U.S. Department of the Interior
U.S. Geological Survey

Prepared in cooperation with the
Puerto Rico Electric Power Authority

Scientific Investigations Map 3442

Abstract

The U.S. Geological Survey, in cooperation with the Puerto Rico Electric Power Authority, conducted a sedimentation survey of Lago Guayabal in 2017 to determine reservoir infill sedimentation rates, generate a bathymetric map of the bottom elevations of the reservoir, and create a stage-volume relation. The original (1913) capacity of Lago Guayabal was 11.82 million cubic meters, and efforts to increase the storage capacity were made in 1950 by the installation of flashboards. The 2017 survey indicated that storage capacity of Lago Guayabal is 4.98 million cubic meters. The estimated full sediment infill of Lago Guayabal is expected in 77 years, based on the long-term sedimentation rate of 0.065 million cubic meters per year determined for the 1972–2017 period.

Introduction

Lago Guayabal is a reservoir located within the municipalities of Juana Díaz and Villalba in southern Puerto Rico and is part of the Juana Díaz Irrigation District (fig. 1). The reservoir was constructed in 1913, is operated and owned by the Puerto Rico Electric Power Authority (PREPA), and has a normal pool elevation of 103.94 meters (m) above mean sea level (PREPA, 1988). Lago Guayabal Dam is a concrete gravity structure; the drainage area of Río Jacaguas Basin at the damsite is approximately 112 square kilometers (km^2), 57.5 km^2 of which is impounded by Lago Toa Vaca Dam on Río Toa Vaca (Soler-López, 2003).

The original capacity of Lago Guayabal, based on a pre-impoundment survey conducted in 1913, was 11.82 million cubic meters (Mm^3). Nine sedimentation analyses have been conducted since the dam was constructed, and the results indicate long-term impairment of the storage capacity of the reservoir. Soil series within the basin include Caguabo and Humatas, which are susceptible to erosion (Soil Conservation Service, 1979). Countermeasures intended to increase storage capacity, such as dredging and sluicing, were conducted between 1940 and 1948 (Soler-López, 2003); however, impairment of the storage capacity has continued despite those efforts. The previous sedimentation survey, conducted in 2006, indicated that Lago Guayabal had lost approximately 50 percent of its original capacity (Soler-López, 2008). In 2017, the U.S. Geological Survey (USGS), in cooperation with PREPA, conducted a sedimentation survey of Lago Guayabal to determine the reservoir infill sedimentation rate, generate a bathymetric map of the reservoir, and create a stage-volume relation.

This report summarizes results of the 2017 sedimentation survey and compares them with the results of previous bathymetric surveys conducted in 2001 and 2006 (Soler-López, 2003, 2008). Other findings presented herein are estimates of sediment yield, trapping efficiency, and long-term annual loss of storage capacity.

Methods of Survey and Analysis

The sedimentation survey was conducted during December 11–14, 2017. Field data collection involved measuring water depth along predetermined navigation lines and following the same navigation lines established in previous sedimentation surveys (Soler-López, 2003, 2008). The spacing between navigation lines was approximately 50 m (fig. 2), although additional navigation lines were added when needed to include some small accessible tributaries that were either inaccessible or not considered in previous bathymetry surveys. A total of 60 navigation lines were used to collect over 270,000 water-depth points across the reservoir. Small reservoir tributaries and other areas having excessive debris or shallow water depths of less than 1 m were excluded from the survey because of equipment limitations. The fact that no water-depth data are collected in shallow areas should be considered as an element of uncertainty in the final calculation of reservoir volume. The initial attempt to conduct a bathymetric survey of Lago Guayabal in September 2017 was interrupted by the passage of Hurricane Maria. Several navigation lines were surveyed before Hurricane Maria made landfall (fig. 3), and a comparison of data collected on both bathymetric surveys is presented later herein.

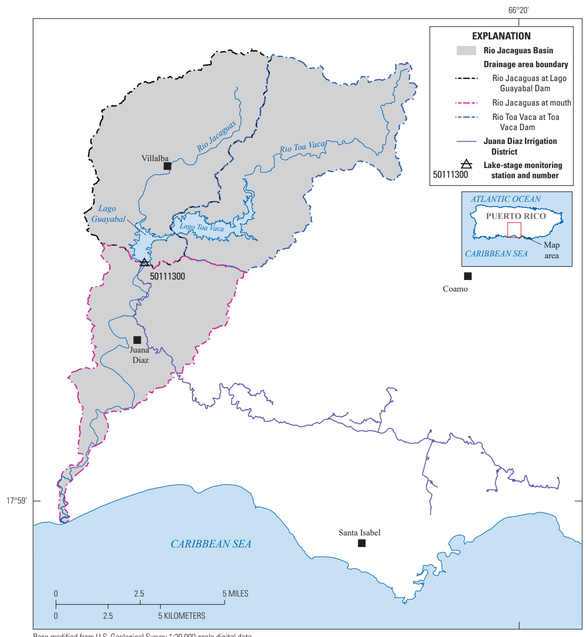

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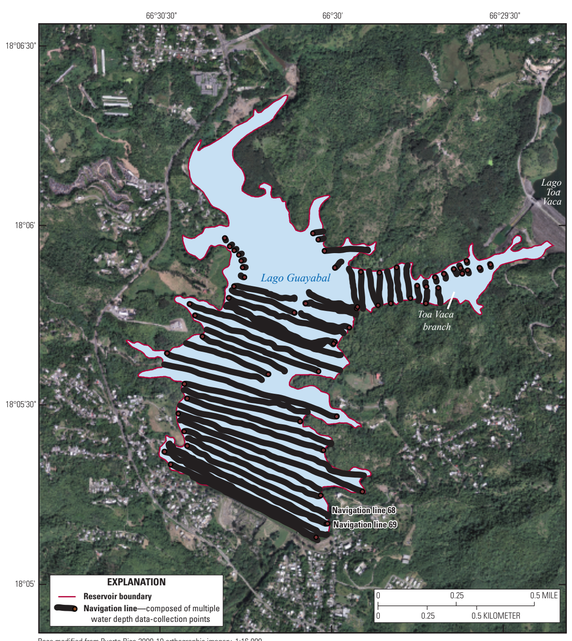
Figure 1. Lago Guayabal in the Rio Jacaguas Basin, Puerto Rico.



Base modified from Puerto Rico 2009-10 orthographic imagery, 1:16,000
State Plane, Puerto Rico Virgin Islands, FIPS 5200
North American Datum of 1983

Figure 2. Bathymetric survey navigation lines in Lago Guayabal, Puerto Rico, December 2017. Aerial orthoimagery courtesy of the U.S. Army Corps of Engineers, Jacksonville District, Geomatics Section.

All water-depth data were collected using a digital depth sounder coupled to a differential Global Positioning System (GPS). The digital depth sounder, an Echotrac CVM developed by Teledyne Odom Hydrographics, has an accuracy of 0.01 m ± 0.1 percent for the water depth data, and the geographic position data have a precision of less than 2 m. The collected water-depth data were horizontally referenced to the North American Datum of 1983 (NAD 83). The depth sounder (fathometer) was calibrated each day prior to data collection using the bar-check method (Wilson and Richards, 2006). The results of each bar-check measurement and further information about the equipment are included in a USGS data release associated with this survey (Gómez-Fragoso and Rosario, 2019).

The raw water-depth data were corrected to the spillway-crest elevation of 103.94 m, referenced to mean sea level, by using continuously monitored water-surface elevations recorded every 15 minutes at USGS gaging station 50111300, Lago Guayabal at Damsite near Juana Díaz, PR (fig. 1; https://waterdata.usgs.gov/pr/nwis/uv?site_no=50111300). The measurements made by the depth sounder therefore represent reservoir-bottom depths below the spillway-crest elevation. The corrected data points were generated by adding the difference between the spillway-crest elevation and monitored water-surface elevations to the raw water-depth data based on the time each transect was navigated. Data generated during this study are available as a USGS data release (Gómez-Fragoso and Rosario, 2019).

Bathymetric survey data were postprocessed using Esri ArcGIS software, version 10.5 (Esri, 2017). The workflow included (1) correction of water-depth points, (2) generation of a triangulated irregular network (TIN) surface model from the corrected data points using the Create TIN tool in the 3D Analyst extension, (3) generation of bathymetric contours from the TIN model using the Surface Contour tool, (4) smoothing of bathymetric contours (manually edited), and (5) calculation of reservoir volume at 1-m intervals from the TIN surface model using the Surface Volume tool. In areas where bathymetric data were not collected, bathymetric contours were interpolated based on bathymetry contours in nearby areas. The reservoir shoreline used for the calculation of volume is the same reservoir extent used in previous surveys. A map showing bathymetry contours for Lago Guayabal is presented in figure 4.

TIN surface models created from the 2006 and 2017 sedimentation surveys were used to generate a surface map showing those areas within the survey extent with either historical net sedimentation accumulation (gain) or scour (loss) (fig. 5). The 2006 and 2017 surveys were compared by using the Surface Difference tool (Esri ArcGIS software, version 10.5). In addition, two cross-sectional profiles were generated for comparison with profiles from the 2006 and 2017 studies; the cross-section locations are shown in figure 6.

Besides generating a bathymetric contour map and the calculation of reservoir volume, the postprocessing of the collected data included the determination of the sediment yield for Lago Guayabal. Sediment yield is defined as the total sediment outflow throughout a measurable point from a catchment or drainage basin measurable for a specific period of time (Griffiths and others, 2006). The sediment yield of the Río Jacaguas at Lago Guayabal Dam Basin was determined by dividing the volume of sediment accumulated in the reservoir by the product of the average long-term trapping efficiency of the reservoir, the contributing drainage area of the basin (minus the surface area of the reservoir), and the number of years between the construction of Lago Toa Vaca Dam and the present survey:

$$\text{Sediment yield} = \frac{SA}{TE * DA * T}, \quad (1)$$

where

SA is the volume of sediment accumulated,
TE is the trapping efficiency,
DA is the contributing drainage area, and
T is the number of years between dam construction and present survey.

Storage Capacity, Sedimentation Rate, and Useful Life

Computation of reservoir volume from the TIN surface model indicated that the 2017 storage capacity of Lago Guayabal with flashboards was 4.98 Mm^3 at a water-surface elevation of 103.94 m above mean sea level (table 1), which represents 42 percent of the original storage capacity of 11.82 Mm^3 (PREPA, 1988). The stage-volume relation is provided for elevations above 91.94 m above mean sea level. Despite the installation of flashboards in 1950, which increased the storage capacity to 12.09 Mm^3 (Soler-López, 2003), the storage capacity with flashboards had decreased by 7.11 Mm^3 by 2017 (table 2). This reduction in capacity represents an annual loss rate of 0.11 million cubic meters per year (Mm^3/yr) since the installation of the flashboards. The long-term loss of storage capacity is 59 percent and indicates that Lago Guayabal is losing approximately 0.9 percent of its original storage capacity annually.

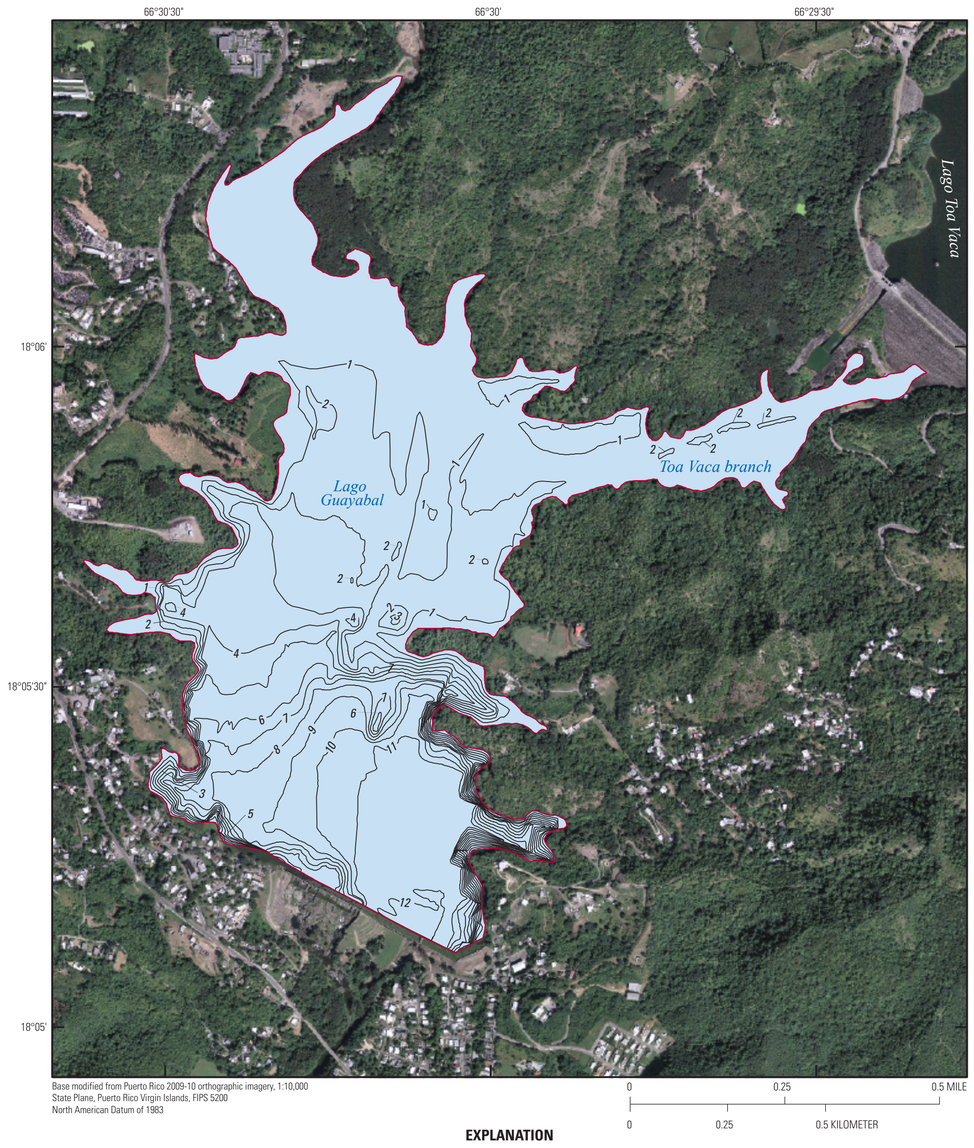
A previous survey conducted in 2006 indicated a 5.82-Mm^3 loss of storage capacity (Soler-López, 2008). Subtracting the 4.98-Mm^3 loss of storage capacity indicated by the 2017 survey from the 2006 loss yields an intersurvey sediment accumulation of about 0.84 Mm^3 from 2006 to 2017 (table 2). This accumulation corresponds to a rate of capacity loss of 0.08 Mm^3/yr from 2006 to 2017, which is slightly greater than the 0.06-Mm^3/yr rate from 2001 to 2006, but less than the 0.11-Mm^3/yr rate from 1950 to 2017. The slight increase in the rate of intersurvey accumulation from 2006 to 2017 relative to that from 2001 to 2006 might be attributed to high sediment influx to the reservoir resulting from the passage of Hurricane Maria on September 20, 2017, and the longer period between the latter two sedimentation studies. Sediment accumulation along the extent of the selected cross sections was somewhat uniform, as indicated by comparison of cross sections generated from the 2006 and 2017 TIN models of Lago Guayabal (fig. 7).

Several factors contribute to the impairment of reservoirs by increased sediment influx, including urbanization, agricultural activities, and runoff associated with rainfall events. Comparison of other bathymetric surveys conducted at reservoirs in Puerto Rico indicates that the passage of hurricanes can affect storage capacity (Gellis, 1993). Comparison of depths along two of the navigation lines used in the September and December 2017 surveys indicated that the storage capacity of Lago Guayabal was affected by the torrential rainfall associated with Hurricane Maria (fig. 8).

One alternative method for estimating the accumulation of sediment in a reservoir is the trapping efficiency method, which utilizes empirically based curves developed by Brune (1953). This method relates trapping efficiency (defined as the ratio of deposited sediments to the total sediment inflow) to the ratio of storage capacity and annual water inflow volume, also known as the capacity-inflow (C/I) ratio (Mulu and Dwarakish, 2015). At the time of the December 2017 survey, the sediment-trapping efficiency of Lago Guayabal was 93 percent, calculated using a storage capacity to mean annual inflow ratio of 0.20 (from Brune's empirically based curve). The mean annual sediment inflow (24.55 Mm^3) needed to compute the storage capacity-mean annual inflow ratio was computed using a contributing drainage area of 54.5 km^2 and an estimated annual runoff of 453 millimeters. To estimate annual runoff, the average ratio of runoff to rainfall developed by Giusti and López (1967) was multiplied by the mean annual rainfall of 1,812 millimeters for the period from 1981 to 2010 (National Oceanic and Atmospheric Administration, 2010).

The contributing drainage area of 54.5 km^2 used for the sediment yield analysis is the reduced drainage area following the construction of Lago Toa Vaca Dam in 1972. The storage capacity of Lago Guayabal that year was 7.89 Mm^3. The volume of sediment accumulated from 1972 to 2017 is the difference in storage capacities determined for the 1972 and 2017 bathymetric surveys: 7.89 Mm^3 − 4.98 Mm^3 = 2.91 Mm^3. Dividing the volume of accumulated sediment by the trapping efficiency (0.93) yields a net volume of 3.13 Mm^3 of sediment eroded from within the drainage basin. The net sediment volume was divided by the contributing drainage area of the basin (the 54.5-km^2 total drainage area minus the 1.25-km^2 surface area of the reservoir), and the number of years (45) since the reduction in drainage area. The sediment yield of Lago Guayabal was calculated to be 1,312 cubic meters per square kilometer, per year ([m^3/km^2]/yr), for the 1972–2017 period. This sediment yield rate is about 6 percent higher than the 1,232-(m^3/km^2)/yr rate estimated for the 1972–2006 period.

The projected useful life of a reservoir is defined as the time remaining until the reservoir is 100 percent full of sediment. The projected useful life of Lago Guayabal was determined by dividing the 2017 storage capacity by a storage capacity loss of 0.065 Mm^3/yr, which was computed as the difference in storage capacities determined for the 1972 and 2017 surveys. Assuming a constant sedimentation rate, the projected useful life of Lago Guayabal—defined as the estimated time when the reservoir is projected to fill with sediment—is about 77 years, ending in 2094. This projection is 8 years earlier than the former projection of 2102 by Soler-López (2008). It is unclear which factors contributed to the reduction in useful life of Lago Guayabal, but torrential rainfall from Hurricane Maria may have been a significant factor (fig. 8).



Base modified from Puerto Rico 2009-10 orthographic imagery, 1:10,000
State Plane, Puerto Rico Virgin Islands, FIPS 5200
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Figure 4. Bathymetry of Lago Guayabal, Puerto Rico, December 2017. Aerial orthoimagery courtesy of the U.S. Army Corps of Engineers, Jacksonville District, Geomatics Section.

Summary

In December 2017, the U.S. Geological Survey, in cooperation with the Puerto Rico Electric Power Authority, conducted a sedimentation survey of Lago Guayabal to determine reservoir infill sedimentation rates, generate a bathymetric map of the bottom elevations of the reservoir, and create a stage-volume relation. From water-depth points measured along predetermined navigation lines during the survey, a triangulated irregular network model of the bathymetric surface was created by using version 10.5 of Esri ArcGIS software. The triangulated irregular network model was used to generate bathymetric contours and compute the storage capacity at 1-meter (m) intervals from an elevation of 91.94 m above mean sea level to the spillway elevation of 103.94 m. The results of the sedimentation survey reflected the continued impairment of the storage capacity of Lago Guayabal, with an accumulation of 7.11 million cubic meters (Mm^3) of sediment since the installation of flashboards in 1950, which increased the storage capacity to 12.09 Mm^3. The long-term annual loss in storage capacity of 0.9 million cubic meters per year did not change between the 2006 and 2017 surveys. A comparative analysis of several transects surveyed prior to the passage of Hurricane Maria showed that the runoff associated with the storm contributed to the sedimentation infill of the reservoir.

The storage capacity of Lago Guayabal decreased from 5.82 Mm^3 in 2006 to 4.98 Mm^3 in 2017. Although the intersurvey sediment accumulation rate of 0.84 Mm^3 for the 11-year period prior to the 2017 survey is more than twice the rate of 0.30 Mm^3 computed from the 5-year period prior to the 2006 survey, the intersurvey annual loss of storage capacity is similar for the 2006 and 2017 studies. The depth of sediment accumulation was somewhat uniform along longitudinal profiles of the reservoir, averaging about 1 m in thickness. As determined from an empirically developed relationship, the trapping efficiency of Lago Guayabal is approximately 93 percent, and the computed long-term sediment yield increased slightly from 1,232 to 1,312 cubic meters per square kilometer, per year, from 2006 to 2017. Based on a constant long-term sedimentation rate of 0.06 million cubic meters per year for the 1972–2017 period, the full sediment infill of Lago Guayabal is estimated to be 77 years, ending in 2094.

Acknowledgments

The authors thank the reservoir operators at the Puerto Rico Electric Power Authority for their support during the study. The authors also thank all colleagues at the USGS who provided reviews or other support for the completion of this bathymetric study, namely Michael Kohn, Daniel Wagner, Amanda Whaling, Michael Deacon, and Kimberly Swidarski. Special recognition is made to hydrologist Luis Soler (USGS, retired) and geographic information system (GIS) specialist Marilyn Santiago (USGS), who helped during the analysis.

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Table 1. Storage capacity of Lago Guayabal, Puerto Rico, December 2017.

Pool elevation (meters above mean sea level)	Volume (million cubic meters)
103.94	4.98
102.94	3.91
101.94	3.15
100.94	2.57
99.94	2.09
98.94	1.66
97.94	1.29
96.94	0.95
95.94	0.65
94.94	0.41
93.94	0.21
92.94	0.07
91.94	0.00

Table 2. Comparison of 2001, 2006, and 2017 sedimentation survey results for Lago Guayabal, Puerto Rico.

Data descriptor	Year of survey		
	2001[a]	2006[b]	2017
Total capacity, in million cubic meters	6.12	5.82	4.98
Years since installation of flashboards	51	56	67
Years since dam construction	88	93	104
Sediment accumulation, in million cubic meters[c]	5.97	6.27	7.11
Intersurvey sediment accumulation, in million cubic meters	0.64	0.30	0.84
Long-term storage loss, in percent[d]	49	52	59
Long-term annual loss of capacity, in million cubic meters per year[e]	0.12	0.11	0.11
Annual loss of capacity, in percent	1.0	0.9	0.9
Intersurvey annual loss of capacity, in million cubic per meters per year	0.04	0.06	0.08
Sediment trapping efficiency, in percent	93	93	93
Long-term sediment yield, in cubic meters per square kilometer per year[f]	1,237	1,232	1,312
Estimated year the reservoir will be filled with sediment	2,101	2,102	2,094

[a]Soler-López (2003).
[b]Soler-López (2008).
[c]Sediment accumulation since the flashboards were installed in 1950.
[d]Long-term storage loss since the flashboards were installed in 1950.
[e]Long-term annual loss of capacity since the flashboards were installed in 1950.
[f]Long-term sediment yield since the construction of Lago Toa Vaca dam in 1972.

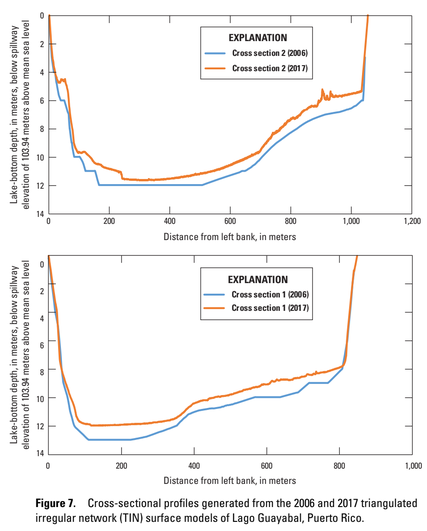

Figure 7. Cross-sectional profiles generated from the 2006 and 2017 triangulated irregular network (TIN) surface models of Lago Guayabal, Puerto Rico.

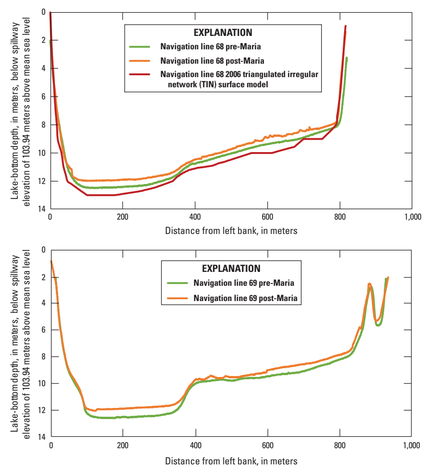

Figure 8. Cross-sectional profiles of Lago Guayabal, Puerto Rico, for September 2017 survey, prior to the passage of Hurricane Maria, and for December 2017 survey.

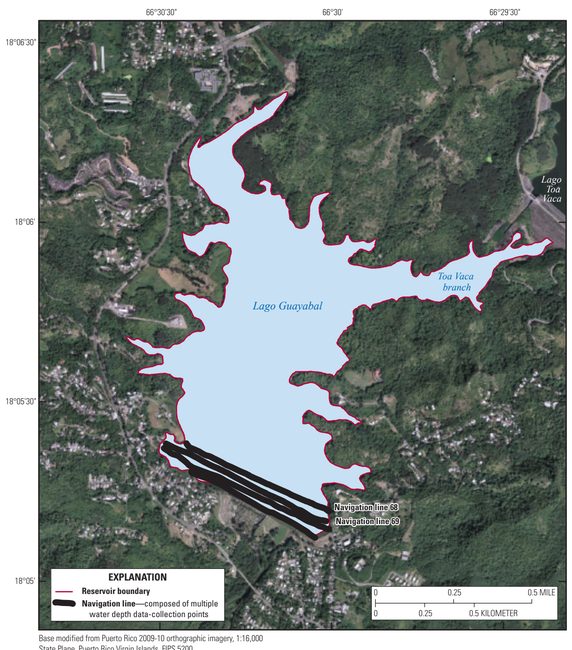

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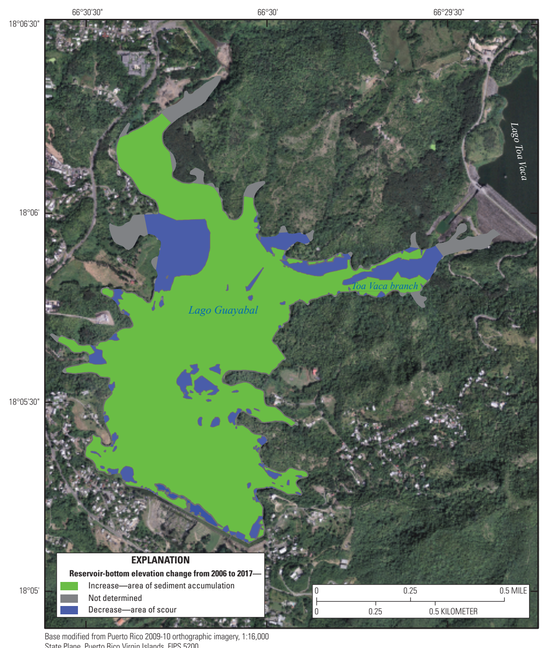
Figure 3. Bathymetric survey navigation lines in Lago Guayabal, Puerto Rico, September 2017, prior to the passage of Hurricane Maria. Aerial orthoimagery courtesy of the U.S. Army Corps of Engineers, Jacksonville District, Geomatics Section.



Base modified from Puerto Rico 2009-10 orthographic imagery, 1:16,000
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Figure 5. Changes in reservoir-bottom elevation between 2006 and 2017 bathymetric surveys of Lago Guayabal, Puerto Rico. Aerial orthoimagery courtesy of the U.S. Army Corps of Engineers, Jacksonville District, Geomatics Section.

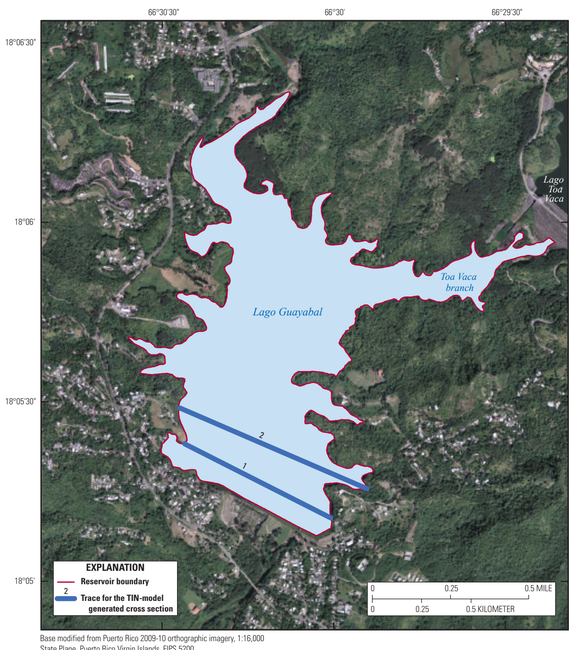

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Figure 6. Selected cross sections generated by triangulated irregular network (TIN) surface model for Lago Guayabal, Puerto Rico, December 2017. Aerial orthoimagery courtesy of the U.S. Army Corps of Engineers, Jacksonville District, Geomatics Section.

Sedimentation Survey of Lago Guayabal, Villalba, Puerto Rico, December 2017

By
Julieta Gómez-Fragoso and Manuel Rosario
2019

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Suggested citation: Gómez-Fragoso, J.M., and Rosario, M., 2019, Sedimentation survey of Lago Guayabal, Villalba, Puerto Rico, December 2017: U.S. Geological Survey Scientific Investigations Map 3442, 1 sheet, https://doi.org/10.3133/sim3442.

Associated data for this publication: Gómez-Fragoso, J., and Rosario, M., 2019, Sedimentation survey data for Lago Guayabal, December 2017: U.S. Geological Survey data release, https://dx.doi.org/10.5066/P9FD12Y5.

ISSN 2329-132X (online)