National Drought Resilience Partnership Data Collection

Bryan Baker, Remote Sensing-GIS Center of Expertise, Cold Regions Research and Engineering Lab, U.S. Army Corps of Engineers, Hanover, NH, bryan.e.baker@usace.army.mil

Ariane Pinson, Albuquerque District, U.S. Army Corps of Engineers, Albuquerque, NM, mailto:ariane.pinson@usace.army.mil

Sean Kimbrel, U.S. Bureau of Reclamation, Denver, CO, mailto:skimbrel@usbr.gov

Dr. Kate White, Headquarters, U.S. Army Corps of Engineers, Washington, DC, mailto:Kathleen.D.White@usace.army.mil

Ariane Pinson, Los Angeles District, U.S. Army Corps of Engineers, Los Angeles, CA, mailto:Amanda.R.WallerWalsh@usace.army.mil

Extended Abstract

Introduction

Drought in the U.S. has caused over $220B in estimated damages since 1980 (NOAA, 2016), and has led naturally to calls for increasing water storage in the nation's reservoirs. In the future, the duration, intensity, and frequency of drought is expected to increase in many parts of the US (USGCRP). At the same time, increased duration, intensity, and frequency of intense precipitation with the potential for large-scale flooding may also occur during droughts, driving the need to maintain or increase flood storage volumes in these same reservoirs. 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]. To balance these conflicting needs, accurate and current understanding of capacity of each pool is essential for assessing potential deviations in the operation of a reservoir to provide during drought periods.

While fixed water volumes or pool elevations may be defined for purposes of water operations, the actual capacity of each pool changes over time due to sediment influx to, movement through, and deposition with each reservoir. Sediment deposition is not confined to deadpool, but may occur anywhere in a reservoir. In addition, changing climate and land use cause the rate of sediment influx to vary from the design influx rate. Therefore, accurate information on current reservoir capacities is essential for routine reservoir operation as well as for planning and implementation 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.

Such surveys can be costly to implement, and in practice are deferred under today's constrained budget environment where operation and maintenance of aging dam infrastructure have a higher funding priority. Consequently, there is a need for a fast, systematic, accurate and cost-effective means to conduct periodic reservoir sediment surveys.

The National Drought Resilience Partnership (NDRP) was established in 2016 to coordinate Federal drought efforts. The objective of the NDRP was to reduce the vulnerability of communities to current and future drought through better coordination of Federal support for drought-related efforts. Under the NDRP, Federal agencies were charged with implementing policies and actions to achieve six key drought resilience goals, and the implementation plan for the NDRP, "Long-Term Drought Resilience: Federal Action Plan of the National Drought Resilience Partnership" (March 2016) charged U.S. Army Corps of Engineers (USACE) , in conjunction with the Bureau of Reclamation (Reclamation) with investigating new ways of conducting reservoir surveys at drought-induced low reservoir levels that would reduce the cost of reservoir surveys and produce data that could be readily shared with partners and stakeholders.

In response, U.S. Army Corps of Engineers (USACE) staff in conjunction with the U.S. Department of the Interior's Bureau of Reclamation (Reclamation) had begun to experiment with using airborne LiDAR to conduct surveys of reservoirs where drought and lowered reservoir levels exposing substantial portions of the reservoir bottom. Under NDRP, USACE and Reclamation saw an opportunity to test this approach of collecting terrestrial data normally underwater under none severe drought conditions at reservoirs in California, Arizona and Nevada.

This NDRP pilot study seeks to establish a set of standards for deployment of airborne LiDAR to collect topographic data at USACE and Reclamation reservoirs with the goal of creating detailed, geospatially-accurate estimates of current reservoir capacities and changes in these capacities over time. The resulting information is essential for water supply, flood risk management, navigation, recreation, and other planning activities at the Nation's reservoirs.

Methods and Results

Time-efficiencies and the resulting dense, georeferenced data already make airborne LiDAR a cost-effective method for obtaining topographic data for terrestrial areas. However, because LiDAR's difficulty penetrating water, LiDAR has not been widely used to estimate reservoir capacities. Deployment of airborne LiDAR during regional droughts provides an opportunity to collect areas in the reservoir more efficiently leaving a reduced area to be collected with bathometric type surveys.

The areas selected for the pilot effort are in the U.S. Southwest (Figure 1) where drought is ongoing in 2016. The study areas span two USACE Districts, Los Angeles and Sacramento, and two Reclamation Areas, Mid-Pacific and Lower Colorado. Multiple reservoirs were surveyed in each of the areas, including both USACE and Reclamation reservoirs, in order to take advantage of the spatial clustering of reservoirs with low water levels due to drought. The three areas where data collection were planned include: Oxnard (14 reservoirs) and Fresno (12 reservoirs), California, and Phoenix, Arizona (7 reservoirs) and are listed in Table 1.

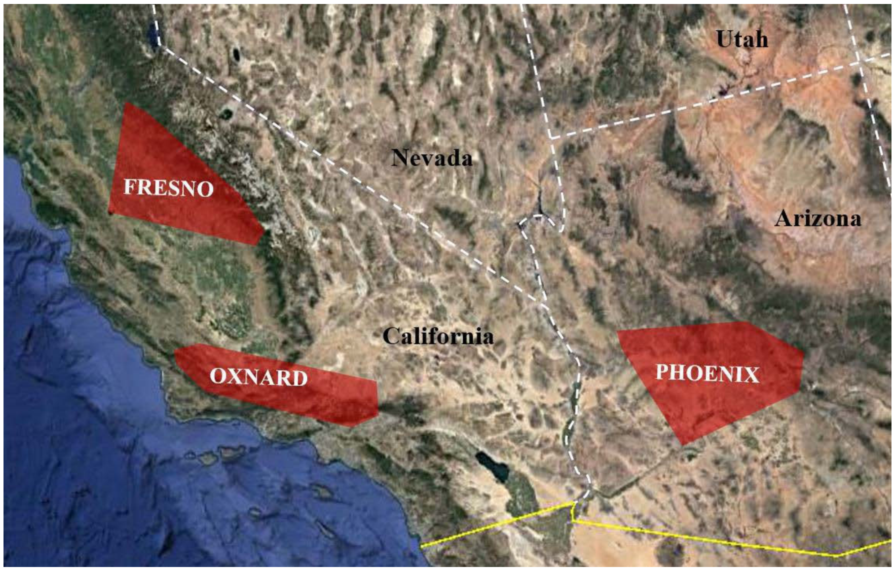

Figure 1 Location of flight areas, highlighted in red. Top left: Fresno CA based sites. Bottom left: Oxnard CA based sites. Bottom right: Phoenix AZ based sites.

Within these three drought-impacted areas, USACE reservoirs were prioritized for data collection based on three criteria:

- Extremely low reservoir water levels occurred 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 48,019 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, and because USACE reservoirs are positioned to receive this sediment when it rains, collection of LiDAR data at these reservoirs was a priority.

- Age since last survey was the third criteria. 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. Further, the lack of precision of older methods of determining remaining reservoir capacity for a given pool elevation mean that existing information on sedimentation rates may even be inaccurate for the period over which it was gathered.

The selection of BOR reservoirs for aerial LiDAR surveys was based on one main factor, which is whether the reservoir was at low water levels or less than 40% of total capacity. Several reservoirs have had at least one reservoir survey since dam closure and first filling of the reservoir, however most Reclamation reservoirs have not had a reservoir survey since dam closure.

The priority reservoirs selected for survey are listed in Table 1. The reservoirs share nearly uniform 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 established by the Drought Monitor (Source: U.S. Drought Monitor (http://droughtmonitor.unl.edu/). Most of the reservoirs had either never been surveyed, or have never been accurately surveyed using modern methods, such as LiDAR or SONAR.

Table 1 Status of USACE and Reclamation Reservoirs considered for inclusion in the pilot study.

Flight Area	Reservoir Name	Agency*	Initial Survey Year	Last Survey Year	Last Survey Method	Wildfire within last 5 years basin	Reservoir % Full (Oct 1, 2016)
Phoenix	Painted Rock	U	1953	1993	Satellite Imagery		0
Phoenix	Alamo	U	1968,63	1985	Bathymetric		4
Phoenix	Whitlow Ranch	U	1957, 39, 56	1984	Contour Map	Yes	0
Oxnard	Whitter Narrows	U	1948	2011	Contour Map	Yes	0
Oxnard	Carbon Canyon	U	1961, 37, 41, 49	2009	Contour Map	Yes	0
Oxnard	Brea	U	1939	1994	Contour Map		0
Oxnard	Fullerton	U	1941	1970	Contour Map		0
Oxnard	Santa Fe	U	1943	2010	Contour Map		0
Oxnard	Hansen	U	1940	2004	Contour Map		0
Oxnard	Lopez	U	1954	2010	Contour Map		0
Oxnard	San Antonio	U	1941	2010	Contour Map		0
Oxnard	Mojave River	U	1965, 62	Same	Contour Map	Yes	0
Oxnard	Isabella	U	1953	1977	Other/Unspecified	Yes	17
Fresno	Pine Flat	U	1973	1973	Range Line	Yes	16
Fresno	New Hogan	U	1959	1978	Other/Unspecified	Yes	25
Fresno	Eastman	U	1967	1975	Other/Unspecified	Yes	8
Fresno	Hensley	U	1967	1975	Other/Unspecified	Yes	19
Fresno	Kaweah	U	1961	1987	Other/Unspecified	No	17

Flight Area	Reservoir Name	Agency*	Initial Survey Year	Last Survey Year	Last Survey Method	Wildfire within last 5 years basin	Reservoir % Full (Oct 1, 2016)
Fresno	Bear	U	1968	1975	Other/Unspecified	No	0
Fresno	Burns	U	1968	1975	Other/Unspecified	No	0
Fresno	Mariposa	U	1968	1975	Other/Unspecified	No	0
Fresno	Owens	U	1968	1975	Other/Unspecified	No	0
Oxnard	Twitchell Reservoir	R	1958	--	Never Surveyed	Yes	0
Oxnard	Lake Cachuma	R	1953	1989	Contour Map	Yes	7
Fresno	San Luis	R	1967	--	Never Surveyed	No	25
Fresno	New Melones	R	1979	--	Never Surveyed	Yes	11
Phoenix	Horseshoe Reservoir	R	1949	--	Never Surveyed	Unknown	1
Phoenix	Theodore Roosevelt	R	1909	2013	Contour Map	Yes	36

** U= USACE, R=Reclamation*

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.

An important opportunity exists to increase the fidelity of sedimentation of a reservoir with LiDAR data collected at reservoirs, in a way that drives down unit costs and maximizes data collection efficiency. In times of drought, a reservoir may be completely or largely drawn down, dewatering an exceptionally large portion of the reservoir bottom. Drought, being a regional phenomenon, likely causes many reservoirs in a local area to experiencing conditions of low water elevations at the same time. This scenario makes it exceptionally cost-effective to fly LiDAR for all the drawn-down reservoirs in a region by reducing the number of unique flights and reducing many of the fixed costs associated with obtaining LiDAR data (primarily mobilization costs). Bathymetry collection via boat has mobilizations costs as well. This also minimizes the amount of sonar data need to be collected to complement the LiDAR data because the extent of the water surface is minimized. 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.

Post-collection data processing and archiving consists of five basic steps: data processing steps identify and correct errors present in the dataset and provides an estimate of the precision and accuracy of the data set; the processed data are then uploaded to a geospatial repository for dissemination; reservoir capacities are calculated for different levels of inundation and area-capacity curves; and finally, the area-capacity data and associated curves are loaded into the USACE sedimentation database.

Discussion

This study occurred within a larger NDRP 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 wadding 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.

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.

LiDAR data collection produces a significant cost reduction for data collection when compared to previous contracts and data collection efforts with transects and or SONAR technologies. Processing costs for LiDAR are generally constant and therefore a small reservoir would have a high cost per acre. One a whole, 28 reservoirs were collected totaling 203,156 acres using LiDAR technologies at a cost around $1.00 per acre in 2016 and is detailed in Table 2

Table 2 Cost details of USACE and Reclamation surveyed.

Flight Area	Reservoir Name	Agency*	Acres	Estimated Flight Time (min)	Estimated Total Cost	Estimated Cost Per Acre
Phoenix	Painted Rock	U	74,892	488	$13,181	$0.18
Phoenix	Alamo	U	14,525	325	$10,508	$0.72
Phoenix	Whitlow Ranch	U	1,322	75	$6407	$4.85
Oxnard	Whitter Narrows	U	4,325	80	$6,489	$1.50
Oxnard	Carbon Canyon	U	358	16	$5,439	$15.19
Oxnard	Brea	U	294	80	$6,489	$22.07
Oxnard	Fullerton	U	5,616	45	$5,915	$1.05
Oxnard	Santa Fe	U	1,810	76	$6,424	$3.55
Oxnard	Hansen	U	1,297	59	$6,145	$4.74
Oxnard	Lopez	U	82	22	$5,538	$67.53

Flight Area	Reservoir Name	Agency*	Acres	Estimated Flight Time (min)	Estimated Total Cost	Estimated Cost Per Acre
Oxnard	San Antonio	U	229	114	$7,047	$30.77
Oxnard	Mojave River	U	3,596	92	$6,686	$1.86
Oxnard	Isabella	U	7,738	215	$8,703	$1.12
Fresno	Pine Flat	U	5,866	140	$7,473	$1.27
Fresno	New Hogan	U	4,299	82	$6,522	$1.52
Fresno	Eastman	U	1,825	30	$6,161	$3.11
Fresno	Hensley	U	1,587	42	$5,866	$3.70
Fresno	Kaweah	U	1,864	75	$6,407	$3.44
Fresno	Bear	U	295	34	$5,735	$19.44
Fresno	Burns	U	709	60	$6,161	$8.69
Fresno	Mariposa	U	594	34	$5,735	$9.64
Fresno	Owens	U	198	22	$5,538	$27.97
Oxnard	Twitchell Reservoir	R	1,759	203	$8,507	$4.84
Oxnard	Lake Cachuma	R	4,693	101	$6,834	$1.46
Fresno	San Luis	R	20,403	241	$9,130	$0.45
Fresno	New Melones	R	11,757	228	$8,917	$0.76
Phoenix	Horseshoe Reservoir	R	3,334	102	$6,850	$2.05
Phoenix	Theodore Roosevelt	R	27,878	265	$9,524	$0.34

One key difference that must be highlighted 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.

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

- 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.

- To a get a complete bathymetric surface, the post-field data processing of LiDAR point clouds are significantly less than with single-beam SONAR for both LiDAR and multi-beam SONAR. There is a little additional preparation on the front end for calibration but once the survey is complete, quality control and getting it the data into the target mapping format remain.

- The LiDAR (as well as multi-beam SONAR) data products are very accurately georeferenced datasets. LiDAR resolution can be improved with added control points even after the data is 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 is backwardly compatible). The reverse is not true: you cannot build a complete reservoir bathymetry dataset from range line data.

The lessons learned to date are focused on maximizing cost efficiency, facilitating regional deployment, and strategies to reduce data co-registration 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.

- Additional studies are needed to better understand how changes in method, LiDAR vs. transects, vs. sonar, 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.

Conclusion

The NDRP lays out a framework under which federal agencies can collaborate to improve community resilience to current drought, whether or not future droughts last longer or occur more frequently. Droughts and floods accelerate and exacerbate the sedimentation problem while simultaneously increasing water demand and the nation's reliance on its reservoirs. Understanding how much sediment is accumulating in our reservoirs, and monitoring the rate of this accumulation, is essential for understanding the magnitude and geographic extent of this problem relative to the nation's water needs. The proposed approach to survey sediment deposition in drought-lowered reservoirs using a combination of LiDAR bathometric type surveys was found to be cost-effective for the 28 locations evaluated.

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