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Acknowledgments

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Abstract

During January 23–30, 2018, the U.S. Geological Survey, in cooperation with the Puerto Rico Electric Power Authority, conducted a bathymetric survey of Lago Carite primarily to update estimates of the contemporary reservoir storage capacity and sedimentation rate. Previously designated transect lines were surveyed by using a depth sounder coupled to a differential Global Positioning System to generate a bottom contour map and, ultimately, the stage-storage relation for Lago Carite. Survey results indicated that the storage capacity was 10.0 million cubic meters in 2018; no substantial sedimentation has occurred since the last survey in 1999 and the annual capacity loss is about 0.20 percent of the original reservoir capacity. The useful life of Lago Carite is projected to be 397 years, ending in 2415.

Introduction

The Lago Carite reservoir is located within the municipality of Guayama in southeastern Puerto Rico and is part of the Guayama Irrigation District (fig. 1). The reservoir impounds the headwaters of the Río de la Plata and has a drainage area of about 21.24 square kilometers (km^2) at the dam. The dam was constructed in 1913 and is an earth-filled structure with a spillway elevation of 543.64 meters (m) above mean sea level (Soler-López and Carrasquillo-Nieves, 2001). The original (1913) storage capacity of the reservoir was 13.95 million cubic meters (Mm^3) at the spillway elevation. Although the reservoir was originally constructed for power generation, about 5.46 million gallons per day (Mgal/d) are withdrawn (as of 2015) by the Farallon Water Treatment Plant to serve the municipalities of Caguas, Cayey, Cidra, and Guayama (Wanda Molina, U.S. Geological Survey, written commun., 2018). Withdrawals from Lago Carite also included those by the Guayama Irrigation District, providing about 1.86 Mgal/d of water in 2015 to agricultural lands (Wanda Molina, U.S. Geological Survey, written commun., 2018).

During January 23–30, 2018, the U.S. Geological Survey (USGS), in cooperation with the Puerto Rico Electric Power Authority, conducted a bathymetric survey of Lago Carite to update the reservoir storage capacity table and determine the reservoir sedimentation rate. The previous (1999) survey indicated the storage capacity was about 10.74 Mm^3 at the spillway elevation, and the estimated mean sedimentation rate was about of 37,000 cubic meters per year (Soler-López and Carrasquillo-Nieves, 2001). The 1999 survey collected a total of 14,264 data points and included 112 cross sections. The 1999 survey was preceded by another bathymetric survey conducted in 1986 (in Soler-López and Carrasquillo-Nieves, 2001), which indicated a storage capacity of 11.13 Mm^3 (Soler-López and Carrasquillo-Nieves, 2001) at a spillway elevation of 543.64 m.

Data from the 1986 survey are not available owing to restrictions (associated with the data being part of the original dam inspection report, which is considered sensitive in nature and not publicly available). Readers should contact the Puerto Rico Electric Power Authority for more information.

Methods of Survey and Analysis

Bathymetric data were collected and analyzed by using field procedures established by the USGS (Wilson and Richards, 2006). Major tasks completed during the bathymetric survey of Lago Carite included survey planning, data collection, and data post-processing. Survey planning involved the establishment of planned transect lines, which were the same as those established for the 1999 survey, and compilation of spatial data needed for the data collection and post-processing, namely aerial photography and reservoir shoreline location. The interval between planned transect lines was about 50 m, which was the same spacing used in the 1999 survey; however, additional transects were surveyed when beneficial, specifically, small reservoir branches found to be accessible and having sufficient water depths.

Water-depth data were collected using a bathymetric data collection system consisting of a digital depth sounder (fathometer) coupled to a differential Global Positioning System (DGPS) that enabled the measurement of water depths along previously established transect lines. The DGPS antenna was mounted at the depth sounder, and the collected water-depth data were horizontally referenced to the North American Datum of 1983 (NAD 83). The fathometer was calibrated each day prior to data collection by using the bar-check method; the accuracy of the fathometer is 1 centimeter, plus or minus 1 percent of the measured depth. All of the bathymetry data were collected by boat, and no terrestrial data were collected to delineate the shoreline. Manufacturer specifications for the equipment and the calibration process are presented in Gómez-Fragoso and Rosario (2020).

A total of 137 planned transect lines were surveyed, and over 269,110 water-depth measurements were made across the reservoir (fig. 2). The bathymetric survey began on January 23, 2018, and ended on January 30, 2018. In small reservoir branches having excessive debris or shallow water, it was difficult to safely navigate the boat and operate the fathometer; therefore, surveying was not conducted in these branches and reservoir bottom contours were interpolated based on the bathymetry contours of nearby areas. During the 2018 survey, the water-surface elevation at the reservoir varied between 0.62 and 0.68 m below the spillway elevation of 543.64 m above mean sea level, meaning that the raw water depth is referenced to the water-surface elevation at the time of the survey. The raw water-depth data were adjusted to represent depths below the spillway elevation of 543.64 m above mean sea level by using continuously monitored stage recorded at USGS station 50039995 at the Lago Carite spillway (fig. 1; https://nwis.waterdata.usgs.gov/nwis/sw). Hydrographic software was used to eliminate noise-data (spikes) prior to the transfer of raw water-depth data into the ArcGIS software geographic information system (GIS). The data generated during this study are available as a USGS data release (Gómez-Fragoso and Rosario, 2020).

All editing, interpolating, and processing of the corrected water-depth dataset were conducted by using the ArcGIS software developed by Esri (Esri, 2019). This computer software allows for spatial visualization of the reservoir shoreline and transect lines, creation of a bathymetric surface model, calculation of reservoir capacity, and the generation of reservoir bottom contours within a spatial mapping platform, among other capabilities. The reservoir shoreline was updated from the 1999 survey by using the edge of water depths and spatial data available for the reservoir, including a 2010 U.S. Army Corps of Engineers aerial photograph of the reservoir (U.S. Army Corp of Engineers, 2012) and USGS topographic maps (U.S. Geological Survey, 1960).

The methodology used to generate reservoir bathymetry included creating a triangulated irregular network (TIN) surface model, and subsequently, the bottom contours of the reservoir. These contours were smoothed by means of interpretive analysis and custom tools in the GIS software. The reservoir capacity was calculated at 1.0-m stage intervals from the smoothed TIN surface model. The TIN surface model of the 2018 survey was also used to compute the difference in reservoir bottom elevation between the 1999 and 2018 surveys.

The trapping efficiency method is widely used to estimate the volume of accumulated sediments in reservoirs and was used for this study. Estimating trapping efficiency is one of the most important elements in sedimentation analysis, because it allows for determination of sediment yield. The trapping efficiency is the total inflowing sediment, in percent, that is accumulated in a reservoir (Waters and Lewis, 2017). This method involves using empirically based curves developed by Brune (1953) and the reservoir capacity-inflow ratio (Mulu and Dwarakish, 2015).

The sediment yield was calculated by dividing the volume of sediment accumulated in the reservoir (2.92 Mm^3) by the average long-term trapping efficiency of the reservoir (94 percent), the contributing drainage area of the basin (20.03 km^2), and the number of years between construction of the reservoir in 1913 and the 2018 survey (105 years):

$$SY = \frac{SA}{TE * DA * T} \quad (1)$$

where

SY = sediment yield, in cubic meters per square kilometer per year;
SA = volume of sediment accumulated, in cubic meters;
TE = trapping efficiency, expressed as a decimal;
DA = contributing drainage area, in square kilometers; and
T = time between construction and present survey, in years.

Storage Capacity, Sedimentation Rate, and Useful Life

Analysis of the bathymetric survey data collected during January 2018 indicated that the storage capacity of Lago Carite is 11.0 Mm^3 at a water-surface elevation of 543.64 m above mean sea level (table 1). This storage capacity represents a reduction of 21 percent since reservoir construction (table 2). Because a decrease in capacity following the 1999 survey was expected, on June 29, 2018, additional water-depth data (available in Gómez-Fragoso and Rosario, 2020) were collected at selected locations to confirm the results of the January 23–30, 2018, survey. Bathymetric data from the June 29, 2018, survey confirmed that the data obtained from the January 23–30, 2018, survey were correct. A bathymetric map showing the reservoir-bottom contours for Lago Carite is presented in figure 3, with depths referenced to the spillway elevation. The maximum reservoir depth is about 20 m.

Comparison of the stage-volume relations for the 1999 and 2018 surveys indicates that little bathymetric change occurred between the two surveys (fig. 4). In addition, results of the comparison indicate that sedimentation is scattered throughout the reservoir and that sediment accumulation is not substantial in many areas; in fact, substantial areas show scour, rather than accumulation (fig. 5). Although uncertainties may exist in the capacity calculations because of the initial survey settings, selection of transect intervals, GIS interpolation, and differences in analyses, the 2018 survey results indicate that Lago Carite did not receive a substantial sediment influx between 1999 and 2018, and that suitable conditions exist for the extension of the useful life of this reservoir.

Table 1. Elevation-capacity table for Lago Carite, Puerto Rico, January 2018.

Water-surface elevation (meters above mean sea level)	Capacity (million cubic meters)
543.64	11.00
542.64	9.91
541.64	8.85
540.64	7.86
539.64	6.94
538.64	6.08
537.64	5.28
536.64	4.54
535.64	3.86
534.64	3.23
533.64	2.66
532.64	2.14
531.64	1.69
530.64	1.29
529.64	0.95
528.64	0.67
527.64	0.45
526.64	0.29
525.64	0.16
524.64	0.07
523.64	0.00

Table 2. Summary of 1986, 1999, and 2018 bathymetric surveys and sedimentation analysis of Lago Carite, Puerto Rico.

Data descriptor	Year of survey		
	1986[1]	1999[1]	2018
Total capacity, in million cubic meters	11.13	10.74	11.03
Years since the 1913 dam construction	73	86	105
Sediment accumulation, in million cubic meters	2.82	3.21	2.92
Long-term storage loss, in percent	20	23	23
Long-term annual loss of capacity, in million cubic meters per year	0.039	0.037	0.028
Annual loss of capacity, in percent	0.28	0.27	0.20
Sediment trapping efficiency, in percent	95	96	94
Long-term sediment yield, in cubic meters per square kilometer per year	2,030	1,940	1,480
Estimated year the reservoir will be filled with sediment	2,274	2,289	2,415

[1]Soler-López and Carrasquillo-Nieves (2001).

The 2018 survey results indicate that accumulated sediments at Lago Carite total about 2.92 Mm^3 (table 2), which represents an annual loss of capacity of 0.028 million cubic meters per year (Mm^3/yr) for the period from 1913 to 2018. Comparison of results of the 2018 survey to those of the 1999 survey indicated that the estimated annual loss of capacity decreased from 0.27 to 0.20 percent for Lago Carite. As described earlier, data from the 1999 and 2018 surveys indicate that the storage capacity of Lago Carite has remained nearly constant during the last 20 years. Unlike the 2018 survey, the 1999 survey had limited access to some areas because of low water levels, and fewer water-depth data points were collected (Soler-López and Carrasquillo-Nieves, 2001). The smaller dataset for the 1999 survey may have necessitated more interpolation compared to the 2018 survey and potentially could explain the small (0.29 Mm^3) reservoir capacity increase from 1999 to 2018.

The sediment trapping efficiency of Lago Carite, determined from the 2018 sediment analysis, is about 94 percent and was calculated by using a storage capacity-mean annual inflow ratio of 0.32 and the empirically based curve of Brune (1952). Because no streamgaging stations were available within the Lago Carite Basin to determine the mean annual inflow into Lago Carite, the estimated mean annual inflow of 33.99 Mm^3 was calculated by multiplying the 21.24-km^2 drainage area by an estimated mean annual runoff of 1,600 millimeters (mm). The annual runoff was calculated by multiplying (1) the average ratio of runoff to rainfall (0.90) as described in Soler-López and Carrasquillo-Nieves (2001) by (2) the mean annual rainfall of 1,778 mm for the period from 1981 to 2010 (National Oceanic and Atmospheric Administration, 2010).

The 2018 survey data indicated that the mean sediment yield of Lago Carite is about 1,480 cubic meters per square kilometer per year for the period from 1913 to 2017 (table 2). The sediment contributing drainage area used for the sediment yield analysis equals the total drainage area at the dam site (21.24 km^2) minus the water surface area (1.21 km^2). The long-term sediment yield rate of 1,480 cubic meters per square kilometer per year is about 24 percent lower than the 1999 survey estimate (table 2).

The projected useful life of Lago Carite is 397 years, ending in 2415 when the reservoir is projected to fill with sediment. This projection is defined as the time remaining until the reservoir is 100 percent full of sediment and is based on the long-term annual storage capacity loss of 0.028 Mm^3/yr computed for the period from 1913 to 2018. The estimate is 126 years longer than the 1999 estimated useful life, which was projected to end in 2289 (Soler-López and Carrasquillo-Nieves, 2001). This apparent difference is judged reasonable, because the estimated long-term annual loss of capacity was lower for the 2018 survey than for the 1999 survey.

Summary

A bathymetric survey of Lago Carite was conducted during January 23–30, 2018, by the U.S. Geological Survey, in cooperation with the Puerto Rico Electric Power Authority, to update estimates of the reservoir storage capacity and the sedimentation rate of the reservoir. A total of 137 previously designated transect lines were surveyed by using a depth sounder coupled to a differential Global Positioning System to generate a bathymetric contour map and, ultimately, the elevation-capacity relation for Lago Carite. Survey results indicated the reservoir storage capacity of 11.0 million cubic meters in 2018 was similar to the capacity of 10.7 million cubic meters in 1999. A bathymetric map of Lago Carite created as part of the study indicated the maximum depth was about 20 meters below the spillway elevation of 543.64 meters above mean sea level. Survey results indicated that no substantial sedimentation has occurred since the last survey in 1999 and that the annual capacity loss is about 0.20 percent of the original capacity. Lago Carite has a 94-percent trapping efficiency, as determined from an empirically developed relationship. Based on a constant long-term annual loss of capacity of 0.028 million cubic meters per year for the period from 1913 to 2018, the useful life of Lago Carite is projected to be 397 years, ending in 2415.

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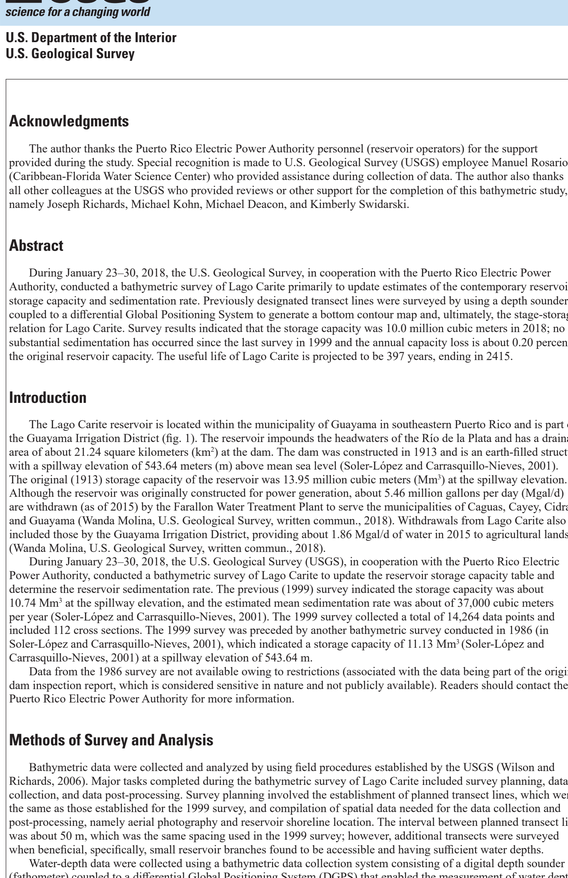

Figure 1. Location of Lago Carite in the Río de la Plata Basin, Puerto Rico.

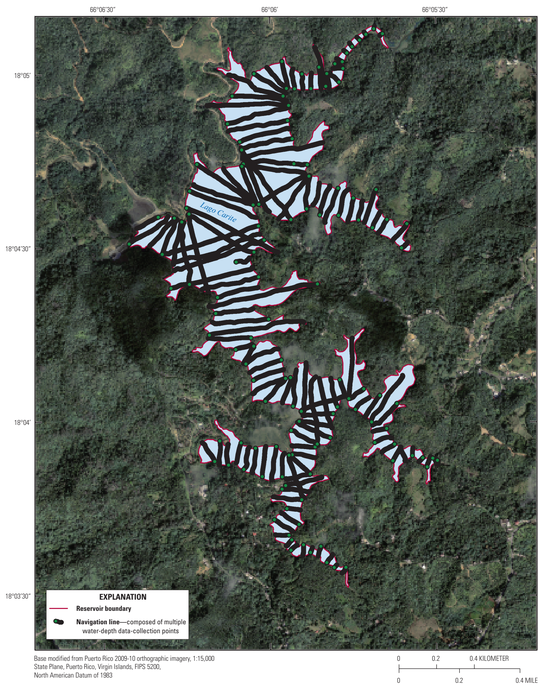

Figure 2. Location of collected water-depth data points at Lago Carite, Puerto Rico, January 2018. Aerial orthoimagery courtesy of U.S. Army Corps of Engineers, Jacksonville, Geomatics Section.

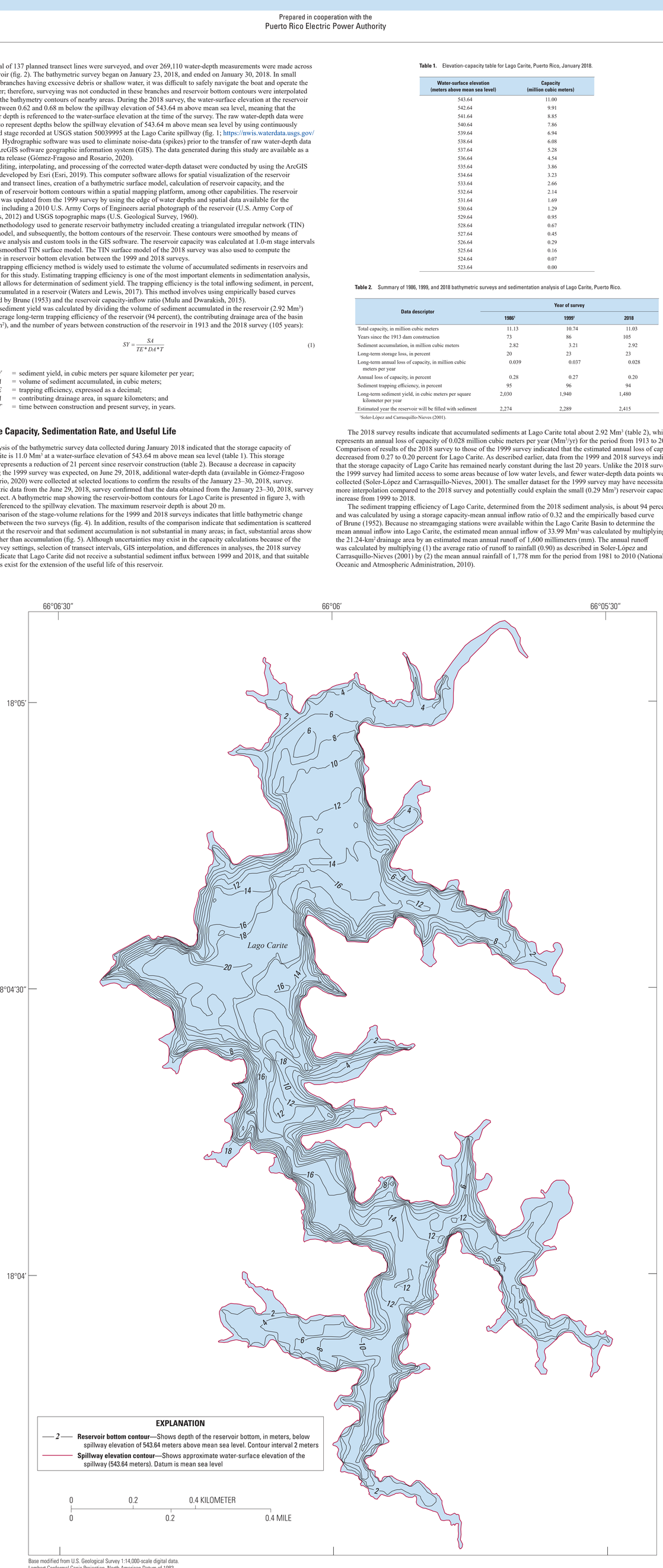

Figure 3. Bathymetric map of Lago Carite, Puerto Rico, January 2018.

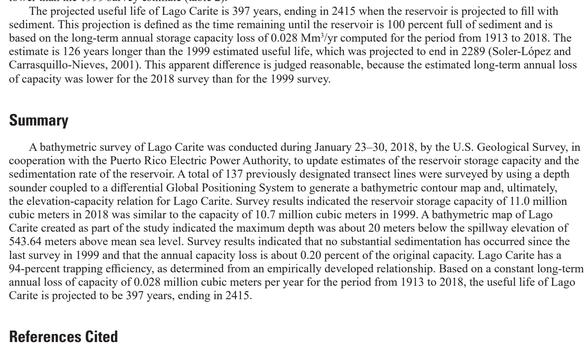

Figure 4. Elevation-capacity curves for the 1999 and 2018 bathymetric surveys of Lago Carite, Puerto Rico.

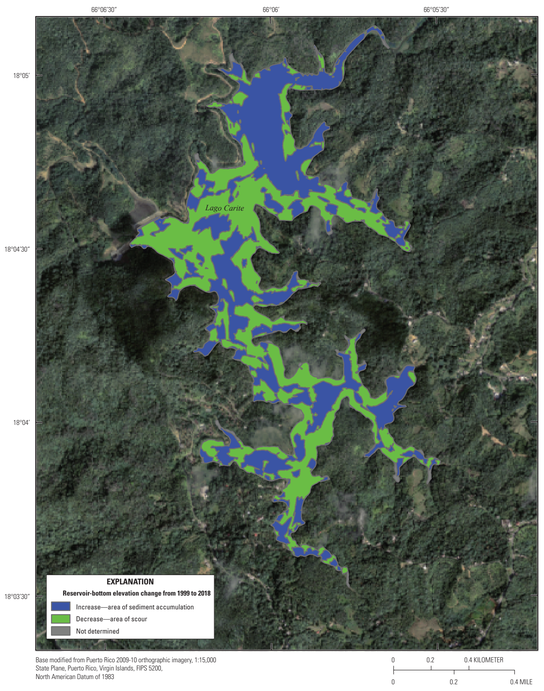

Figure 5. Changes in reservoir-bottom between 2018 and 1999 bathymetric surveys of Lago Carite, Puerto Rico. Aerial orthoimagery courtesy of U.S. Army Corps of Engineers, Jacksonville, Geomatics Section.

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Bathymetric Survey and Sedimentation Analysis of Lago Carite, Puerto Rico, January 2018

By

Julieta M. Gómez-Fragoso

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