving planning for and adaptation to drought and drought risk.

2. Communicate drought risk to critical infrastructure to State, regional, tribal and local officials.

3. Assist State, regional, tribal, and local governments to improve their local planning capacity for drought preparedness and resilience.

4. Improve the coordination and integration of drought-related activities at the Federal level, to enhance the collective benefits of Federal programs and investments.

5. Provide support for innovative investment models and market-based approaches to increase resilience, flexibility, and efficiency of water use and water supply investments.

6. Support efforts to conserve and make efficient use of water through relevant research, innovation, and international engagements.

The memorandum was accompanied by a "Long-Term Drought Resilience: Federal Action Plan of the National Drought Resilience Partnership." The plan, also released in March 2016, identifies actions Federal agencies should take in fiscal years 2016 and 2017 to meet these goals. For each action, a Federal lead coordinating agency is identified. USACE is the lead agency for Goal 1, Task 4, which is intended to encourage Federal reservoir surveys to take advantage of drought-induced low reservoir levels to increase knowledge of the state of reservoir sedimentation, identify and pursue ways to reduce the cost of reservoir surveys, and to share data from these surveys.

The US Department of the Interior's Bureau of Reclamation (Reclamation) is partnering with USACE in this effort because the two agencies are the primary Federal agencies charged with maintaining the Nation's water resources, with separate and complementary water management authorities and responsibilities. The primary authorized purposes of USACE water resources infrastructure and projects are navigation, flood control, or ecosystem restoration. Secondary objectives that include hydropower, recreation, and water supply. USACE projects and programs also support disaster preparedness (including advanced measures authorized by Public Law 84-99), disaster response and recovery, as well as regulatory responsibilities. The primary authorized purposes of Bureau of Reclamation (Reclamation) water resources infrastructure and projects are to fulfill water delivery obligations for irrigation and water supply, water conservation, water recycling and reuse, and hydropower generation in the Western United States.

This report details the approach being implemented by USACE and Reclamation to evaluate the use of airborne light detection and ranging (LiDAR) as a method with potential to rapidly, accurately, and cost-effectively collect reservoir sediment information. LiDAR is a widely-used technology for obtaining topographic information using a downward-pointed laser mounted on an aircraft. LiDAR cannot penetrate water and thus is unable to obtain reservoir bathymetry (the topography of the reservoir bottom below the pool level). However, if water levels are low in a reservoir due to drought (Figures 1 and 2), seasonal draw-down, repairs, or for another reason, LiDAR can efficiently collect detailed topographic data for the potentially significant area of the reservoir shoreline and bottom that has been temporarily dewatered. This could enable improved estimates of reservoir capacity at a fraction of the cost of a reservoir survey using traditional methods such as transect surveys above the water surface and SOund Navigation and Ranging (SONAR) surveys below the water surface. For reservoirs only partially drawn down, where significant portions remain water-covered, the LiDAR topographic data can later be combined with bathymetric data collected by SONAR for the remaining portion of the reservoir.

High-density data collected for reservoir sedimentation and sustainability analyses can also be used for other purposes. For example, previously-collected LiDAR data purchased from the Truckee-Donner Public Utility District was used to create a digital elevation model of USACE's Martis Creek Dam, near Truckee, California, to support a dam safety assessment. The repurposed high-resolution (1.5-2.4 points/m^2) LiDAR data were of a high enough quality to enable the identification of a completely unknown fault, the Polaris Fault, running adjacent to the left abutment of the dam and the spillway, indicating a significant new hazard at the dam [Hunter et al., 2010]. Subsequent field work supported this identification, and suggested that the faults are probably Holocene-active with a maximum earthquake magnitude of between 6.4 and 6.9 [Hunter et al., 2011].

Figure 1 Low water levels at USACE's Black Butte Lake, California, in 2013, with water levels typically reaching the top of the boat ramp in the distance, a difference of nearly 28 feet in elevation and 59,500 acre-feet of water.

Figure 2 Low water levels at USACE's Hensley Lake, California, in February 2015, showing large areas of exposed reservoir surface that could be reliably imaged using LiDAR. At high water level, the red floats mark the location of the submerged staff gauges, so that boaters do not collide with them.

Current and Future Drought Impacts

Droughts are a normal, recurrent feature of the climate system. The term drought refers to a lack of precipitation over an extended period from weeks to years that results in a water shortage impacting vegetation, animals, and people. Meteorological drought (lack of precipitation) may result in agricultural drought (insufficient soil moisture for plants) and/or hydrologic drought (low stream flows and low water storage in lakes). Over the last two centuries, reservoirs, irrigation ditches, and other water supply systems have been developed in the U.S. to store and deliver water during times of drought or of seasonal shortfall. Water supply systems are typically designed to buffer the size and duration of drought typical for an area, whether seasonal drought, which occurs in the Northeast, or multi-year drought, which is common in the Southwest.

Climate change in the form of increased average, minimum, and maximum air temperature and intensified heat waves is occurring in many areas of the US. These factors, combined with observed and projected changes in precipitation, are anticipated to increase the frequency, duration, and intensity of drought in many areas of the US over the course of the 21st century relative to the baseline period of the last half of the 20th century [Melillo et al. 2014]:

- Across the northern tier of states, the Southeast and parts of the Southern Plains, in general, storms are increasing in size and intensity as warmer temperatures have increased the energy available for convection. These trends are anticipated to continue into the future, accompanied by reductions in the number of days of drizzle or light rain, and resulting in longer periods of no rain (drought) between periods of intense rain.

- In the western US and especially the Southwest, gradual increasing winter temperatures over the last half of the 20th century into the early 21st century have led to reductions in snowpack volumes through increased sublimation/melt during the cold season, and changes in precipitation form from snow to rain. An increasing proportion of snowmelt runoff occurs earlier in the spring during the dormant season (when it isn't needed) and less water for plants coping with ever-lengthening growing seasons (when it is needed). These reductions in spring runoff flows and reductions in late summer base flows are expected to continue into the 21st century.

- In the Southwest especially, higher temperatures may increase drought intensity, and help create drought conditions during years when precipitation is modest or low but still present. Drought is expected to intensify in this region in the 21st century [Ault et al., 2016; Cook et al., 2015; Seager et al., 2007].

- Extreme La Nina conditions, which contribute to Southwestern drought, are projected by some climate models to increase in frequency in the 21st century [Cai et al., 2015]. Extreme El Nino (wet) and La Nina (dry) conditions may occur more frequently in back-to-back years.

Consistent with these observed and projected changes, the duration, intensity, and frequency of drought is expected to increase in many parts of the US. At the same time, increased duration, intensity, and frequency of intense precipitation with the potential for large-scale flooding may also occur during droughts. Record flooding during drought has already been observed in several parts of the U.S., including the Memorial Day floods in central Texas in 2015 [Di Liberto 2015] and September 2013 flood in central Colorado [Howard 2013].

Sedimentation Process

Reservoir sedimentation occurs when river water transporting sediment enters a reservoir so that the water slope changes from steep (river) to gentle (reservoir) and the corresponding velocity slows, decreasing sediment carrying capacity (Figure 3). This reduction in sediment carrying capacity causes the larger, heavier grain sediment particles to deposit first. Smaller and lighter sediment may be carried farther into the reservoir. Over time, as a delta forms and restricts flow, increasing velocity and water slope (Figure 4), so that the sediment carrying capacity changes and the larger particles are deposited farther into the reservoir.

Some processes important in reservoir storage loss due to sedimentation are represented in Figure 4. The top of Figure 4 shows a typical profile along a river and reservoir, along with some technical terms used. to describe parts of the delta that forms in reservoirs from sediment deposition. The figure includes a typical configuration of outlet works, where releases of water from a reservoir occur. Reference lines indicate the maximum pool elevation and the normal pool elevation. Moving from left to right in the upper section of Figure 4, one can see the change in water slope which causes the heavier sediments carried by the river to deposit. Finer sediments that remain suspended and deposit farther downstream in the reservoir are labeled as lake bed deposits or muddy lake deposits in the figure. Over time, as reservoir surface and river flows fluctuate, the sediment deposition can occur and migrate toward the dam (lower image of Figure 4). Thus, sedimentation impacts all of the reservoir storage zones and can potentially impact the function of the outlet works.

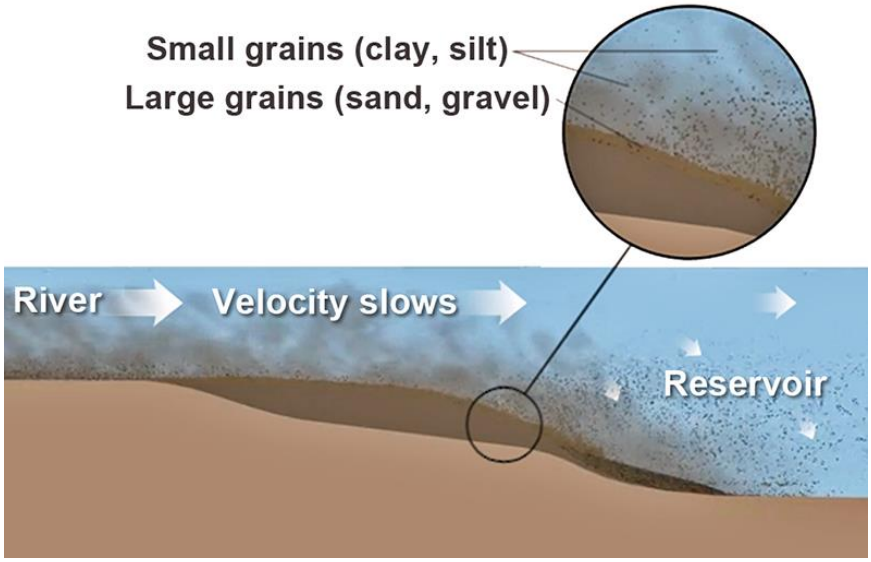


Figure 3 Sediments entering a reservoir and depositing. (Original figure was from the COMET training courses, paid for by Reclamation and USACE).

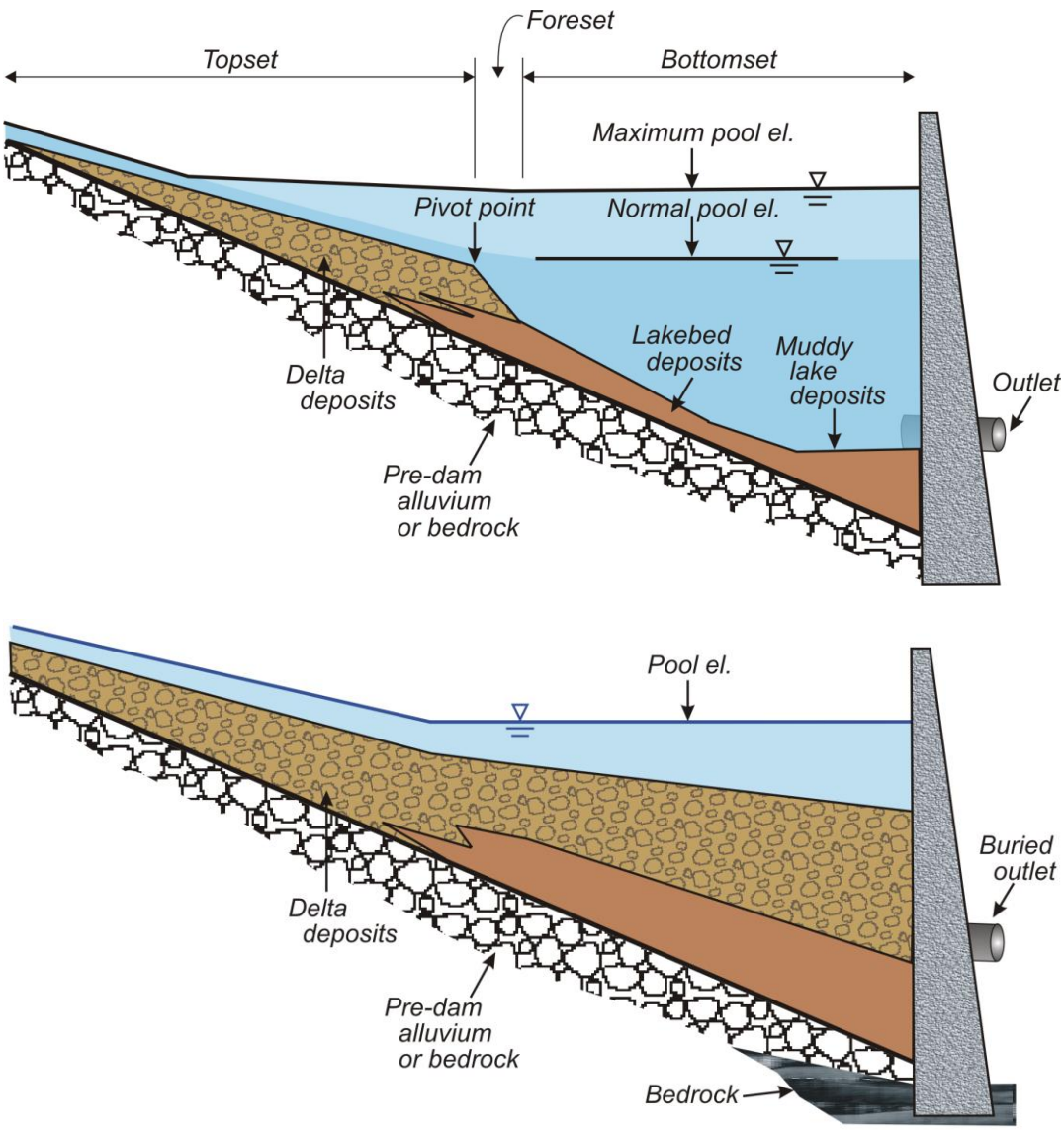


Figure 4 Sediment migration over time in a reservoir illustrating reduce storage capacity with the potential to obstruct outlet works. (From Reclamation 2016).

Sedimentation and Reservoir Capacity

The observed and projected changes in drought and precipitation not only pose challenges for water managers but also affect both the rate at which sediment is produced in a watershed and the ability of streams to transport this sediment and ultimately deliver it to reservoirs. Watershed sediment yields are expected to increase with increases in rainfall intensity, especially after wildfire, and as more precipitation occurs as rainfall rather than snowmelt. Changes in the amount of sediment eroded and transported from a watershed also result when land cover is altered (such as through forest conversion to farmland or by wildfire), and land use is changed (such as from rural to urban). These factors can be exacerbated by the observed and projected changes due to warmer conditions. Typically, but not always, USACE and Reclamation reservoir designs account for incoming sediment accumulation over time (sediment yield),

and allow for a certain volume of sediment to be deposited in the reservoir over a designated time period known as its sediment design life (typically 100 years). The sedimentation rates assumed in the original project designs may be changing now and are likely to continue to change in the future: Therefore, the design assumption of stationary conditions [Brekke et al., 2009; Milly et al., 2008] must be updated to account for these changes so that USACE and Reclamation reservoirs will continue to function beyond their original sediment-design life.

Each Federal reservoir has one or more authorized purposes. Within a reservoir, water is stored in allocated units termed "pools" (Figure 5). Each pool represents the maximum amount of water that the reservoir is authorized to store for a given authorized purpose, which may include flood risk management, water supply, hydropower, recreation, fish and wildlife, irrigation, water quality, and navigation. The inactive pool (also called the dead pool or permanent pool) is the amount of water in a reservoir that is located below the outlet works, and is not available for use downstream. The flood risk management pool is typically empty to provide room for a reservoir to store incoming flood waters on very short notice. Water for another purpose cannot generally be stored in the flood pool because it might not be possible to evacuate that water fast enough in an emergency, especially as precipitation is becoming more intense. The pools located between the flood control pool and the inactive pool are collectively referred to as the conservation pool (or multi-purpose pool).

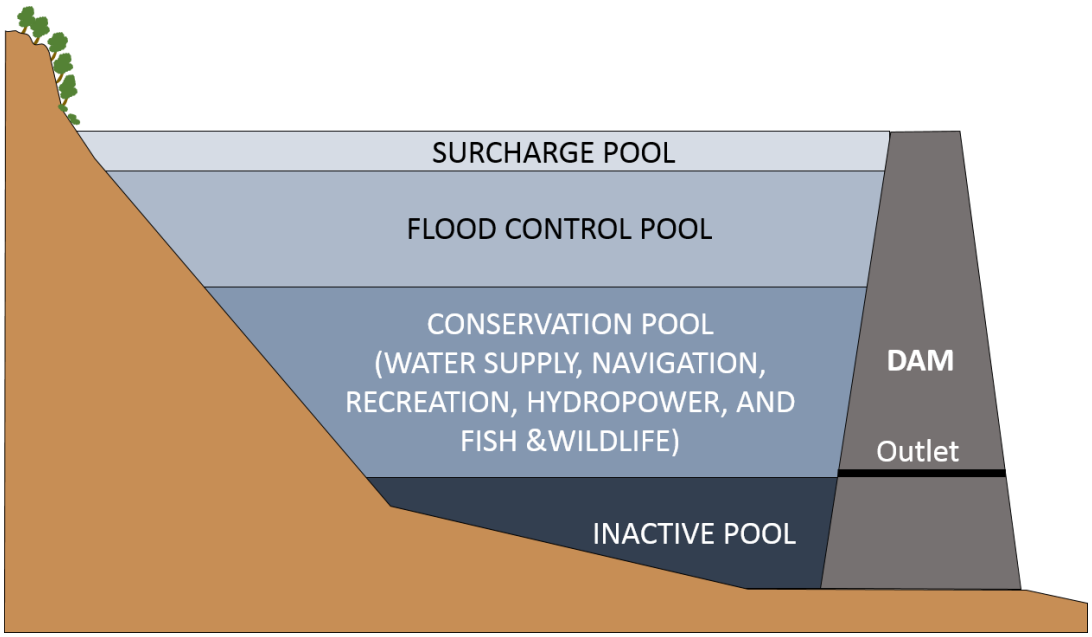


Figure 5 General diagram showing the relationship between pools in a reservoir and the dam outlet.

While sediment deposition occurs throughout the reservoir, the volume of the inactive pool often represents the volume of sediment that is expected to fill a reservoir over its lifetime at the dam. However, this does not mean that the original designers expected sediment deposition to occur only within the demarcated inactive pool. Sediment can accumulate wherever water slows, forming a large, mobile delta at the head of the reservoir and at the mouths of streams tributary to the reservoir. The delta will even extend along the river channel upstream from the reservoir. In addition, water flowing into and through a reservoir at different water levels may redistribute sediment over time. Thus, sediment volume in a

reservoir may impinge on both the conservation and flood control pools, depending on where the actual sedimentation occurs.

Water capacity (volume) in a reservoir is a function of the depth and surface area. Because a reservoir's shape is irregular, the shape of a pool varies as the total volume of water in the reservoir changes. Consequently, accurate water volume estimates for each pool at a given water elevation must be known if the water is to be properly allocated for its authorized purposes. Since sedimentation rates and locations may vary with time in each pool, monitoring, and accurate estimation of sedimentation volumes in each of the pools within a reservoir is necessary.

Sediment deposition within a flood pool can present a risk to public health and safety because the flood pool is used to store flood waters and to allow for gradual release of this water in preparation for the next flood event. Section 7 of the Flood Control Act of 1944 (16 U.S.C. 460d; P.L. 78-534, December 22, 1944; 58 Stat. 890, 33 U.S.C 790), as amended, gives USACE the authority to manage the flood control pools at its own reservoirs and at other reservoirs constructed wholly or in part with Federal funds which have allocated storage for flood control or navigation purposes during a flood event. This excludes reservoirs in the Tennessee Valley Authority, except in cases of danger from floods on the lower Ohio and Mississippi Rivers. The Section 7 authorization allows for the coordinated management of flood peaks and reduces the chance that multiple small peaks combine to form a larger flood event.

Regardless of sedimentation, the current flood water capacity at each reservoir must be understood for effective regulation. As sedimentation occurs in the flood pool, releases may be increased, or storage duration reduced, to compensate for the lost storage to avoid exceeding the dam's design capacity. During drought periods, there is a constant tension between maintaining storage in the flood pool and impinging on the flood pool to provide additional storage to alleviate drought impacts. Existing legislation gives the USACE authority to use its reservoirs for municipal and industrial (M&I) water supply storage (the Water Supply Act of 1958), for withdrawals of surplus water (Section 6 of the Flood Control Act of 1944), and for agricultural water supply storage in limited circumstances (Section 8 of the Flood Control Act of 1944). These authorities are constrained, however, in that allocations for water supply at USACE reservoirs must be fully paid for by the non-Federal sponsor and must not interfere with other authorized purposes unless authorized by Congress.

Accurate and regular assessment of reservoir capacity is increasingly essential to effectively manage water supplies and flood flows under nonstationary (changing) conditions. Piloting the use of technologies and methods that make this data less costly and more efficient to acquire is critical if the Nation is to reduce the vulnerability of communities to current and future drought, while continuing to effectively manage flood risk.

NATIONAL DROUGHT RESILIENCE: IMPROVED RESERVOIR SEDIMENT SURVEYS

The cost-effective reservoir surveys project described here builds on a preliminary pilot study completed at Lake Isabella in California on 21 August 2015 (Figure 6). Lake Isabella had not been surveyed since 1977, and it provided a good example of a project where an accurate understanding of current storage capacity is essential for long-term water planning. At the time of LiDAR data collection, lake levels were low due to drought, allowing a large portion of the pool to be scanned (Figure 7). Unfortunately, the 2015 pilot resulted in incomplete data collection at the east end of the reservoir, primarily because the pilot was not able to distinguish the reservoir boundaries after sustained drought. The lesson learned was to build fight plans around established reservoir boundaries rather than rely on visual inspection to determine these boundaries, which may be difficult to distinguish from the air during periods of extended drought. However, the August 2015 data collection at Lake Isabella did provide a proof of concept for the airborne LiDAR method and provided insight into more robust flight planning, data processing methods, and associated tools required to compare this new data to existing reservoir survey information.

The goal of the current NDRP Goal 1, Task 4 reservoir surveys project is to develop standardized data collection methods (equipment, configuration, flight characteristics, data quality) and efficient data processing, quality control, and dissemination through application at three clusters of reservoirs in the South Pacific Division in Northern California, Southern California, and Southern Arizona. These methods are described in detail in subsequent sections of this report, along with a comparison to costs for airborne LiDAR surveys compared to multi-beam SONAR and other methods.

Lake Isabella is among the lakes at which data collection was conducted on 12 November, 2016 for this effort. A large wildfire occurred along the southeast side of Lake Isabella in the summer of 2016. The November 2016 flight completed of data collection at the east end of the reservoir missing from the 2015 data collection. Importantly, comparison between the 2015 and 2016 data sets provides information on rates of sedimentation due to two key processes at the lake in the intervening year: sediment redistribution and post-fire sedimentation. A winter storm redistributed sediment within the reservoir during winter 2015-2016. The amount of sediment moved, and the places from which sediment was lost and gained can be determined from image comparison. Comparison of the two LiDAR datasets will provide information about the rate and volume of sediment influx due to erosion within the burn scar area that can be used to inform other post-wildfire sedimentation studies being undertaken by USACE.

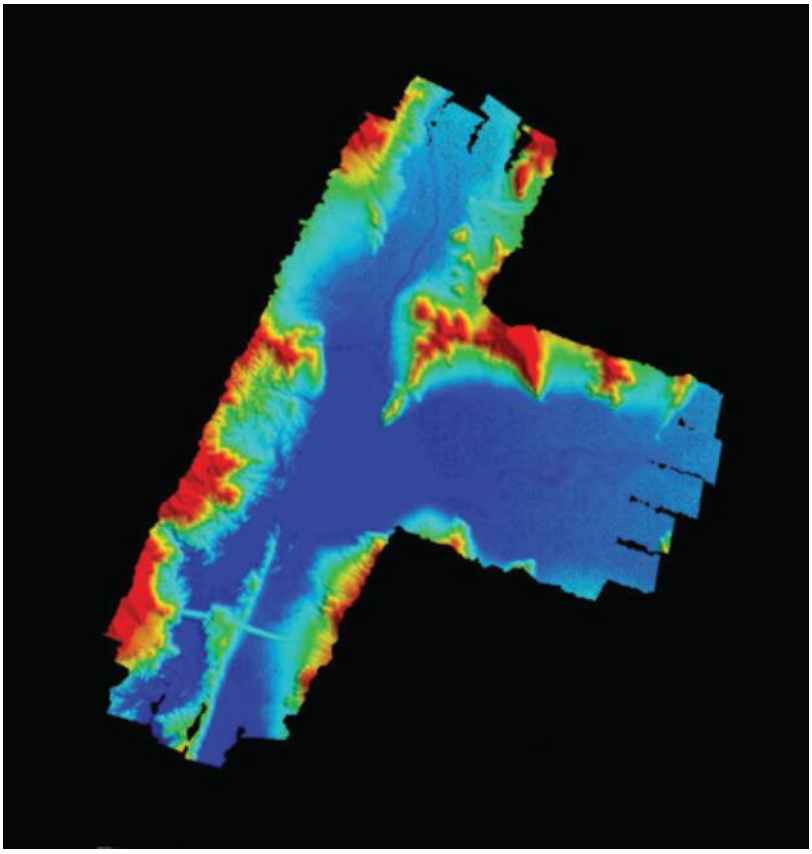


Figure 6 Digital elevation model based on LiDAR data collected at Lake Isabella by the USACE in FY2015.

Figure 7 Low water levels in Lake Isabella in September 2014.

Reservoir Surveys Site Selection

The areas selected for the NDRP reservoir survey project are located in the U.S. Southwest (Figure 8) where drought is ongoing (Figure 9). The study areas span two USACE Districts, Los Angeles and Sacramento, and two Reclamation Regions, Mid-Pacific and Lower Colorado. Within these drought-impacted areas, USACE reservoirs were prioritized for data collection based on three criteria:

- Extremely low reservoir water levels are currently occurring due to drought, maximizing the area within each reservoir over which LiDAR data can be successfully collected.

- Regionally, dry conditions have contributed to wildfires in the region. In 2016, the Erskine fire in Kern County, California, burned 48,000 acres on the southeast side of Lake Isabella, and the San Gabriel Complex Fire burned approximately 5,400 acres within the watershed of Santa Fe Reservoir below Morris Dam [InciWeb, 2016]. Because precipitation on recent burn scars can result in extensive erosion and downstream transport of sediment, and because USACE reservoirs are positioned to receive this sediment when it rains, collection of LiDAR data at these reservoirs is a priority.

- Age since last survey is the third criterion. Because sedimentation rates are not constant over time, and sediment may move within a reservoir in response to changes in flow, past estimates of sedimentation rates may no longer reflect current conditions. The timespan between reservoir surveys is typically measured in years. As such, this activity while routine, is often competing for resources with other priority items and are often not funded for resurveys.

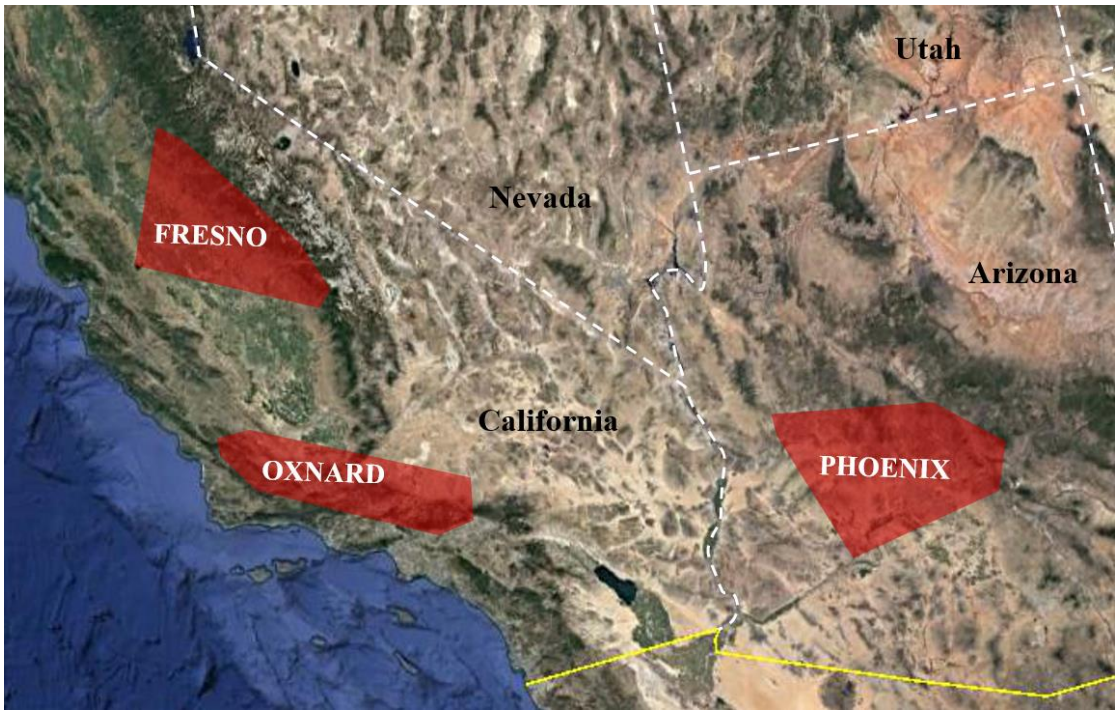


Figure 8 Location of reservoir survey project focus areas, highlighted in red.

The selection of Reclamation reservoirs for aerial LiDAR surveys was based on one primary factor: whether the reservoir was at less than 40% of total storage capacity.

The priority reservoirs selected for the NDRP reservoir survey project are listed in Table 1. The reservoirs share nearly uniformly low water levels, with many reservoirs completely dry. Most areas where the reservoirs are located are in Moderate to Extreme Drought [D2-D4 on the US Drought Monitor Scale, see Figure 9 legend].

Multiple reservoirs were surveyed in each of the three areas shown in Figure 8 in order to take advantage of the spatial clustering of reservoirs with low water levels due to drought. The three areas where data collection occurred surround three airports: Oxnard, California (11 reservoirs); Fresno, California (12 reservoirs); and Phoenix, Arizona (5 reservoirs).

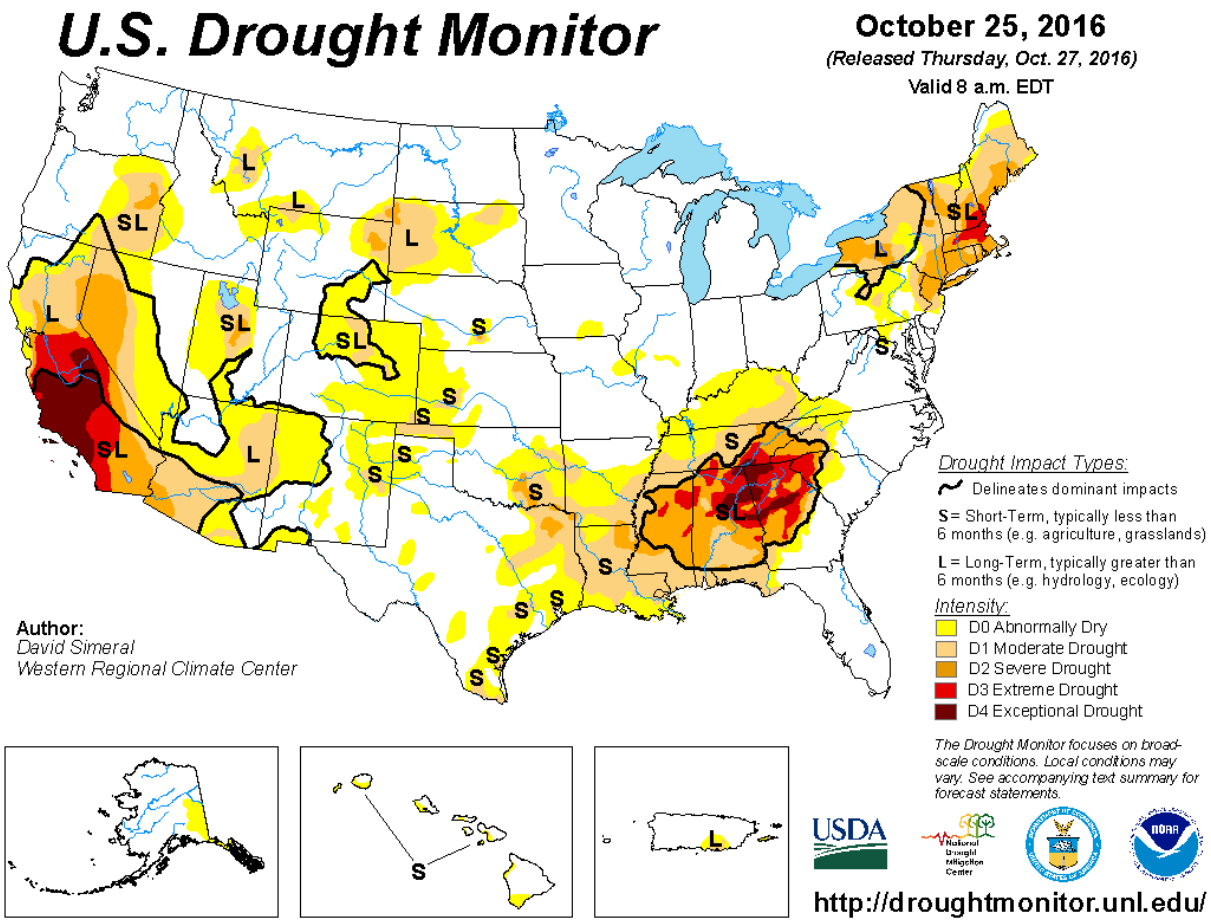


Figure 9 Status of Drought in the US on October 26, 2016.

Source: US Drought Monitor (http://droughtmonitor.unl.edu/, accessed 1 November 2016).

Table 1 Status of USACE and Reclamation Reservoirs in the NDRP Reservoir Survey Project.

Flight Base	Reservoir Name	Agency*	Initial Survey Year	Last Survey Year	Last Survey Method	Previous Sediment Removal	Filling Faster than Designed	2016 Wildfire in Basin	Wildfire within last 5 years basin	Reservoir % Full (Oct. 1, 2016)	Drought Status (Oct 1, 2016)
Fresno	Bear	U	1968	1975	Transect	No	Unknown	No	No	0	Extreme
Fresno	Burns	U	1968	1975	Transect	No	Unknown	No	No	0	Extreme
Fresno	Eastman	U	1967	1975	Transect	No	Unknown	No	Yes	8	Extreme
Fresno	Hensley	U	1967	1975	Transect	No	Unknown	No	Yes	19	Extreme
Fresno	Lake Kaweah	U	1961	1987	Partial Contour	No	Unknown	No	No	17	Exceptional
Fresno	Mariposa	U	1968	1975	Transect	No	Unknown	No	No	0	Extreme
Fresno	New Hogan	U	1959	1978	Transect	No	Unknown	No	Yes	25	Extreme
Fresno	New Melones	R	1979	--	Never Surveyed	No	Unknown	No	Yes	11	Extreme
Fresno	Owens	U	1968	1975	Transect	No	Unknown	No	No	0	Extreme
Fresno	Pine Flat	U	1973	1973	Transect	No	Unknown	No	Yes	16	Extreme
Fresno	San Luis	R	1967	--	Never Surveyed	No	Unknown	No	No	25	Extreme
Oxnard	Brea	U	1939	1994	Contour Map		No			0	Exceptional
Oxnard	Carbon Canyon	U	1961, 37, 41, 49	2009	Contour Map	Yes	No		Yes	0	Exceptional
Oxnard	Fullerton	U	1941	1970	Contour Map		No			0	Exceptional
Oxnard	Hansen	U	1940	2004	Contour Map	Yes	Yes[ǂ]	Yes		0	Exceptional
Oxnard	Isabella	U	1953	1977	Other	No	Unknown	Yes	Yes	17	Exceptional

Flight Base	Reservoir Name	Agency*	Initial Survey Year	Last Survey Year	Last Survey Method	Previous Sediment Removal	Filling Faster than Designed	2016 Wildfire in Basin	Wildfire within last 5 years basin	Reservoir % Full (Oct. 1, 2016)	Drought Status (Oct 1, 2016)
Oxnard	Lake Cachuma	R	1953	2013	Contour Map	No	Unknown	No	Yes	7	Exception al
Oxnard	Lopez	U	1954	2010	Contour Map	Yes	Yes			0	Exceptional
Oxnard	Mojave	U	1965, 62	Same	Contour Map		Unknown		Yes	0	Extreme
Oxnard	San Antonio	U	1941	2010	Contour Map	Yes	Yes			0	Exceptional
Oxnard	Santa Fe	U	1943	2010	Contour Map		Yes[ǂ]	Yes		0	Exceptional
Oxnard	Twitchell	R	1958	2007	Contour Map	Yes	Unknown	No	Yes	0	Exceptional
Oxnard	Whitter Narrows	U	1948	2011	Contour Map		No	Yes**	Yes	0	Exceptional
Phoenix	Alamo	U	1968,63	1985	Bathymetric		No			4	Moderate
Phoenix	Horseshoe Reservoir	R	1949	--	Never Surveyed	No	Unknown	No	Unknow n	1	Abnormally Dry
Phoenix	Painted Rock	U	1953	1993	Satellite Imagery		No			0	Moderate
Phoenix	Theodore Roosevelt	R	1909	2013	Contour Map	No	Unknown	No	Yes	36	Moderate
Phoenix	Whitlow Ranch	U	1957, 39, 56	1984	Contour Map		No		Yes	0	Moderate

** U= USACE, R=Reclamation*

*** = Wildfire was in the reservoir project land.*

ǂ = The sediment allowance was revised upward since the original project design. The rate of sedimentation exceeds the original design but not the revised sediment allowance.

Examples of NDRP Reservoir Survey Project LiDAR Data Collects

LiDAR data for this NDRP reservoir survey project was collected for the 28 projects shown in Table 1. The following figures show some of the project results from the effort. The examples show digital elevation model data from two USACE reservoirs, Lake Isabella (Figure 10), Pine Flat Lake (Figure 11) and one Reclamation reservoir, Twitchell Reservoir (Figure 12).

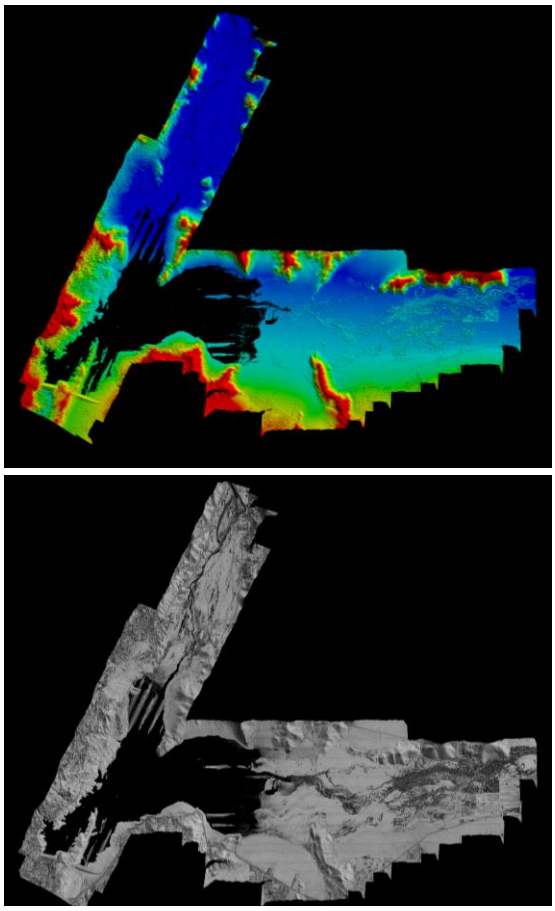


Figure 10 LiDAR data collected, in color and black greyscale, at Lake Isabella for the NDRP reservoir survey project in November 2016.

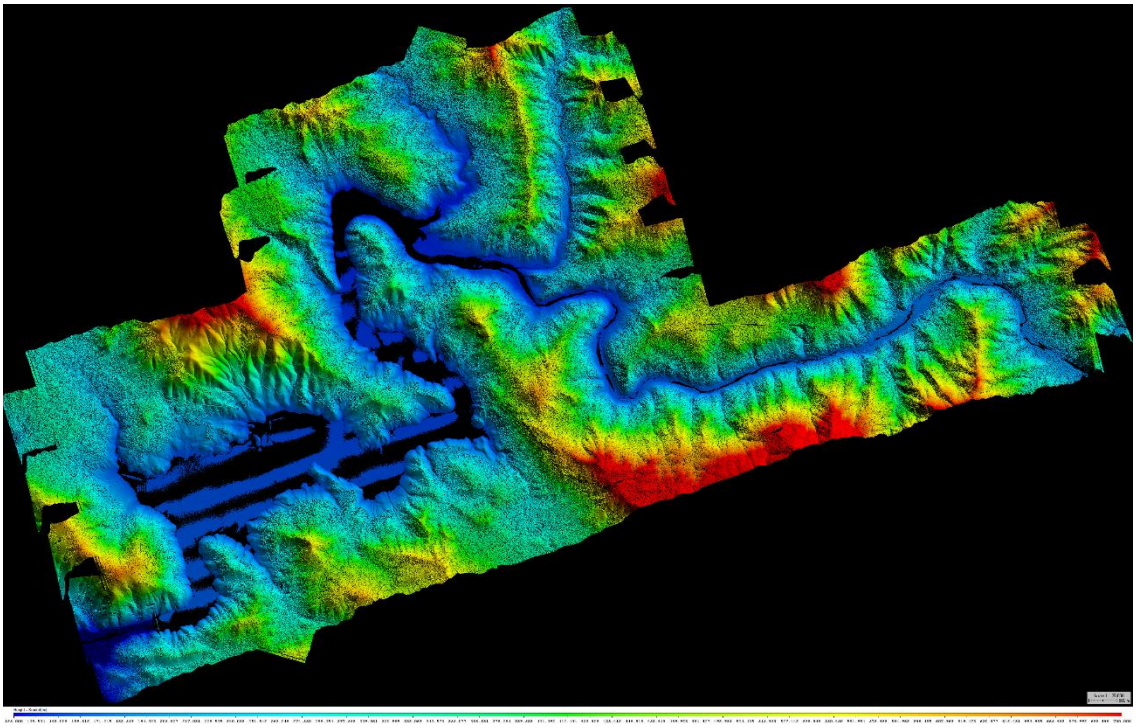


Figure 11 LiDAR data collected at Pine Flat Lake for the NDRP reservoir survey project in November 2016.

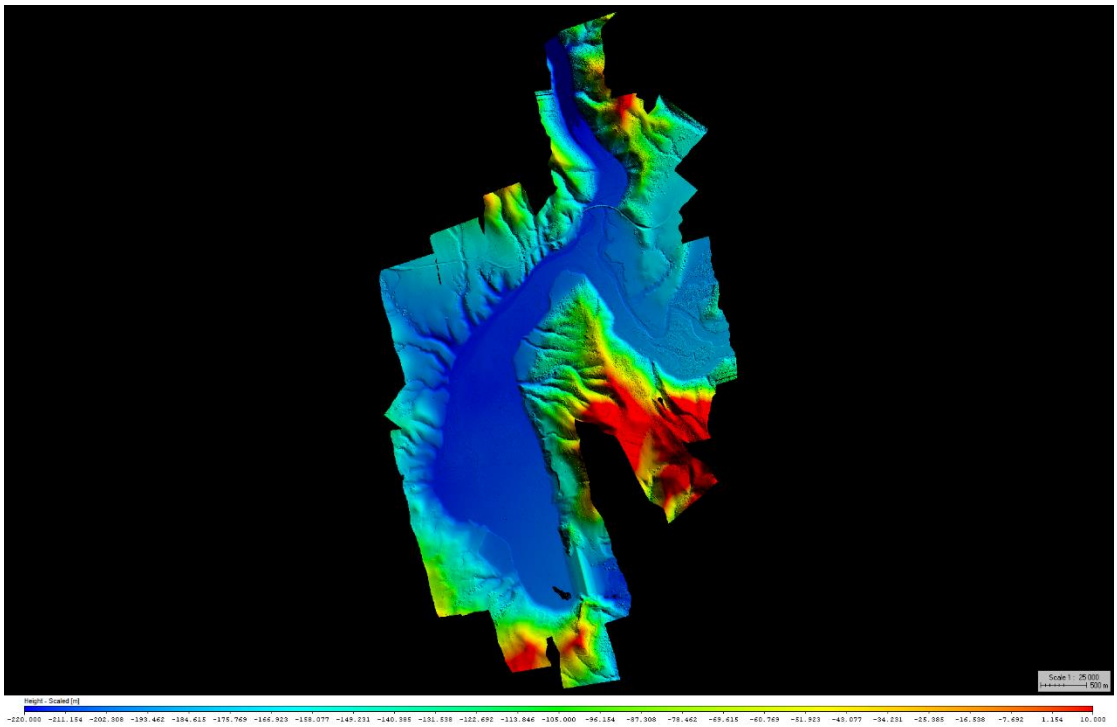


Figure 12 LiDAR data collected at Twitchell Reservoir for the NDRP reservoir survey project in November 2016.

LiDAR Data Collection and Processing

Although collection and processing of LiDAR data are highly technical activities, the time and effort involved for actual data collection are significantly less than using traditional survey techniques and single-beam SONAR data collection efforts. This section of the report provides a brief overview of LiDAR data collection, processing and dissemination, setting the stage for the discussion of costs in the next section of the report.

Background

Reservoir sedimentation surveys are typically performed by collecting both topographic (above water) and bathymetric (below water) surveys of position and elevation. Combining both sets of survey data can be defined as a hydrographic survey. In the case of bathymetry surveys, there are multiple ways to collect underwater elevations. Traditionally, when many of the projects were constructed in in the early-to-mid 20th century by USACE and Reclamation, the best technique for measuring and analyzing sediment accumulation in a reservoir was based on repeat measurements along predefined transects. Transects (also called range lines, or cross sections) are lines that cross the reservoir at fixed locations identified by survey monuments on the reservoir shoreline. These lines are surveyed from a boat using a sounding weight or depth sounder (and some method for determining the horizontal position) at fixed intervals along the transect, with comparison between repeat surveys forming the basis for estimating changes in sedimentation along the transect. When combined, the transect data provides an estimate of sediment volume for the reservoir as a whole. During the 20th century, several methods were employed to determine the horizontal position along the transect, including tag lines, theodolites, microwave positioning systems, electronic distance meters, and eventually GPS (Ferrari and Collins, 2006).

Transect lines are typically spaced at coarse intervals (from hundreds of feet to miles depending on reservoir size), both along the main stem of the reservoir and along any significant tributaries entering the reservoir. For example, Figure 13 shows the location of transects along a portion of Lake Oahe, a USACE reservoir in South Dakota. The range lines are numbered by the distance in miles from the confluence of the Missouri River. Subtracting the transect values yields the distance between them. For example, the distance between transects 1197.5 and 1187.9 is 9.6 miles. Some of the gaps between transects contain significant tributaries. Sediment may accumulate in these areas, and although this sediment could significantly change the available reservoir capacity, this would not be reflected in the estimate of sedimentation made using the bounding transects. Figure 14 shows how the bottom of the reservoir along a transect for Oahe Lake varies between the original survey in 1968 and the most recent survey in 1980. Significant changes in the bottom of the reservoir are seen at some locations along the transect. The deposition exceeds 20 feet of accumulated sediment in some places.

Established techniques, such as the average-end-area method described in the USACE Engineering Manual on Sedimentation (EM 1110-2-4000) [USACE, 1989] or Reclamation's Erosion and Sedimentation Manual [Ferrari and Collins, 2006], are used to estimate the volume of sediment that is deposited in the reservoir and the remaining storage available at various water elevations. These techniques assume that the topography between transects is uniform and bank station changes are linear (the reservoir is straight), which simplifies the volume estimation. This assumption introduces spatial error if the inter-transect area surface is significantly convex, concave, or convoluted, or contained significant sediment volumes tapering towards the transect lines. As sediment redistributes within a reservoir, repeat surveys might yield very different volume estimates as the sediment is gradually transported past a transect, or fills in a concavity between transects. In addition to being inaccurate, this system was also time consuming to undertake, contributing to limited repeat data collection over time in many reservoirs.

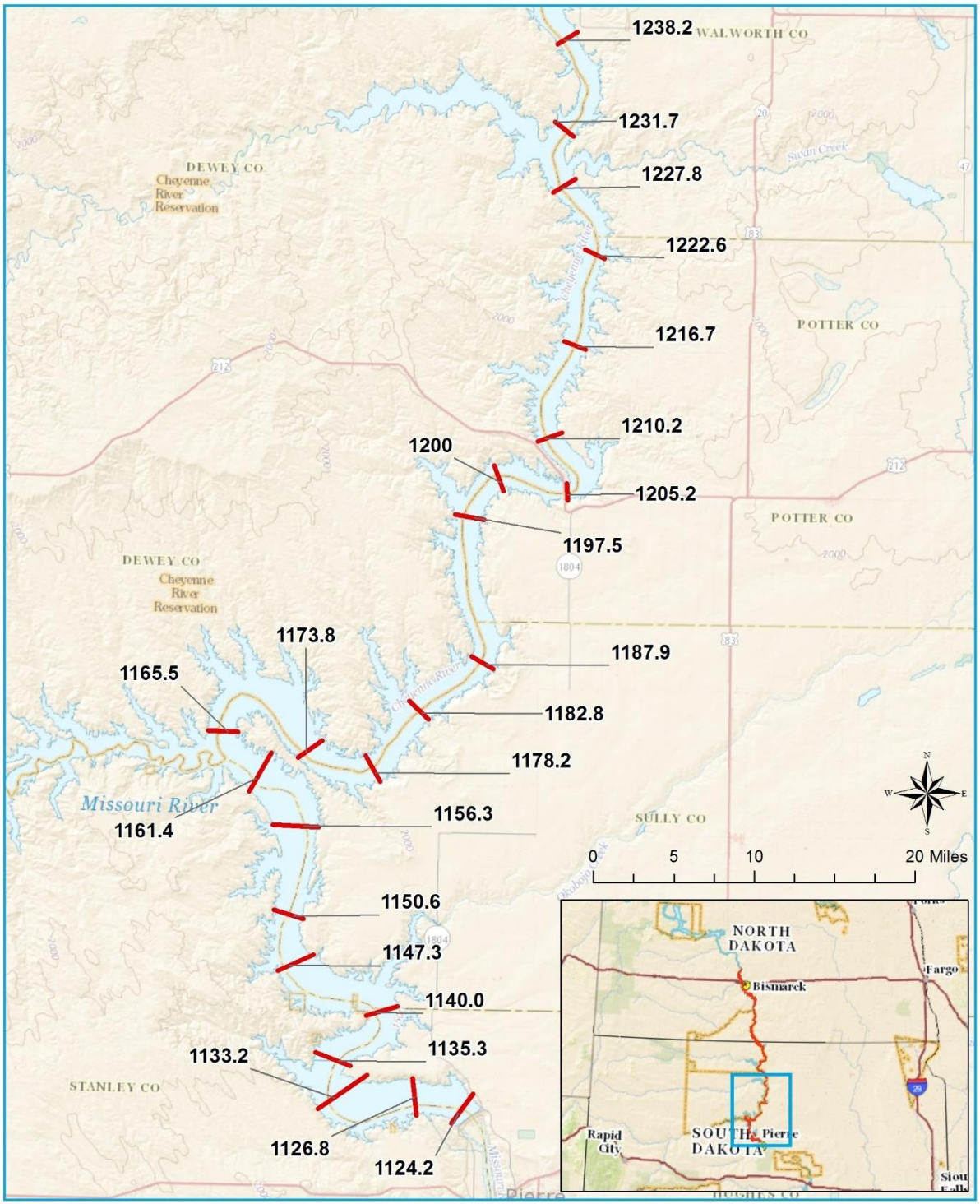


Figure 13 Map of Oahe Reservoir showing the location of transects.

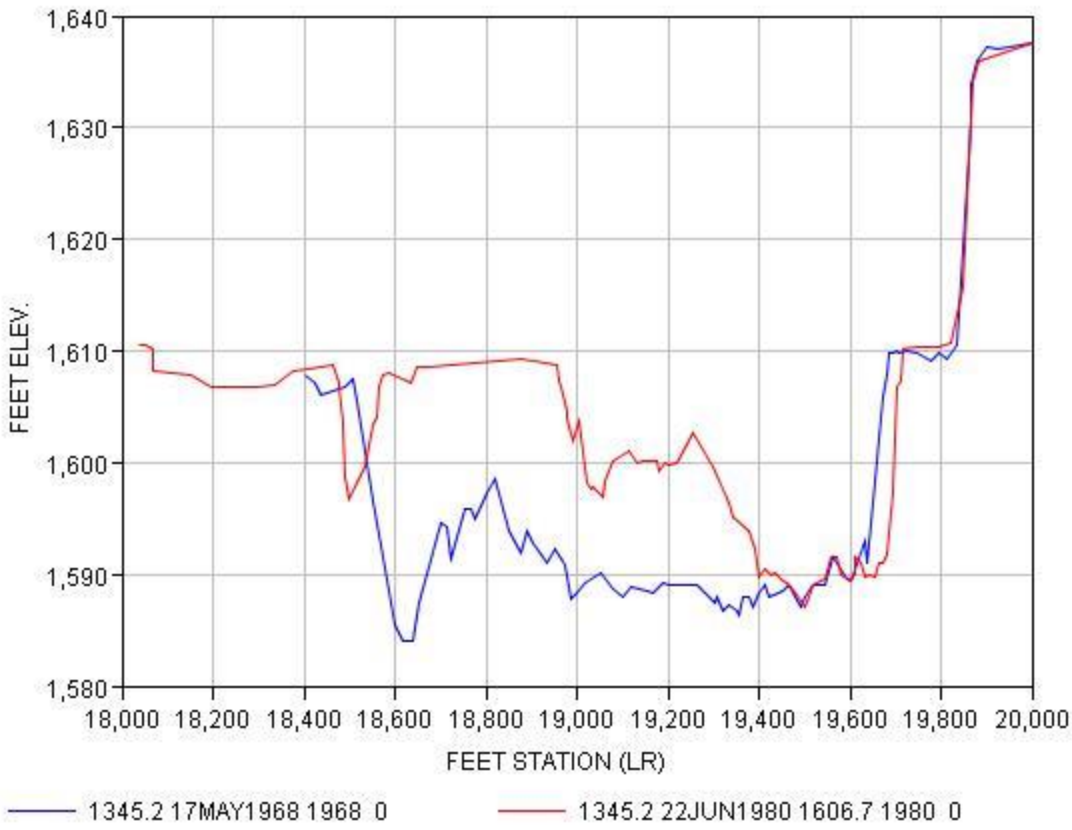


Figure 14 Sediment along Transect 1345.2 on Lake Oahe. Data from the original survey in 1968 is shown by the blue line, while the red line shows the data from the most recent survey in 1980.

In recent years, SONAR (depth sounder) has been used to conduct bathymetric or to supplement hydrographic surveys. Despite its greater initial cost, there are significant accuracy and coverage gains from using SONAR that make it an attractive solution for determining reservoir capacity. SONAR is an active remote sensing technique in which reflected sound waves are used to measure elevation, with shallower depth (higher elevation) surfaces reflecting the sound wave sooner than deeper depth (lower elevation) surfaces because of the longer there-and-back travel distance of the sound wave.

Bathymetric surveys are collected using one of two SONAR techniques, single beam, or multi-beam. The top portion of Figure 15 shows the basic principle of the single beam technique, in which a single SONAR beam is used to collect data directly below the boat. The bottom portion of Figure 15 shows the basic principle of a multi-beam SONAR. With multi-beam collection systems, hundreds of SONAR beams are used simultaneously and at different angles to collect a wide swath of reservoir bottom elevations under water from a single point source or transect, whether predetermined at the original spacing or at higher densities to obtain overlapping swaths. The advantage of multi-beam SONAR is its ability to collect data from a much larger portion of the reservoir bottom: with sufficient overlap, the entire reservoir bottom can be mapped, yielding a complete and relatively accurate picture of the reservoir bottom.

Geospatial tools can be used to analyze the bottom surface of the reservoir and compute area and capacity data for various pool elevations, including critical elevations like the top of the flood pool. Other geospatial tools can be used to calculate the amount of erosion and deposition between two successive multi-beam surveys to analyze the movement of sediment in a reservoir relative to important infrastructure. An example of this use for multi-beam SONAR data collection to examine sediment accumulation at Reclamation's Paonia Reservoir, Colorado, is discussed later in this report.

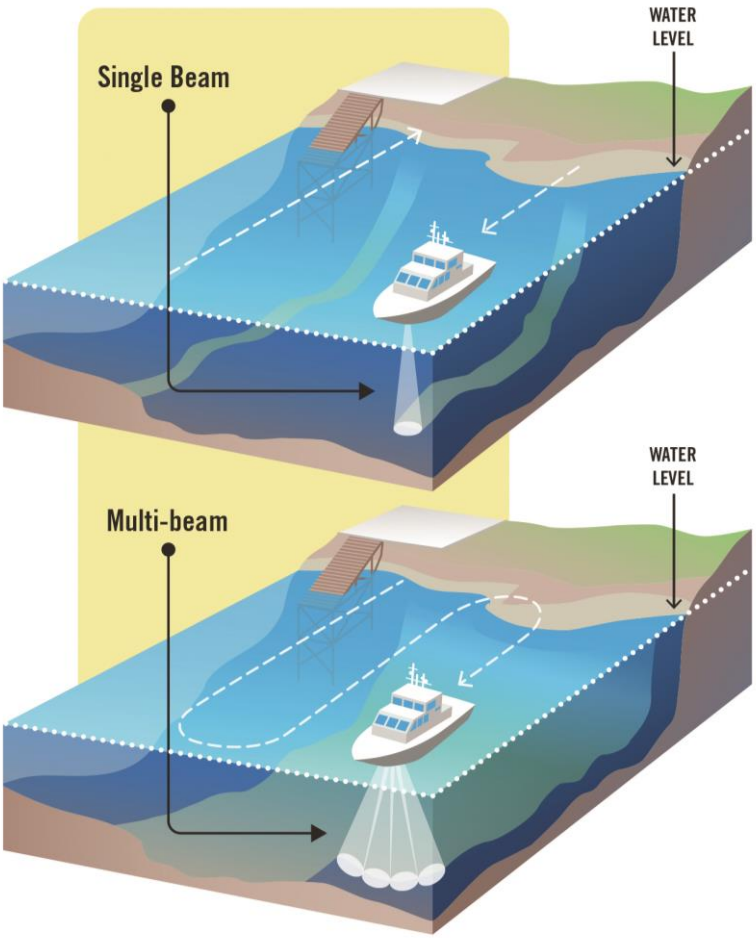


Figure 15 Comparison between single- and multi-beam SONAR.

While use of multi-beam SONAR systems has replaced the original sounding weight transect (transect) system, with improved accuracy and reduced cost, and is the dominant method for surveying reservoirs, it is both still relatively expensive to collect and process, and can only be used to collect information from below the water line. If a reservoir is not full when bathymetry data are collected, important capacity information at higher elevations is missing from the dataset. However, a completely full reservoir could be experiencing a flood emergency, and life safety concerns would prevent initiation of a bathymetric survey.

For obtaining topographic data in non-reservoir settings, LiDAR is the dominant technology because it marries high accuracy and speed with cost-efficiency. A benefit of LiDAR is the ability to collect a large

amount of data in a small amount of time. Like SONAR, LiDAR is a form of active remote sensing, in which a laser light rather than sound is used to determine elevations. LiDAR can be collected from many types of vehicles or stationary positions such as airplanes, unmanned aerial systems (drones), boats, or mounted to vehicles. Because the wavelengths of light used in LiDAR are attenuated by water, LiDAR cannot be used to collect bathymetric data except when the water is clear and shallow. Thus, LiDAR and SONAR constitute complementary technologies for measuring reservoir capacity, and they are often used together for this purpose.

In times of drought, a reservoir may be completely or largely drawn down, dewatering an exceptionally large portion of the reservoir bottom (Figure 16). Because drought is a regional phenomenon, causing many reservoirs to experience conditions of low water elevations at the same time, LiDAR may be very cost-effective in a region by reducing the number of unique flights, and by reducing many of the fixed costs associated with obtaining LiDAR data (primarily mobilization costs). Because the pool volume is lower during drought the amount of SONAR data needed to complement the LiDAR data is also reduced. A region with a series of dry dams (typically single-purpose flood damage reduction structures) could also achieve similar economies of scale while obtaining LiDAR data. Our investigation suggests that a combination of LiDAR and single-or multi-beam SONAR could be an effective way to collect detailed reservoir sedimentation data for reservoirs that are not in drought conditions (Figure 17).

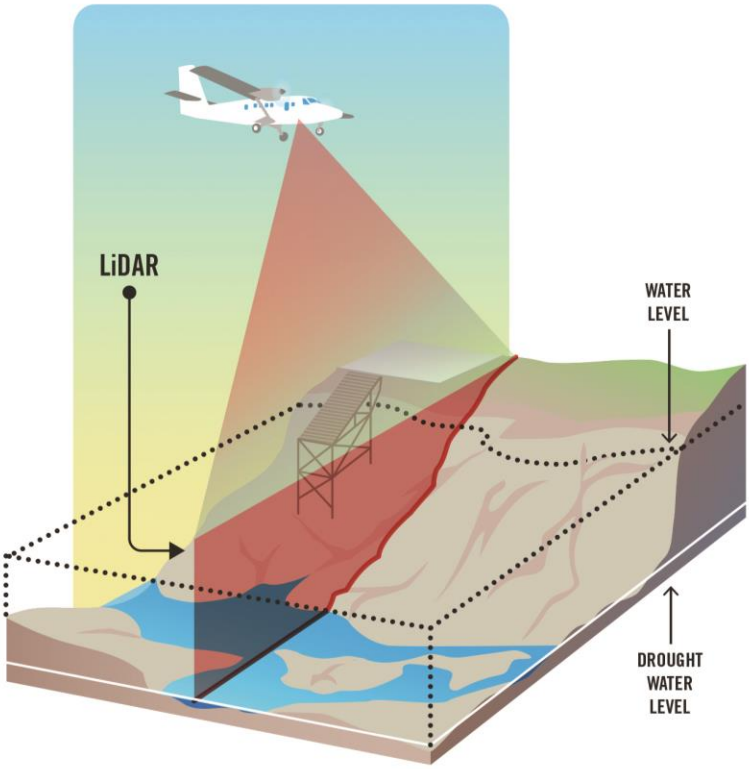


Figure 16 Topographic data being collected with airborne LiDAR in a drought-lowered reservoir.

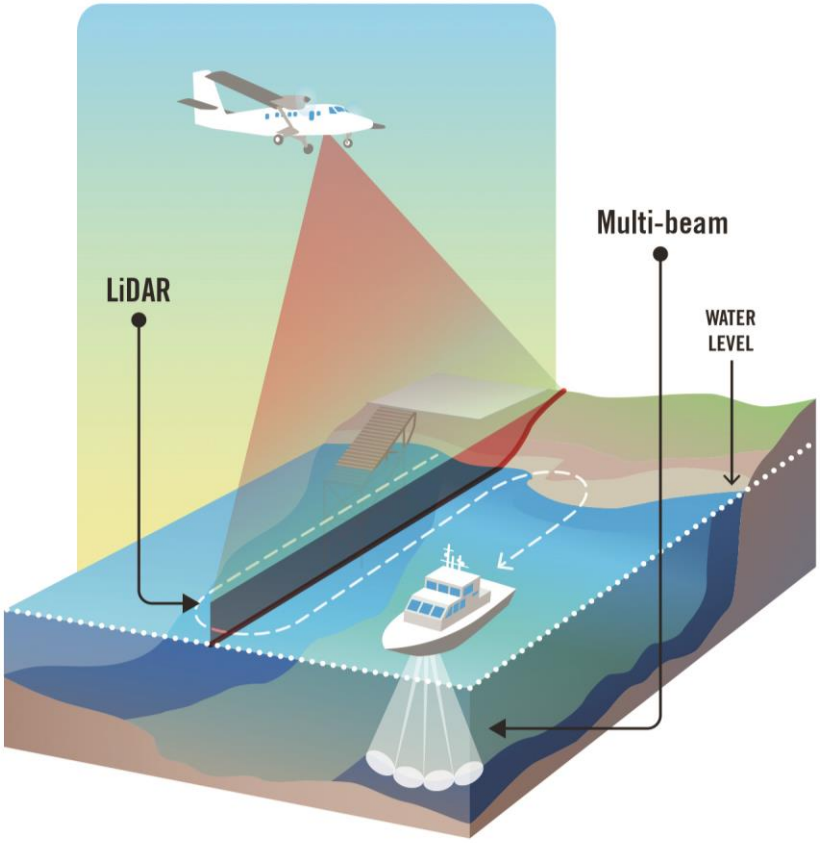


Figure 17 Combination of multi-beam SONAR and LiDAR.

LiDAR Data Collection for the NDRP Reservoir Surveys Project

LiDAR data collection requires three key components: the LiDAR instrument, flight management system that tracks the location of the LiDAR instrument and its position relative to the ground at all times, and vibration isolating mounting hardware. For the NDRP reservoir surveys project, the selection of the LiDAR instrument was governed by the accuracy needed to calculate accurate area capacity data, and factored other uses for which the data might also be used. The USACE Remote Sensing/GIS Center of Expertise (RS/GIS CX) used their in-house LiDAR system, consisting of a custom airborne laser scanner system mounted to a Partenavia P68 fixed-wing aircraft (Figure 18) [David Finnegan, CRREL, personal communication, November 2016]. The LiDAR scanner is a Riegl VQ-480i airborne laser scanner that is combined with an iXBlue Atlans-C inertial navigation system for LiDAR and trajectory data acquisition. A single operator inside the aircraft runs the system, as well as assisting the pilot with flight-line navigation. This system has an across-track (perpendicular to flight path) field-of-view of 60º. An integrated NexTrack 2 Flight Management System provides a pilot's display for flight line tracking and guidance.

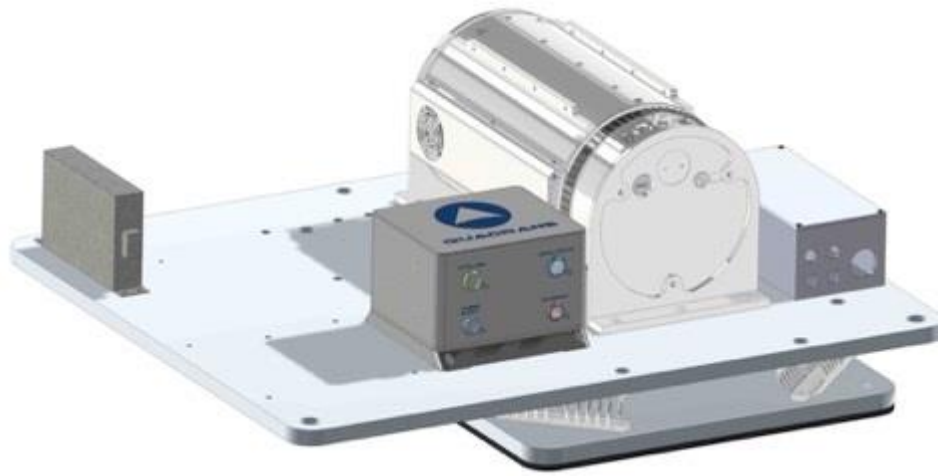


Figure 18 CAD model of the VQ-480i ALS system integrated onto the Partenavia P68 installation plates.

During collection, the aircraft flies at an airspeed of 80-knots, at an above ground level of 500 meters with a 50% overlap of the laser beams between parallel flight lines. Calculated point density for these parameters is 7 points/meter^2 for a single pass. With 50% overlap, a final point density of 14 points/m^2 is anticipated. A contour accuracy of one foot is expected given these flight parameters. First order vertical error, if all the equipment is performing at the marginal end of their specifications is approximately 8 centimeters. For the purposes of computing the volume of a reservoir, 8 centimeters accuracy is acceptable.

A boresight calibration flight must be conducted at the start and end of each survey. The initial boresight calibration is conducted on the day of installation. Intermediate boresight calibrations are conducted upon arrival at subsequent base airfields. The final boresight calibration is conducted on the final flight day, and may overlap with one of the Area of Interest (AOI) that has building rooftops present.

Post-Collection Data Processing and Archiving

Post-collection data processing and archiving of the LiDAR data consists of four general steps:

- Identify and correct errors present in the dataset and provide an estimate of the precision and accuracy of the data set.
- Upload the processed data to USACE'S Geospatial Repository and Data Management System (GRiD) for dissemination.
- Calculate reservoir capacities for different levels of inundation and area-capacity curves generated using the Reservoir Inundation Calculator.
- Load the area-capacity data and associated curves the Reservoir Sedimentation Information Data Portal.

These steps are described in more detail below.

Data Processing

Although the positional accuracy and precision of LiDAR data far exceeds those afforded by traditional remotely sensed imagery, laser return coordinates do contain random and systematic errors. Both error types originate in one or more of the laser system's components. Random errors relate to noise in the computed location of the aircraft, in the recording of aircraft attitude and scanning angles, or in the recording of time between pulse emission and backscatter reception, which ultimately determines the distance (range) to the target. The magnitude of random errors can be calculated during system calibration.

The assessment of relative accuracy is possible only between data obtained in overlapping swaths. The assessment has the advantage that it can be performed exclusively by data post-processing in the office. Generally, the higher the swath overlap (over a minimum of 20 percent), the more precise the assessment would be. There are two approaches in computing relative accuracy, with different degrees of complexity. The first approach relies on computing raster, or triangular irregular network (TIN), surfaces of elevation or intensity for each (or part) of the two flight lines and then evaluating their spatial correspondence [Gruen and Akca 2005, Maas 2002, Okatani and Deguchi 2002].

Loading Data into GRiD

Data collection by LiDAR, SONAR, and other techniques results in datasets with millions of points and associated metadata, posing significant challenges for storage, dissemination, and manipulation. The mass of raw and/or processed point data are typically referred to as a point cloud.

The GRiD Management System was developed in a partnership between USACE Cold Regions Research and Engineering Laboratory (CRREL) and the National Geospatial-Intelligence Agency's InnoVision to efficiently warehouse and distribute both three-dimensional point cloud data, such as LiDAR data, as well as related and derived two dimensional geospatial products, such as imagery and digital elevation models (DEMs) [Finnegan and Butler 2015]. Leveraging this archive facilitates efficient management and dissemination of the complex, multi-dimensional point cloud data resulting from LiDAR, multi-beam SONAR, and other remote sensing techniques. USACE manages separate instances of GRiD for Department of Defense (DoD) and civilian Federal government users. In addition to directly accessing GRiD through its website interface, users can also gain access through Open Geospatial Consortium services, including Web Mapping and Web Feature Services.

GRiD consists of an ORACLE database containing data that have been processed, organized, and compressed using the open source Point Data Abstraction Library (PDAL) [Finnegan and Butler 2015]. The database underlies an online data portal that enables users to subset, query, filter, and process point cloud data and derivative products by attributes, sensor, collection date, and geographic area. Users can also execute exploitation algorithms on their selected data, including the ability to perform bare earth extraction and classification, coordinate system reprojection, generation of digital terrain models and surface models, and derivation of information such as slope and line-of-sight analysis.

GRiD to Reservoir Inundation Calculator (RIC)

GRiD offers the user the ability to create an area of interest within its map interface. This feature enables the user to query a subset of data from the overall LiDAR collection which expedites the export process to input data into the Reservoir Inundation Calculator (RIC). The red highlighted area in Figure 19 represents a user's area of interest and the hashed red tiles represent an entire LiDAR collection within GRiD. The user exports the data contained within their area of interest and downloads it for analysis. The

user has the option to preview their data in a browser based viewer before downloading, if they desire (Figure 20).

Reservoir Inundation Calculator for Area-Capacity Curves and the RSI Data Portal

USACE had previously developed a software tool to compute reservoir area and capacity tables known as the Reservoir Inundation Calculator (RIC). RIC provides various input and output options, including the ability to calculate area and capacity for multiple water elevations at once. The minimum data requirement is a digital elevation model (DEM) of the reservoir area that includes both land elevation data and any bathymetric data in the reservoir. The DEM represents bare-earth conditions with trees, buildings, and water removed from the land surface. The RIC was modified for use in the NDRP reservoir surveys project.

Figure 21 shows the RIC software loaded with a DEM for the Whittier Narrows Dam, a USACE reservoir just outside of Los Angeles, California. The area in blue represents areal extent that water in the reservoir would occupy at the selected water elevation. The RIC computes the volume of water that would be present in the reservoir at the water surface elevation and area shown in blue. By computing the water volume (capacity) and surface area at successive water surface elevations (such as 0.1-foot intervals), an area versus elevation and capacity versus elevation curves, commonly called area-capacity curves, are developed for the reservoir.

The computed data are written to a file (Figure 22), which can be easily loaded into the USACE Reservoir Sediment Information (RSI) Data Portal, which is described in more detail by Pinson et al., 2016. To upload, the user navigates to the appropriate reservoir (Figure 23), creates a new record related to the data of the survey data collection, and uploads the area-capacity curve computed by RIC.

Figure 24 shows the elevation-capacity plot for Prado Dam, a USACE reservoir in California, in the RSI portal. In Figure 24 the brown line lies to the left of the blue, indicating that at each elevation of the pool, sedimentation has resulted in a net loss of water capacity at the reservoir. The horizontal dashed line represents the elevation for the base of the flood control pool. Where that flood pool line intersects the other two capacity curves gives the capacity of the reservoir at the designed flood control pool elevation. It shows that in 1941, when water rose to the base of the flood control pool, the reservoir held approximately 225,000 acre-feet of water, but (at that same elevation in 2008) it held approximately 175,000 acre-feet, a 50,000 acre-foot (20%) loss of capacity in 67 years**.**

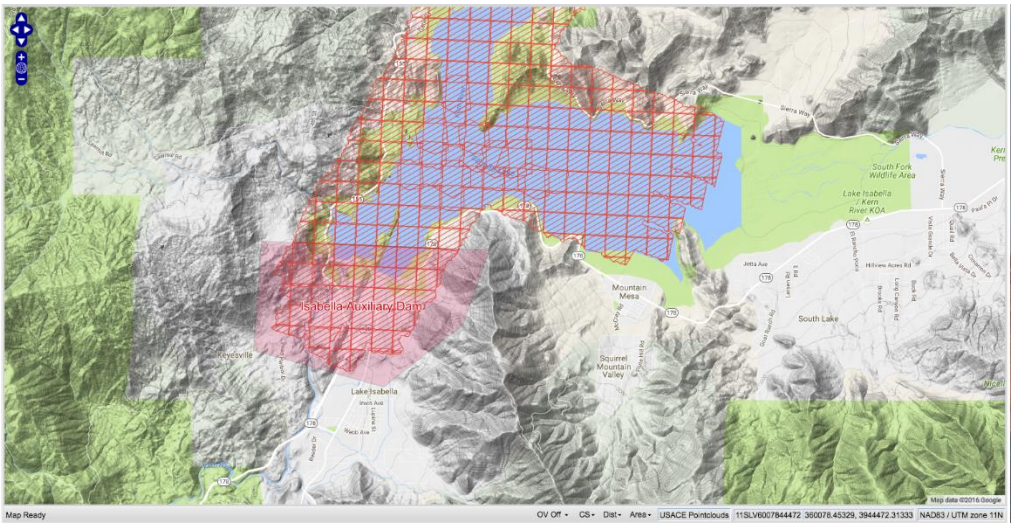


Figure 19 Screenshot of the LiDAR data collection area (red shaded squares) for the area of interest in GRiD.

Figure 20 Screenshot of a LiDAR DEM in the GRiD data portal.

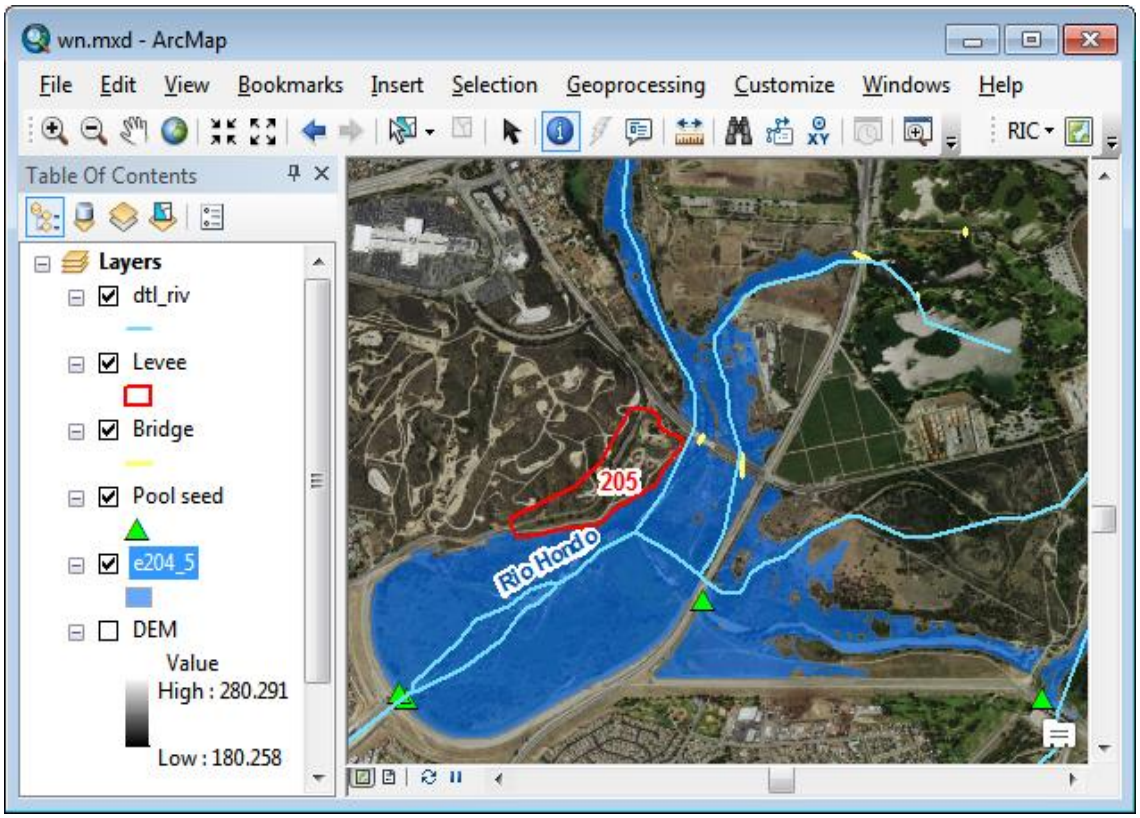
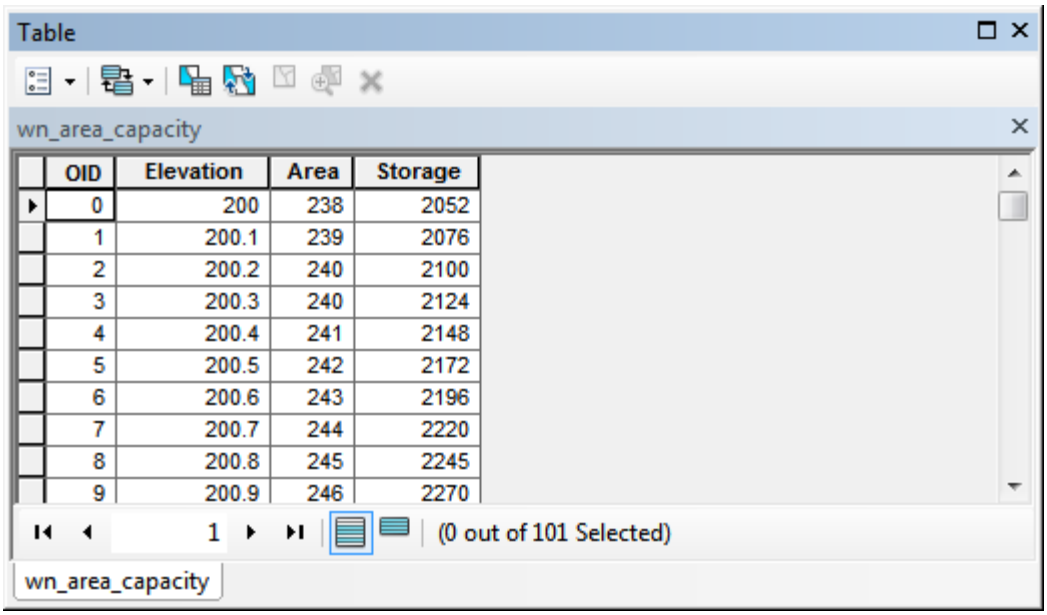


Figure 21 View of the RIC software with a DEM of Whittier Narrows, near Los Angeles, California.



Table

wn_area_capacity

OID	Elevation	Area	Storage
0	200	238	2052
1	200.1	239	2076
2	200.2	240	2100
3	200.3	240	2124
4	200.4	241	2148
5	200.5	242	2172
6	200.6	243	2196
7	200.7	244	2220
8	200.8	245	2245
9	200.9	246	2270

1 (0 out of 101 Selected)

wn_area_capacity

Figure 22 Example of the computational output from the RIC calculator.

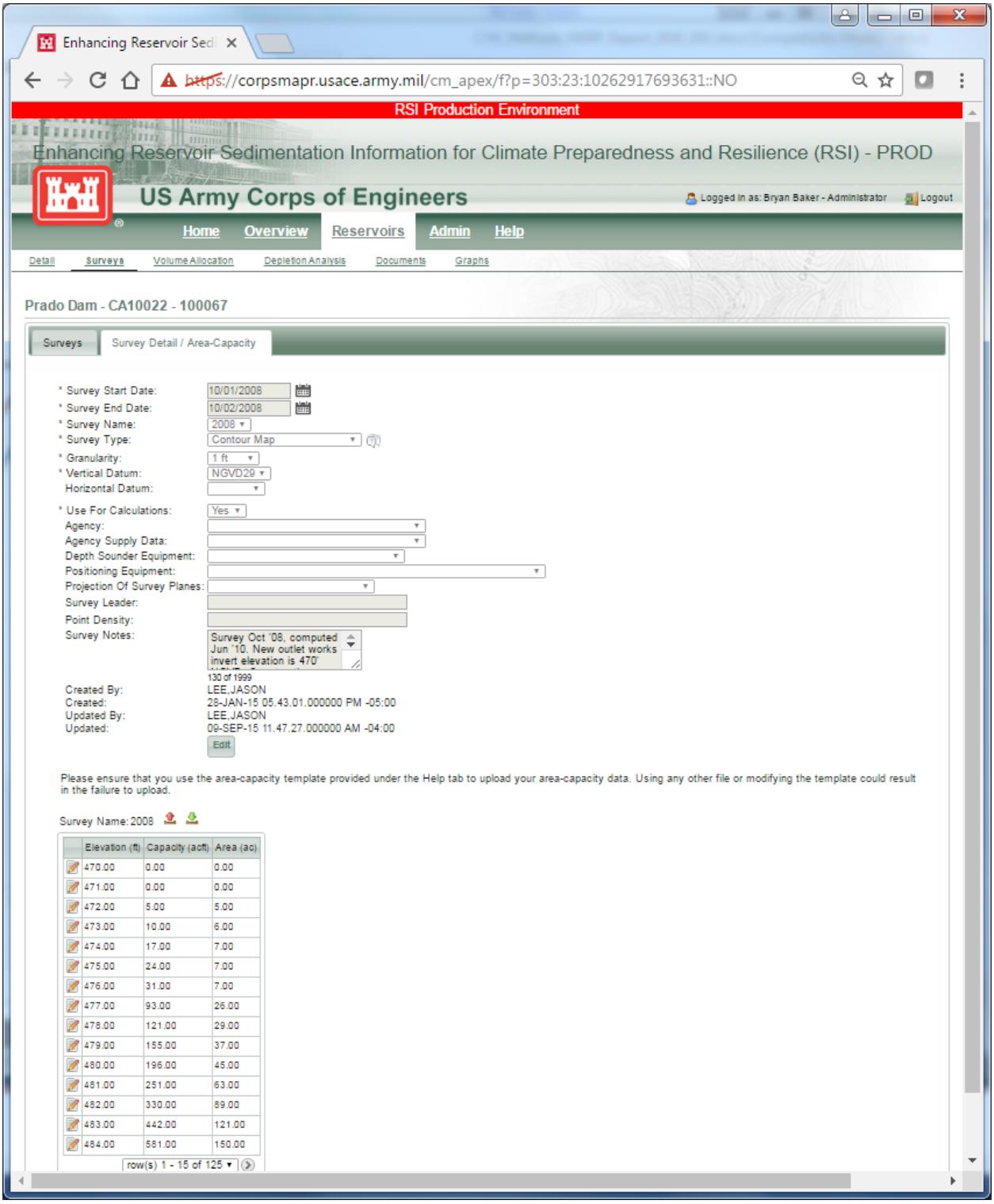


Figure 23 Data selection screen in the Reservoir Sedimentation Information (RSI) Data Portal.

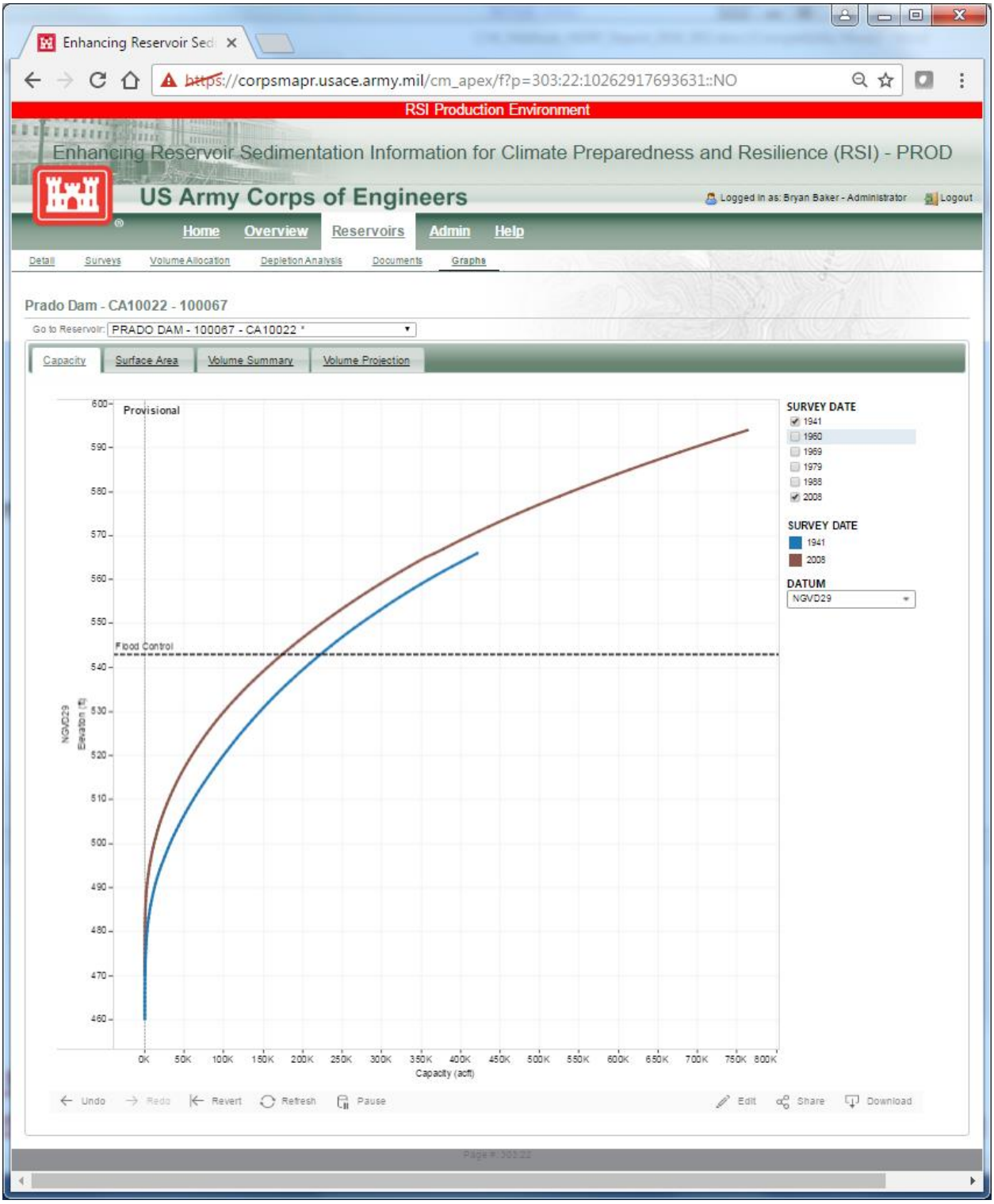


Figure 24 Elevation capacity curve for Prado Reservoir, California, as displayed by the Reservoir Sedimentation Information (RSI) Data Portal. The blue line represents the capacity of the reservoir at each water depth (elevation) in 1941, and the brown line represents capacity at each elevation in 2008.

Time Requirements for LiDAR Data Collection, Processing, and Archiving

This section provides a brief overview of the amount of time it takes to collect, process, and archive LiDAR data. Although large datasets are involved, many of the steps are now automated, particularly in data-post processing. This automation greatly reduces the labor involved in LiDAR data collection and dissemination.

Time to Determine Area of Interest

The minimum data needed for the flight path determination is a geospatial file in the form of a polygon outlining the area of interest for data collection. Figure 25 shows a polygon outlining the boundary of the lake formed by Prado Dam. In addition, there are factors such as determining flight restriction to consider because mobilization efforts are a major expense, whereas adding additional locations to collect data typically entail smaller financial increments. These determinations can take anywhere from a day to several weeks, depending on optimization, polygon files, and coordination needs if accommodating multiple agencies or office jurisdictions.

Figure 25 LiDAR flight lines used to collect data at Twitchell Reservoir, California.

Time to Compute Flight Path

The factors in determining the flight path depend on the desired data collection density, precision, and accuracy, as well as the number of locations and their proximity to each other. These data parameters along with the polygon file for each reservoir are used as input into software that determine the optimal flight paths needed to collect airborne LiDAR. Once done, ferry time (the time to fly the plane from one

location to the next) is determined to best sequence the order of reservoirs needed for data collection. Pilots are restricted to eight hours of flight time. Sufficient buffers are necessary to ensure that conditions such as higher winds do not contribute to excess hours flown in a day. The sequencing of project locations and the order in which to collect them is determined manually and is often an iterative process. For this effort, it was initially planned to use Oxnard, California and Phoenix, Arizona airports to collect data from 33 projects (5 were unable to be collected due to extenuating conditions high winds and flight restrictions around Los Angeles airport). The final flight path staged the aircraft at three different airports, Oxnard, California, Fresno, California, and Phoenix Arizona, to best capture the data. For this reservoir survey project, it took approximately 2 days to compute the flight paths, with most of the effort spent checking and determining optimal order of collection to minimize the flight time.

Time for Contracting Process

A key decision in a LiDAR collection is whether in-house resources or contractors are used. In some cases, a mix may be appropriate. For this NDRP reservoir survey project, a mix was used. In-house LiDAR expertise at the USACE RS/GIS CX capabilities was used to collect the actual LiDAR data, with a contract to cover the services for airplane charter and pilot for the data collection. The contracting process to acquire an airplane charter took over five weeks, as existing aircraft charter contracts do not exist for the RS/GIS CX LiDAR group.

The USACE St. Louis District office and Reclamation has a standing contract, known as an Indefinite Delivery, Indefinite Quantity (IDIQ) contract, for its surveying needs. Having an IDIQ contract in place can reduce the overall time, with a typical execution time around three to four weeks and product delivery and additional three to four weeks. Using contractors exclusively was not appropriate for the NDRP reservoir survey project for several reasons. For our effort, the determination of the flight time could not begin until October 2016 with deliverables available until mid-to-late November. Data collection needed to be completed prior to the onset of winter, the time of peak precipitation in most areas of California, especially northern California. The costs associated with the IDIQ were estimated to be higher than using the mix of in-house LiDAR capabilities coupled with an airplane charter contract. In this case, the existing IDIQ entailed additional ground control to verify the data collection with a survey accuracy of 5 centimeters. Since the LiDAR system used has an accuracy of 8 centimeters when the system is performing at its worst, it was determined 5-10 centimeter accuracy was acceptable for volume calculations and thus the ground control and additional associated costs were not necessary.

Time and Cost to Acquire Data

The total distance flown is the biggest factor in determining acquisition time. Total distance flown is based on the number of projects, the distance apart, and any special flight restrictions imposed by the Federal Aviation Administration (FAA). There may be altitude restrictions due a variety of factors, such as proximity to exiting airports or other airspace restrictions. An example time estimate is provided for Twitchell Reservoir, a Reclamation project that is also a USACE Section 7 project in the Los Angeles District. With a size of 1,759 acres, the number of flight lines computed is 28 strips. With the data collection parameters defined above, the estimated acquisition time is approximately 174 minutes. This does not include the time to fly to and from the reservoir to collect the data. Figure 25 shows the flight lines computed and the boundary for Twitchell Reservoir. The LiDAR collection cost, labor, plane, and instrumentation, was $3,329 with a flight time nearly 203 minutes including ferry time from Oxnard, California, airport. Table 4 outlines the LiDAR collection and processing costs along with the flight times for the reservoirs collected in the NDRP reservoir survey project.

Time and Cost to Process Data

Data processing of the raw LiDAR data consists of removal of data noise, outliers, classifying the points, tiling the data, and assigning a spatial reference system. Typical processing time for a project the size of Twitchell as shown in Figure 25 would be two weeks. Assuming a GS-12 level skill set for the processing, the average processing cost is estimated to be $5,200.

Additional LiDAR post-processing may be required on the processed data to support the creation of a bare earth DEM used in the RIC software. This requires the removal of non-ground points yielding a set of bare earth point clouds; which are then used to create a DEM. Processing time for bare earth point clouds and a DEM varies depending on data density and terrain. For a project the size of Twitchell Reservoir (Figure 25) would take two to three weeks at the GS-12 level, costing about $5,500.

Time and Cost to Load to GRiD

Processed data is copied to GRiD's file system. System administrators organize the data and stage associated metadata for export of the data to RIC or other needs. The data passes through a series of quality control verifications as it is loaded into the GRiD database. Typically, the process for a reservoir the size of Twitchell (1,759 acres) would take 3 days from starting the process until it is available to users to interrogate and develop DEMs need for the RIC software. Most of this time is based on computer execution. The skill set for this effort is at the GS-11 level and an average cost of $1,000 would be expected.

Time and Cost to Extract DEM

The biggest factor determining the length of time to generate a DEM needed by the RIC software is the area of interest. Since LiDAR data can contain anywhere between 3 million and 7 million points per square mile, the size of the area of interest plays a large role in the data processing. Typically a DEM generation for an area the size of Twitchell Reservoir would be three days. GRiD can also store DEMs too. If an area is downloaded repeatedly in the DEM format, it if often beneficial to store the DEM in GRiD rather than the raw point cloud data. This saves the typical three days of computation of a DEM, and the user can simply download the DEM immediately. In this case, download time for an area the size of Prado Dam would be approximately 4 hours depending on the user's internet connection speed. Human interaction is minimal in this task outside of defining the area of interest to download and initiating and monitoring the actual download process. Assuming a GS-11 level staffer, labor cost would be about $500 per location.

Time and Cost to Run RIC

The RIC software has been modified to compute the area underwater behind the reservoir for multiple elevation simultaneously, which dramatically reduces the computational time. Several factors unrelated to the software remain the dominant variable for time to run RIC. The primary factor is the size of the DEM used in the processing. For example, using the DEM for Whitter Narrows (Figure 21), approximately one day was required to compute the area capacity data. Additional time is needed to perform data quality checks on the resulting area capacity tables generated from the software. Such quality checks may require additional runs to incorporate any corrections. Assuming no additional runs and staffing at a GS-11 level, the RIC processing is estimated to cost approximately $2,200 per site.

Time and Cost to Load to the RSI Data Portal

The RSI Data Portal is able to consume comma-delimited text files for upload into the portal. The steps involved with uploading the data include navigating to the proper reservoir, creating a new record in the

data base, documenting the time of the survey, and entering the metadata (e.g., data accuracy, survey type). After the completion of the survey record, the area-capacity calculations file, consisting of three columns (elevation, capacity, area), are bulk loaded via the upload buttons as shown in Figure 23. Once the area-capacity tables are loaded, the RSI will provide graphs to visualize the new information loaded and computed in RSI and will compute storage loss values if previous data exist for the reservoir. A reasonable time to navigate and create the survey records coupled with uploading the new area capacity data is roughly 30 minutes. Most of this time is required for the survey metadata. At a GS-11 level salary, the cost would be around $100.

DATA COLLECTION COMPARISONS

This section provides information about four case studies that illustrate the ability of multi-beam SONAR and LiDAR to provide precise, accurate, georeferenced topographic data that can greatly improve reservoir operations and maintenance, and allow USACE and Reclamation to get a better understanding of which reservoirs are most vulnerable to sedimentation. These case studies rely on data collected by the USACE Omaha District and the USACE National Portfolio Assessment for Reallocations program for other purposes.

This section begins with a discussion of two SONAR studies and their associated high-data-density hydrographic data sets. An example of the application of a combined multi-beam SONAR and LiDAR data collect is then provided, followed by a comparison to examples of the LiDAR data collected for the NDRP reservoir survey project. These last examples show the rich detail available in a LiDAR data collected using the NDRP reservoir survey project protocols, which not only benefit reservoir sustainability decision-making, but will also enable activities such as cultural resources studies, post-wildfire sediment management, and dam and reservoir operations and maintenance activities.

Case Study 1: Bear Creek Reservoir Single-Beam and Multi-Beam Sonar

Bear Creek Reservoir is a USACE reservoir located in Lakewood (suburban Denver), Colorado. Bear Creek Dam and Reservoir is part of a three -reservoir system that provides flood risk reduction and other benefits to the greater Denver area and the South Platte River. Due to wildfires in the Front Range over the past 20 years, there is increased concern over the loss of reservoir storage due to sedimentation. The USACE has increased the reservoir survey frequency to reduce uncertainty about reservoir storage changes that may affect water management.

Area-capacity estimates were computed using both single-beam SONAR along transects and with multi-beam (Figure 26 – top and bottom maps) in 2016. In 2016, the hydrographic survey area-capacity was collected using multi-beam SONAR collected while the lake level was high. The data density compares favorably with LiDAR surveys, providing an example of the difference between transect-based and high-data-density, geospatially-accurate survey data, and also the methods needed to compare the area-capacity information between the two methods. LiDAR data for the land surface above the reservoir pool level were collected by the State of Colorado. The LiDAR data was necessary to geographically locate the transects and match the multi-beam SONAR data to these locations.

Since complete bathymetry, via multi-beam SONAR, and transects via single beam SONAR, were collected, area-capacity values were computed from both data sets. While a typical area-capacity table would have many rows and cover the entire elevation range of the reservoir, only a subsample is used to illustrate the difference in the volume computed based on the data density. Transect data typically uses an average area estimation method described in the USACE Engineering Manual on Sedimentation (EM 1110-2-4000) [USACE, 1989], while the complete bathymetry collected can compute the exact values for every location in the reservoir. Table 2 summarizes the volumes calculated using the two data types for Bear Creek reservoir. Negative values in Table 2 indicate a storage greater at that elevation using the single beam data for computations vs the multi-beam data for area-capacity calculations. Figure 27 shows the results from the 1980 and the 2016 average end area capacity estimation using the 2016 single beam data to be consistent with the 1980 data collection and computations (i.e., lines overlap).

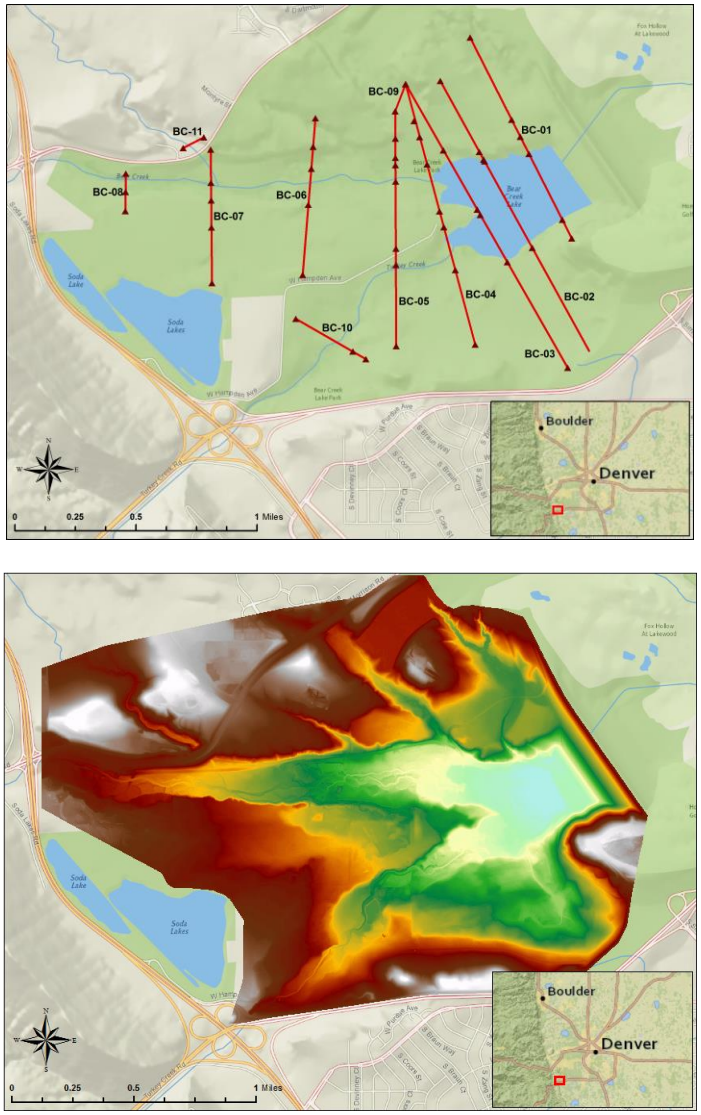


Figure 26 Map showing (top) the bed map and the single-beam SONAR transects of Bear Creek Dam and (bottom) Bear Creek Reservoir DEM created by a combination of multi-beam SONAR and LiDAR.

Table 2 Data for USACE's Bear Creek Reservoir located near Denver, Colorado. Negative volume difference indicates a storage greater at that elevation using the single beam data than the multi-beam data for area-capacity calculations.

Elevation (ft)	Reservoir feature or Pool	Volume based on transect using single-beam SONAR(acre-ft) in 2016	Volume based on bathymetry from multi-beam SONAR (acre-ft) in 2016	Volume Difference between multi-beam bathymetry and single beam at transects (acre-ft)
5522	Lowest Elevation	1.0	0.0	-1
5528	Inactive Pool	47	27	-20
5558	Joint Use	1,786	1,748	-28
5636	Flood Control	30,694	30,644	-50
5685	Surcharge	72,200	72,413	213

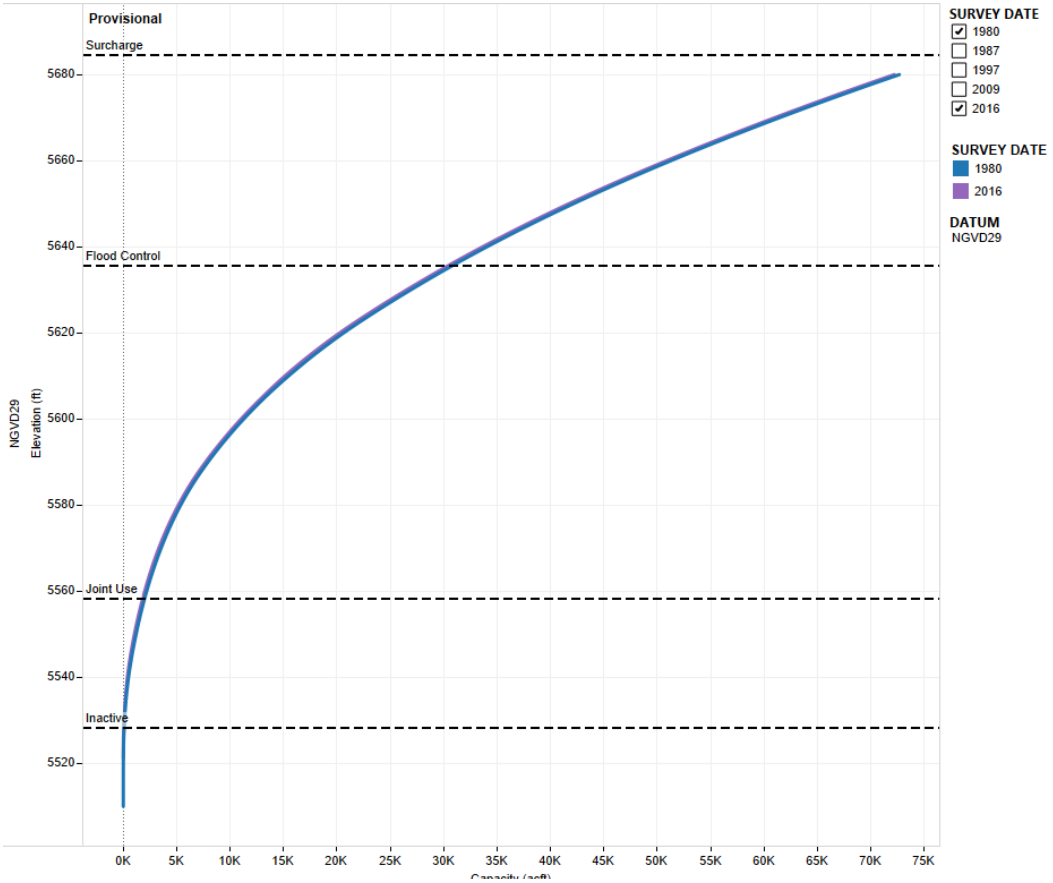


Figure 27 Area capacity data from Bear Creek, Colorado, showing that changes in pool capacity over the last 36 years due to sedimentation have been small. (Purple line is essentially the same as the blue line).

The storage volume computed with the 2016 single beam data increased since the previous transect survey in 1980, approaching the volume reported in the mid-1990s transect surveys. A review of the survey data from the 2016 and previous datasets (1980, 1984, 1987, 1997, and 2009) identified a historical discrepancy that has been carried through the analysis for the past three decades.

The increase in storage volume between the 2009 and 2016 surveys was due to an apparent bank recession on range line BC-08 (see Figure 28 between station 1500 and 1600). The bank recession between station 1500 and 1600 feet first appears in the 2016 survey. This recession, when projected upstream and downstream by average-end area methods outlined in USACE EM 1110-2-4000 area capacity analysis constitutes an increase in the calculated storage volume.

While reviewing the 1987 survey, the bank recession was noted by visual inspection. However, other data gaps precluded the use of the 1987 survey in an area-capacity analysis. Additionally, above-water shoreline topographic data used for the 1997 and 2009 surveys were copied from the 1984 survey. As a result, it is not known exactly when the bank recession occurred, but it was present by 1987. Copying the above-water shoreline topographic data was common over the past few decades due to limited funding for surveys. If a full survey has been conducted any time before 2016, the discrepancy would have been discovered at that time.

Figure 28, between station 1100 and 1300, also illustrates that the dominant location for sediment deposition along that transect occurs at this area. The lines show the approximate time that sediment deposited and the thickness of the deposits. For example, at Station 1200 between the years 1984 and 1997, over 10 feet of sediment deposited at that location. The figure also illustrates that most of the water conveyance is between station 1050 and approximately 1150.

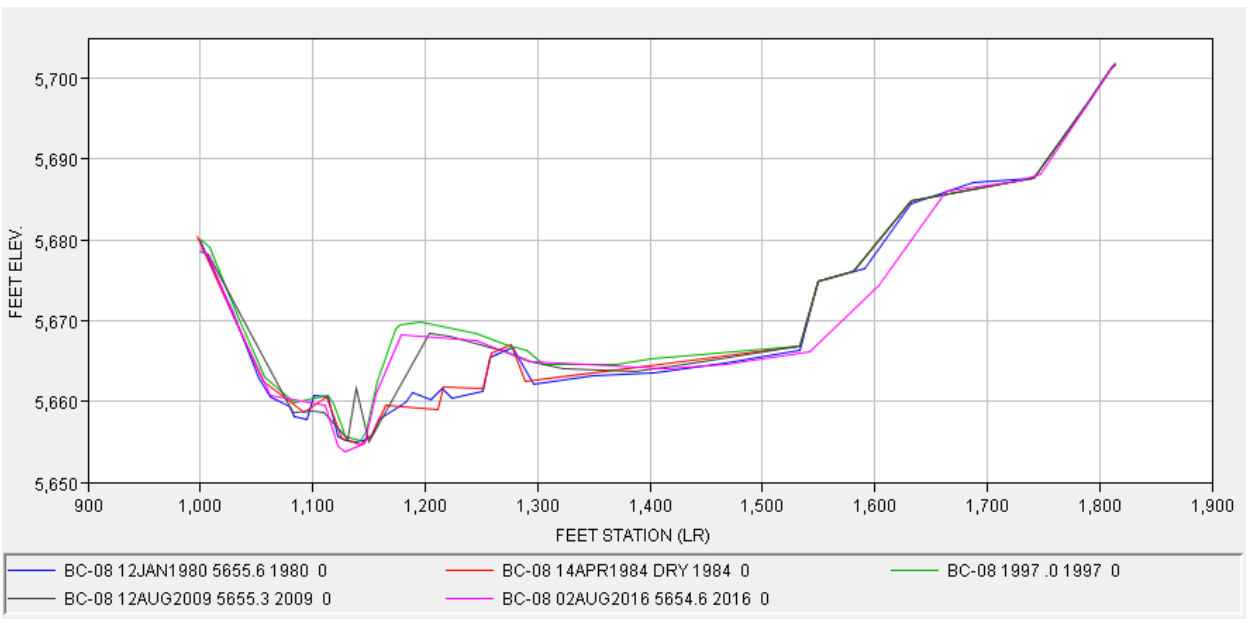


Figure 28 Bankline recession observed at Bear Creek range line BC-08 shown by the magenta line between station 1500 and 1650.

Case Study 2: Bluestem Lake, Nebraska Combination of Multi-Beam SONAR and LiDAR

In 2013, sediment surveys were conducted at Bluestem Lake behind Salt Creek Dam No. 4 on the North Tributary of Olive Branch Creek in Nebraska (Figure 29). The sediment surveys were conducted for the purpose of comparing the storage capacities calculated from a combination of LiDAR topography and multi-beam SONAR bathymetry. The reservoir storage capacities were estimated using historic transect surveys and the modified average end area method [USACE, 1992]. The historic transect surveys had used a standard, but inaccurate model of the landscape above the transect end points (the end area), which included areas within the maximum operating pool (Figure 30). Survey monuments at the higher elevations of the reservoir were never set along the transect and the upper banks of the reservoir were estimated. Consequently, transect surveys were also coupled with data extracted from LiDAR to extend the transect into the end area above the maximum operating pool.

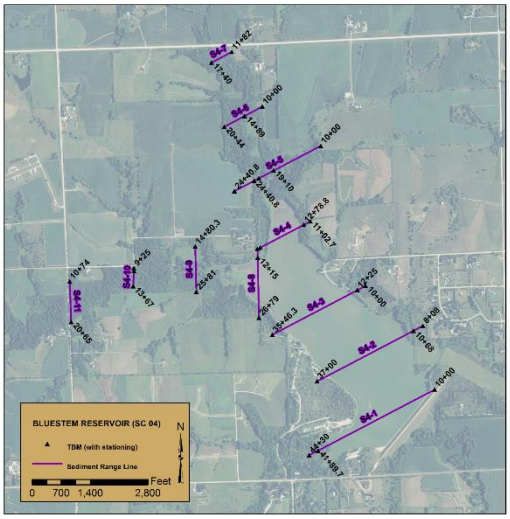


Figure 29 Photo of Bluestem Lake, Nebraska, showing location of transects.

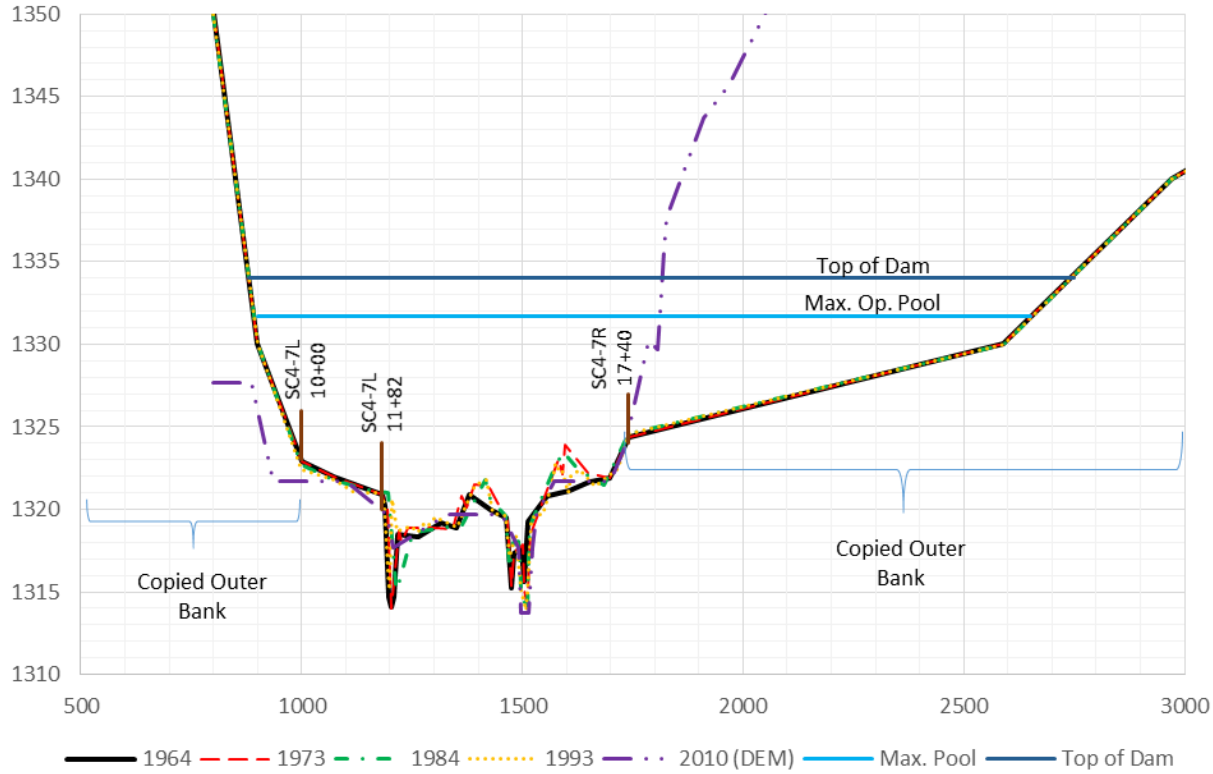


Figure 30 Bluestem Lake transect 7, showing the difference between the LiDAR DEM end area (purple dashed line) and the end area used in historic transect surveys (copied outer bank).

Reservoir storage capacity was computed from historic sediment transect survey data using the standard modified average end area method, and from the LiDAR and SONAR data using a geographic information system (GIS) after a digital elevation model (DEM) had been created. Capacities were estimated for both the historic transect survey end areas, and for the historic transect end areas as estimated using LiDAR data. The differences in reservoir capacity between these methods is significant (Table 3), with the more accurate LiDAR plus SONAR method showing pool capacities 8 to 16% lower than estimated from transect data. Both water supply (conservation pool) and flood risk management (flood control pool) are both smaller than expected: during irrigation season, less water is available for farmers while during a flood, the water holding capacity of the reservoir is significantly smaller than water managers assume, increasing the potential of a spill in spite of active water management.

Table 3 Table of capacity differences at Bluestem Lake, Nebraska, by survey method.

Pool Level	Elevation (NGVD 29)	Historic transect surveys[1] (ac-ft)	Historic transect surveys[1] LiDAR data in end areas (ac-ft)	LiDAR+ multi-beam SONAR (ac-ft)	Difference 1: LiDAR+ SONAR vs. transect w/LiDAR above pool surface (%)	Difference 2: LiDAR+ SONAR vs. Historic transect survey (%)
Maximum Operating Pool	1331.7	16,344	16,569	14,709	-11.20	-10.00
Top of Flood Control	1322.5	9,258	9,414	8,489	-9.80	-8.30
Top of Conservation	1307.4	2,343	2,337	1,998	-14.50	-14.70
Top of Sediment Pool	1306.1	1,968	1,962	1,661	-15.30	-15.60

[1]These are traditional transect surveys, with capacities calculated using the modified average end area method and historic overbank topography estimates.

Similar magnitude differences were observed in a study at Cherry Creek, Colorado, which compared capacity estimates from transect surveys using the end area method with those calculated from LiDAR data [USACE, 2011]. LiDAR data showed approximately 10% greater capacity at the top of the multi-purpose pool (5550 ft), and a 3-4% increase in capacity at the top of the flood control pool (5598 ft).

These differences are consistent with other studies comparing high resolution and low resolution topographic data collection. For example, at five northeastern Washington lakes and reservoirs, capacity estimates based on SONAR data collected at 300-m transect spacing was 4.2% to 9.6% lower than data collected at 50-m transect spacing [Cross and Moore, 2014]. The accuracy of the higher-density data collect was estimated at 99.0% to 99.6% (95% confidence interval, 98.3% to 100.5%) compared to modeled reservoir volume.

In recent years, high-density surveys of reservoirs using SONAR with or without LiDAR have been conducted without simultaneously collecting data using historic methods [e.g., Reclamation, 2013; Lee, 2013]. The methodological differences invariably produce different area-capacity estimates, but without simultaneous data collection using both methods, there is no clear way to eliminate the differences due to method from those due to changes in the reservoir.

One of the important tasks undertaken in the Bluestem Lake study was to simultaneously collect data across multiple methods, in order to be able to compare the capacity estimates from the historical transect survey methods with those derived from LiDAR data along the same transect lines, using the same methods to compute capacity. The resulting area capacity estimates were significantly larger than the historic transect surveys (with or without LiDAR end areas), as well as significantly larger than the high-density LiDAR and SONAR composite data set. Because these data were collected concurrently, these differences can be attributed entirely to data collection method. More studies like these are needed to understand the differences in capacity estimates from different survey method so that valid, long-term sedimentation rates from reservoirs can be reliably estimated and correlated to changes in land use, climate, and other factors. More frequent surveys using LiDAR and multi-beam SONAR are needed to more accurately measure reservoir sedimentation rates and predict future trends.

Case Study 3: Paonia Dam, Colorado Multi-Beam SONAR Volume Change

To understand change over time in reservoir sedimentation, elevation data collected in one year can be subtracted from elevation data collected in another year. This difference map can be used to estimate reservoir-wide variables of interest, such as changes in reservoir storage capacity, or a subset of the data can be used to focus on changes around key pieces of infrastructure, such as the outlet works in this example. The top of Figure 31 shows a complete coverage multi-beam survey for Paonia Dam, owned by the Bureau of Reclamation, using data acquired from a survey completed in 2013. In the lower left of the figure, the square symbol represents the location of the outlet works for the dam. During the 2013 Survey, the bottom of the reservoir around the outlet works was four feet below the intake sill (elevation 6358 ft). The bottom image in Figure 31 shows the 2015 survey where the reservoir bottom is now at the same elevation as the intake sill due to the redistribution of sediment downstream in the outlet works area.

Between these two images in Figure 31 – top (2013 survey) and bottom (2015 survey), subtle differences can be identified by visual inspection. Nonetheless, by having complete reservoir DEMs for those years, geospatial software can compute the elevation differences of the surfaces to better illustrate changes that may be too subtle for the eye to see. Figure 32 is the change (difference map) between the 2013 and 2015 reservoir bottom measurements. Negative values indicate erosion of the bed since 2013 and positive values indicate deposition since 2013. In this figure, the color red indicates areas of deposition since 2013 and blue represents areas where sediment was eroded. Figure 32 shows that in the area near the outlet works, Roughly 9 to 12 feet of sediment deposited near the structure over the two-year span between surveys. The type of visualization and analysis would not be possible without repeat and continuous reservoir bottom surveys.

The photo in Figure 33 shows the reservoir under drained conditions during emergency maintenance to remove sediment and wood that was blocking the outlet works intake. Not all changes in sedimentation are as dramatic as at Paonia, but repeat high-density data collection can reveal significant changes in sediment within a reservoir. For example, comparison of the 2009 LiDAR data collected at Lake Mead was compared to the 2001 SONAR data collection, revealed significant sedimentation in the Overton Arm along the Virgin River that was likely the result of a 2005 flood along the Virgin River [Reclamation, 2009]. Redistribution of this and other sediment deposits is expected in response to storm influx and changing lake levels.

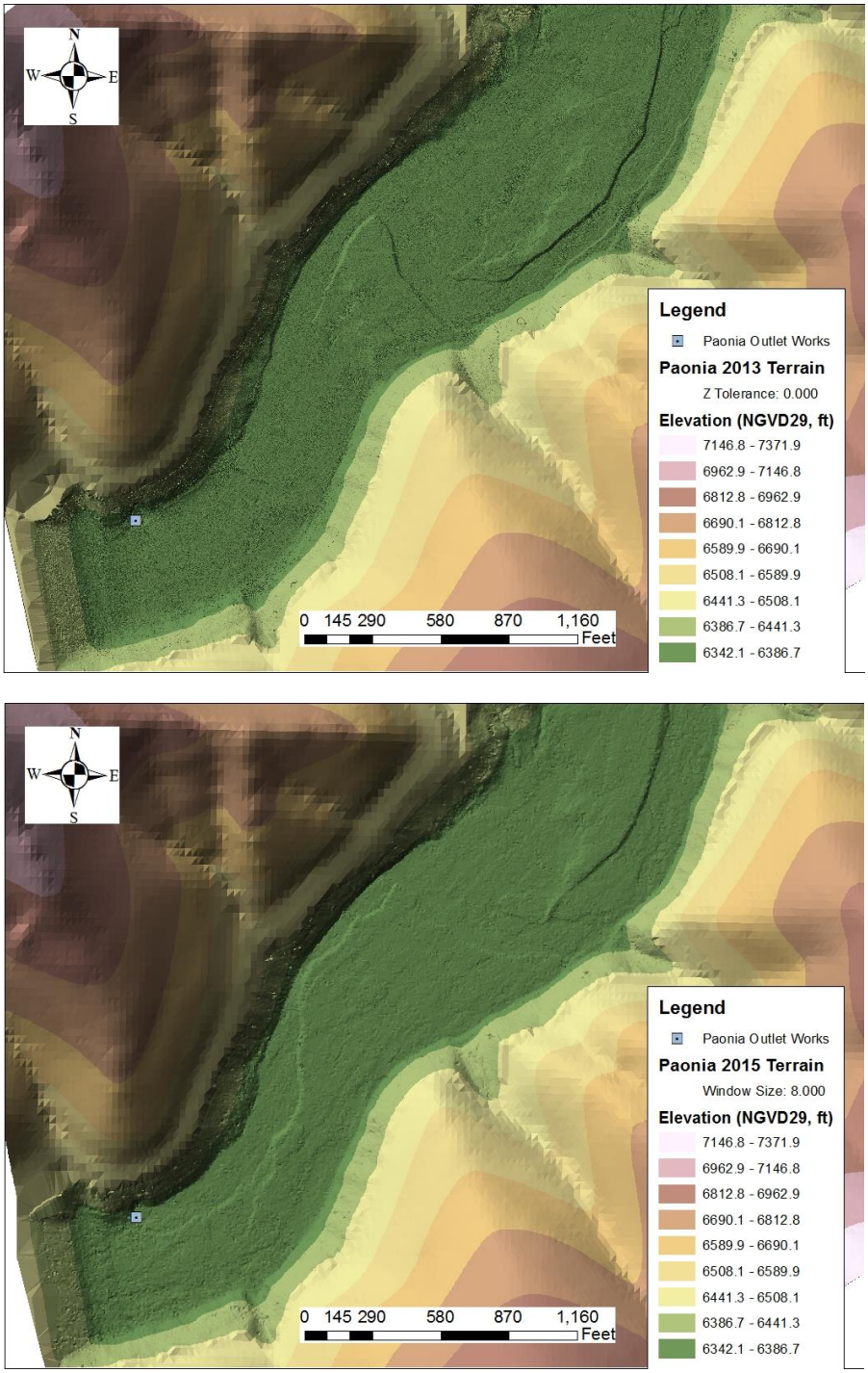


Figure 31 DEM based on multi-beam SONAR data collected in 2013 (top) and 2015 (bottom) at Paonia Dam, Colorado.

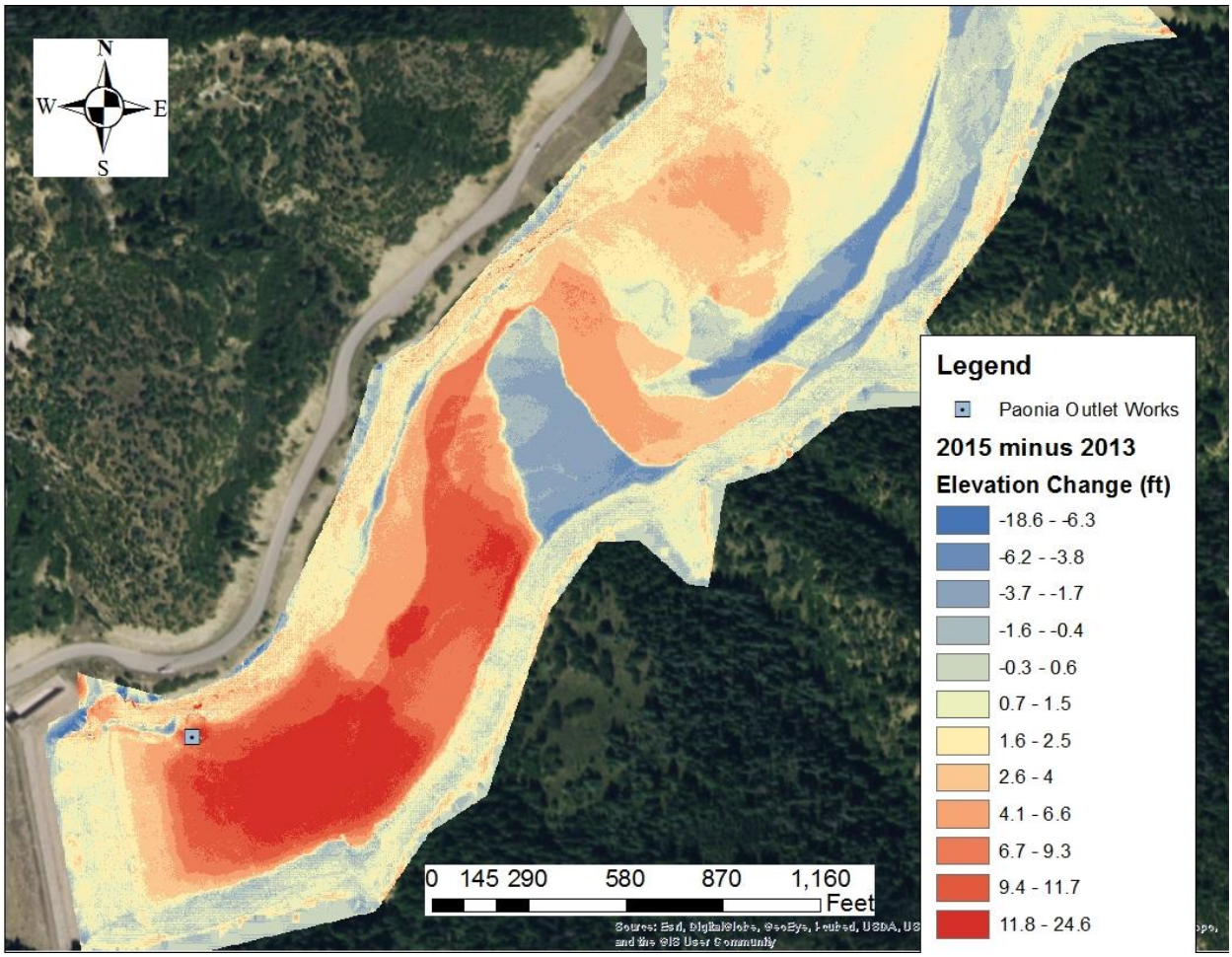


Figure 32 A map showing the elevation change based on subtracting the 2013 Multi-beam DEM from the 2015 Multi-beam DEM, Paonia Dam, Colorado. Negative values indicate erosion from 2013 and positive values indicate deposition since 2013.

Figure 33 Photo looking upstream from Paonia Dam, Colorado, in November 2014 showing the arrival of sediment at the outlet works intake and racked debris being cleared away by manual labor with the assistance of a 60-ft-long reach excavator.

Case Study 4: Conchas Lake, New Mexico LiDAR Coupled with Multi-Beam Sonar for Reservoir Volume Calculations

In 2015, the USACE Albuquerque District used a combination of multi-beam SONAR and LiDAR surveys to produce a full volumetric digital terrain model of USACE's Conchas Lake Reservoir in New Mexico. The survey was performed to update the area-capacity table used in reservoir management operations. Conchas Dam was built during the period 1935-1939 under the Federal Works Progress Administration and has been in operation for 83 years. Prior to the 2015 survey, the reservoir had last been surveyed in 1986 using the transect method. The contributing watershed area above the reservoir is 7,409 mi^2.

Multi-beam SONAR (Figure 34) and LiDAR (Figure 35) data were collected early in 2015. LiDAR data were collected with a 0.9-m nominal point spacing sufficient to derive a 2-foot, bare-earth surface topographic contour map. Twelve geodetic control points were established, with three times as many classification control points. More than 100 million data points were collected. The multi-beam SONAR

and LiDAR datasets were fused and converted to a bare earth digital terrain model (Figure 36). The USACE RIC tool was then used to compute area-capacity data from the fused digital terrain model data. The resulting data (Figure 37) showed reductions in reservoir volumes have occurred at all elevations within the reservoir, indicating sediment deposition throughout the reservoir and not just in the inactive pool. The LiDAR data collected for this project also capture information vital for surveying and managing cultural resources at the reservoir. For example, the remains of late 19th to early 29th century buildings in the abandoned community of Alamosa Plaza, NM, are readily visible in the lower right portion of the inset image in Figure 36. These structures lie below the average water elevation and are only accessible during the driest years.

Figure 34 Multi-beam SONAR data collection at Conchas Lake showing data collection instrumentation. Top: view of the boat exterior, with SONAR unit on the bow. Bottom: view of the boat interior.

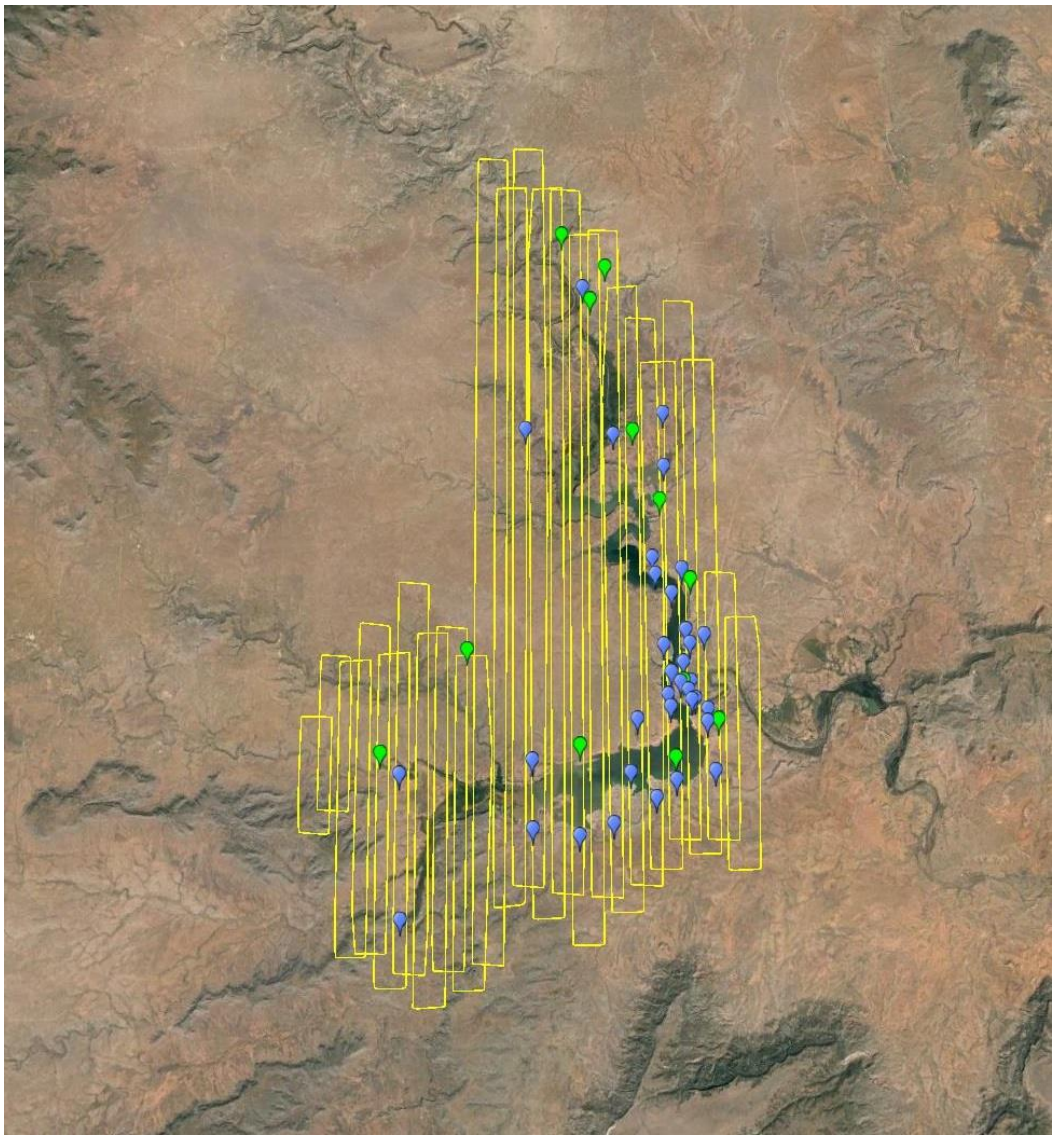


Figure 35 Flight lines for LiDAR data collection at Conchas Lake, New Mexico.

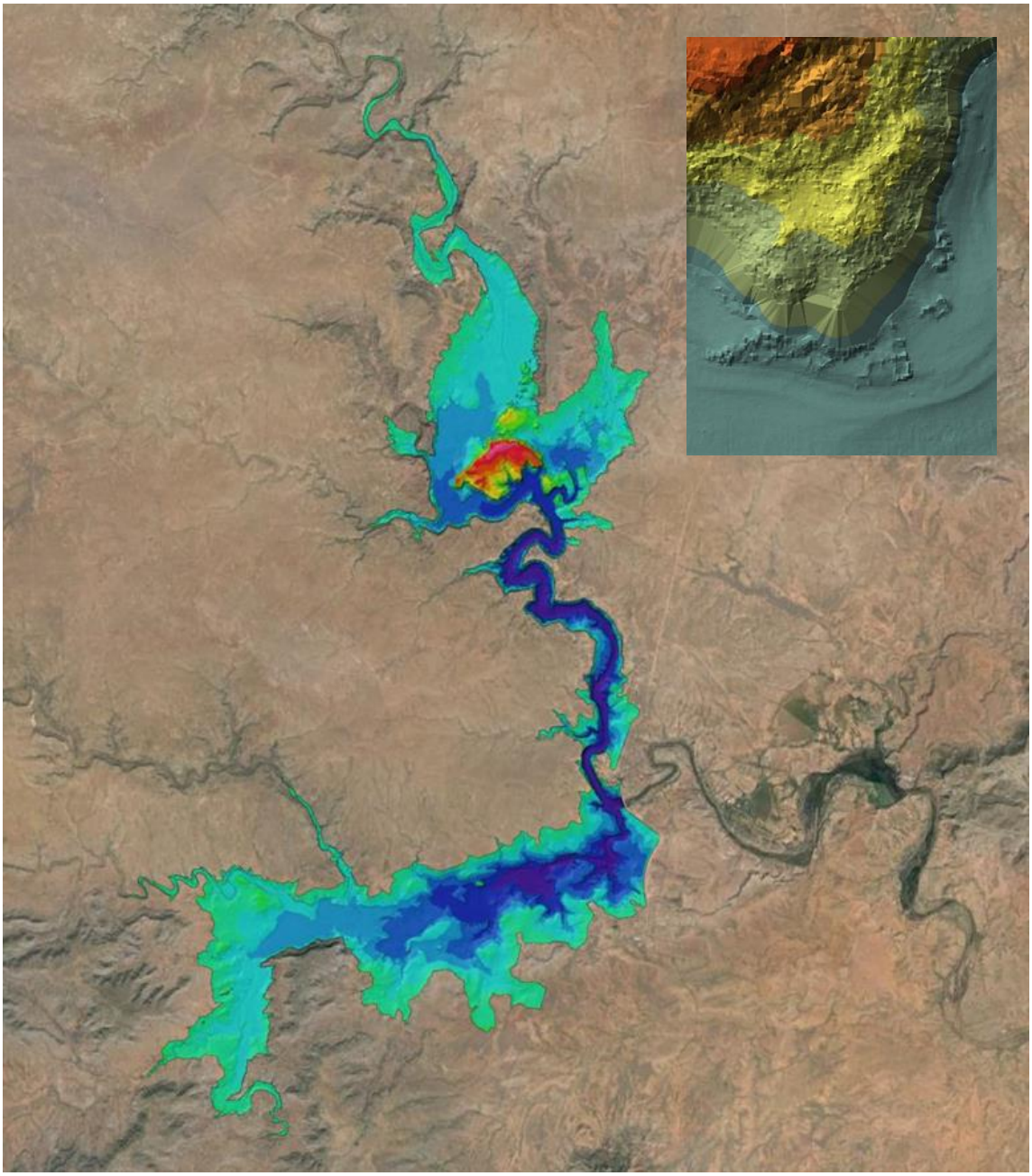


Figure 36 Resulting fused digital elevation model, clipped to the extent of the pool at the elevation of the top of the dam. Historic structures inundated by Conchas Lake are visible just to the lower right of the promontory in the inset graphic.

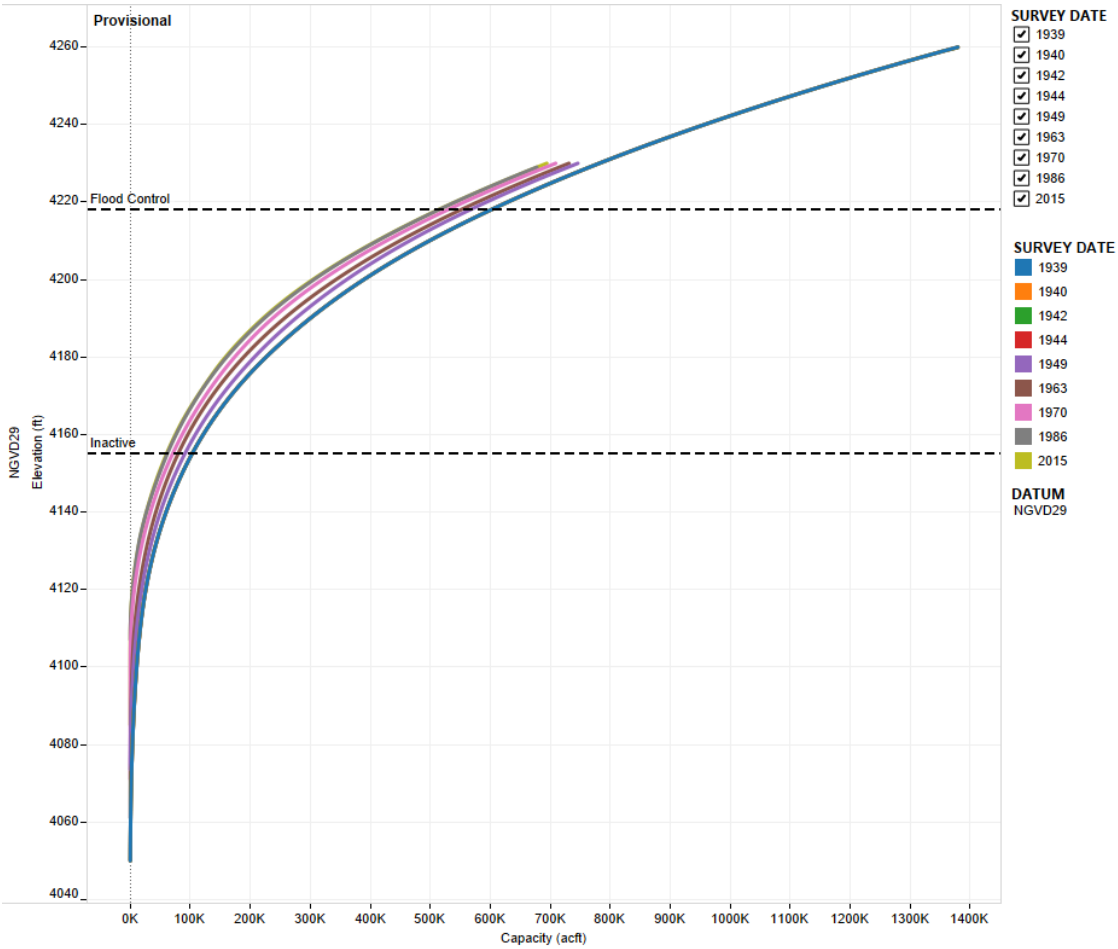


Figure 37 Area-capacity graphs comparing the results of surveys at Conchas Lake, New Mexico.

DISCUSSION AND CONCLUSIONS

LiDAR data collection efforts completed for this NDRP reservoir survey project represent a collaboration by USACE and Reclamation, USACE districts, Reclamation regions, the USACE Cold Regions Research and Engineering Lab GIS/Remote Sensing Center of Expertise (RS/GIS CX), the Reclamation Technical Services Center, other Federal agencies and partners, and contractors. The data collection effort focused on using LiDAR to capture reservoir topographic information for drought-lowered reservoirs.

This study occurred within a larger framework in which LiDAR is increasingly used for topographic data collection in support of the many USACE and Reclamation missions. The collection of high resolution LiDAR data are ideal for topographic mapping of the exposed reservoir shoreline and the upstream delta areas, which are difficult and expensive to survey by boat or by wading or walking. Deltas can often extend well upstream from the full pool of the reservoir, causing problems for upstream lands, and these areas are often ignored during bathymetric reservoir surveys. LiDAR data are also useful for other purposes, including reservoir storage reallocation studies, project planning, and cultural resources

management. The LiDAR data thus enables repeated cost savings down the line as subsequent projects tap into the existing data instead of conducting their own field surveys.

Costs

For the LiDAR test collection, the effort used the RS/GIS CX to research and collect the data. Table 4 shows the locations and estimated cost for the efforts. The data collection effort by the RS/GIS CX consists of a fix cost contract aircraft charter which translates into a number of hours of flight time. Flight conditions and weather may play a key role in the final projects surveyed. The data in the table represent the costs for the data collected based on priorities established to ensure the critical projects from both agencies get collected.

Table 5 show the costs to conduct single beam SONAR data collection along the existing range lines. Table 6 shows the cost for multi-beam SONAR data collection in August 2016. The average cost per acre for single-beam SONAR was $8.72, with two of three surveys closer to $8 per acre, and one twice this amount. The cost difference resulted from a shift in data provider between surveys. Multi-beam SONAR costs were consistent across all three reservoirs, coming in at $15.37 per acre.

Comparing the data in Tables 4 through Table 6, LiDAR data collection produces a significant cost reduction for data collection. While there are some costs per acre values in Table 5 that are significantly higher in some cases, they turn out to be reservoirs that are very small in size. Processing costs for LiDAR are generally constant and therefore a small reservoir would have a high cost per acre. When looking at Table 4 as a whole and contrasting to the multi-beam SONAR, which also generates a complete bed surface, the cost differences are dramatic. Even comparing similar acreages shows dramatic difference. For example the total acreage and cost in Table 6 is 12,360 acres at a cost of $15.37 per acre. Looking at Table 4 for a similar size project is the New Melones project in the Fresno flight base. New Melones has 11,757 acres and a cost of $0.76 per acre.

One key difference that must be highlighted in the data centers is that some water remains in the reservoirs and the surface below the water cannot be collected with LiDAR. One possible solution would be to survey the remaining location underwater with the multi-beam SONAR dataset and merge it with the LiDAR data collected. This would have the benefit of getting a complete surface of the entire reservoir. Because much can change in a short time, it would be advisable to collect the data with the two technologies as close in time as possible.

Table 4 LiDAR data collection costs at twenty-eight reservoirs in California and Arizona, fall 2016.

Flight Base	Project	Acres	Estimated Total Flight Time (min)	Estimated Total Cost	Estimated Cost Per Acre
Fresno, CA	Bear	295	34	$5,735	$19.44
Fresno, CA	Burns	709	60	$6,161	$8.69
Fresno, CA	Eastman	1,825	30	$5,669	$3.11
Fresno, CA	Hensley	1,587	42	$5,866	$3.70
Fresno, CA	Lake Kaweah	1,864	75	$6,407	$3.44
Fresno, CA	Mariposa	594	34	$5,735	$9.64
Fresno, CA	New Hogan	4,299	82	$6,522	$1.52
Fresno, CA	New Melones	11,757	228	$8,917	$0.76
Fresno, CA	Owens	198	22	$5,538	$27.97
Fresno, CA	Pine Flat	5,866	140	$7,473	$1.27
Fresno, CA	San Luis	20,403	241	$9,130	$0.45
Oxnard, CA	Brea	294	80	$6,489	$22.07
Oxnard, CA	Carbon Canyon	358	16	$5,439	$15.19
Oxnard, CA	Fullerton	5,616	45	$5,915	$1.05
Oxnard, CA	Hansen	1,297	59	$6,145	$4.74
Oxnard, CA	Isabella	7,738	215	$8,703	$1.12
Oxnard, CA	Lake Cachuma	4,693	101	$6,834	$1.46
Oxnard, CA	Lopez	82	22	$5,538	$67.53
Oxnard, CA	Mojave	3,596	92	$6,686	$1.86
Oxnard, CA	San Antonio	229	114	$7,047	$30.77
Oxnard, CA	Santa Fe	1,810	76	$6,424	$3.55
Oxnard, CA	Twitchell	1,759	203	$8,507	$4.84
Oxnard, CA	Whittier Narrows	4,325	80	$6,489	$1.50
Phoenix, AZ	Alamo	14,525	325	$10,508	$0.72
Phoenix, AZ	Horseshoe	3,334	102	$6,850	$2.05
Phoenix, AZ	Painted Rock	74,892	488	$13,181	$0.18
Phoenix, AZ	Theodore Roosevelt	27,878	265	$9,524	$0.34
Phoenix, AZ	Whitlow	1,322	75	$6,407	$4.85
Total		203,156		$199,837	$0.98

Table 5 Single-beam SONAR data collection costs at three reservoirs near Denver, Colorado, in August 2016.

Project	Costs	Number of Transects	Cost Per Transect	Acres	Cost Per Acre
Bear Creek	$18,777	13	$1,444	1,167	$16.09
Chatfield	$51,030	22	$2,320	6,453	$7.91
Cherry Creek	$37,916	13	$2,914	4,740	$8.00
Total	$107,723	48	$2,244	12,360	$8.72

Table 6 Multi-beam SONAR data collection costs at three reservoirs near Denver, Colorado, in August 2016.

Project	Costs	Acres	Cost per Acre
Bear Creek	$17,939	1,167	$15.37
Chatfield	$99,197	6,453	$15.37
Cherry Creek	$72,864	4,740	$15.37
Total	$190,000	12,360	$15.37

Benefits of Reservoir LiDAR Surveys

The reservoir LiDAR survey methodology used in this NDRP reservoir survey project has multiple benefits compared to either a piecemeal LiDAR approach or to uses of other technologies alone:

- LiDAR in conjunction with multi-beam SONAR provides the lowest net cost per acre for determining reservoir surface area and capacity across all pool elevations for the 28 sites collected. In most cases, the lower the reservoir elevation, the less the net cost will be. It is also quicker to collect LiDAR data than to collect SONAR data. For example, the LiDAR flights for the reservoir survey project collected three projects in a single day, while the multi-beam SONAR collection took 5 days for one reservoir in Denver, Colorado.

- The higher data density of LiDAR results in a more accurate snapshot of what the real volume of the reservoir is and the location of deposition relative to critical assets like dam outlets, water intakes, and boat marinas, when compared to traditional transect survey and single-beam SONAR methods.

- Post-field data processing required for a complete bathymetric surface is significantly less for both LiDAR and multi-beam SONAR than with single-beam SONAR. There is a little additional preparation necessary on the front end for calibration, but once the survey is complete, the remaining steps are primarily quality control and transferring the data into the target mapping format.

- Single-beam SONAR surveys provide a generalized picture of reservoir bathymetry. The method is unable to show in detail the encroachment to critical assets such as intakes unless by chance the intake is located directly on or very near a transect or range line.

- The LiDAR and multi-beam SONAR data products are very accurately georeferenced datasets. LiDAR resolution can be improved with added control points even after the data are collected to meet other agency needs, such as design. Thus, if the initial vertical accuracy of the LiDAR data is sufficient for area-capacity estimates, but not for a subsequent engineering task (e.g., a dam safety study), additional control points can be surveyed and that data used to improve the vertical control of the original LiDAR data set. New LiDAR would not necessarily have to be reflown.

- Transect or range line cross section can be produced from the LiDAR and multi-beam SONAR datasets. These can then be used to compare to data from traditional or single beam range line surveys (i.e., the new data are backwardly compatible). The reverse is not true: A complete reservoir bathymetry dataset cannot be built from range line data.

Lessons Learned

The lessons learned to date are focused on maximizing cost efficiency, facilitating rapid deployment, and strategies to reduce data mismatch between the LiDAR and multi-beam SONAR data collection during low pools:

- Because mobilization costs are significant, data collection for the NDRP reservoir survey project capitalized on economies of scale by collecting numerous sites in a geographical region. Instead of standing up the aircraft, LiDAR equipment, and technical teams separately for individual reservoirs, the cost and effort of standing up the LiDAR is amortized across multiple reservoirs. This results in a significant decrease in per-acre survey costs.

- Because drought affects Federal, state, and local reservoirs equally, collaboration among agencies could be used to further reduce costs depending on authorities. By partnering with Reclamation on this effort, total costs of LiDAR data collection are reduced because only one LiDAR effort needs to be mobilized in the area. This is important because reservoirs within a watershed are typically operated as a system in response to a drought (or flood), rather than individually. Accurate data on surface area and capacity across the system, not just at selected reservoirs, provides a stronger foundation for better decision-making. Lower costs ease the burden for smaller municipalities and agencies funding LiDAR data collection at their reservoirs as part of this collective effort, which benefits all.

- Because of the very low per acre costs achieved by the NDRP reservoir survey project, the most cost-effective strategy is to maximize the amount of LiDAR data that can be collected and minimizing the remaining multi-beam SONAR data collection effort. Working with reservoirs experiencing drought or other draw-down minimizes costs while maximizing data quality.

- In some cases, it may be desirable to stand up LiDAR quickly: for example, a reservoir may be lowered to make an emergency repair at a hydroelectric turbine. Having a mechanism in place to rapidly stand up a LiDAR effort would be valuable, such as an existing indefinite delivery-indefinite quantity (IDIQ) contract with a local LiDAR provider and memoranda of agreements with cooperating agencies. However, in many places drought is a long-term (seasonal, annual, multi-year) phenomenon, giving the user time to explore different approaches to LiDAR data acquisition to determine which is most cost-effective. These approaches include data acquisition by internal USACE components, collaboration on regional data collection efforts already under way and being led by another agency or state, local or tribal governments, and contracting out the data collection.

- The USACE and Reclamation both have an IDIQ mechanism. The NDRP reservoir survey project was conducted with the RS/GIS CX in-house LiDAR capabilities coupled with a contract for aircraft flight time. Careful planning to streamline and optimize data collection resulted in data collection at twenty-eight projects in less than three weeks in November 2016.

- If using LiDAR and multi-beam SONAR together to collect above- and below-water surface data, it is important to collect both sets of data within a relatively short time period, so that subsequent sedimentation in the reservoir does not create a mismatch between the two datasets at their survey boundaries.

- Interagency agreements can be used to collaborate in data collection, particularly where combining funding from several agencies can be used to take advantage of IDIQs already in place.

- Additional studies are needed to better understand how changes in method affect capacity estimates, so that long-term sedimentation rates at the nation's reservoirs can be better estimated, and the factors that affect these rates be identified.

Conclusions

Water demand is becoming increasingly variable in time and space as populations increase, development and demographic patterns evolve, the economy grows, and as water conservation measures become increasingly more effective. Future water supplies are also likely to be more extreme, with increases in drought severity, duration, and frequency coupled with increases in heavy precipitation and associated flood risks. As a result, the balance between water management for flood risk reduction and for water supply during drought is shifting. This change brings with it the need to identify as early as possible situations warranting a request to deviate from standard operations defined in reservoir Water Control Manuals. In addition, there is increasing emphasis on the joint management of water resources at the basin scale through integrated water resource management planning for both human and ecological benefit. Because there remain few locations suitable for siting new reservoirs, it is necessary to prolong the useful lives of the nation's existing reservoirs by managing and minimizing the amount of sediment that accumulates in them [Graf et al., 2010; Juracek, 2015]. All of these management activities rest on timely and accurate assessments of the existing reservoir capacity and the types of events that may cause changes in storage zones (e.g., wildfire). Because sedimentation steadily reduces zonal storage capacity in a nonlinear fashion, frequent repeat assessments are necessary, especially where sedimentation rates are high or variable.

The NDRP lays out a framework under which Federal agencies can collaborate to improve community resilience to current and future droughts, which are expected to occur more frequently and last longer. Understanding how much sediment is accumulating in our reservoirs and monitoring the rate of this accumulation are essential for understanding the magnitude and geographic extent of sediment-related storage reductions relative to the nation's water needs. This project evaluated an approach to survey sediment deposition in drought-lowered reservoirs using LiDAR, which was found to be cost-effective for the 28 locations evaluated. Further study should evaluate the combination of low-pool LiDAR coupled with multi-beam SONAR as an additional method for USACE and Reclamation to rapidly assess and monitor sedimentation throughout their reservoir inventory.

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