Acknowledgments

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Abstract

In August 2019, the U.S. Geological Survey, in cooperation with the Puerto Rico Electric Power Authority, conducted a bathymetric survey of Lago Patillas to update stage-volume data in order to determine the sediment infill rates and to generate a bathymetry map. Water-depth data were collected along predefined lines using single-beam depth sounder and Differential Global Positioning System technology. The study also included delineating a new reservoir shoreline based on 2016–17 light detection and ranging data and the establishment of a new official vertical datum at the reservoir referenced to the Puerto Rico Vertical Datum of 2002 (PRVD02). Survey results indicated that the storage capacity was 12.96 million cubic meters in 2019 at an elevation of 67.55 meters above PRVD02. The mean annual loss of capacity from 1961 to 2019 is 0.08 million cubic meters per year. The point of zero remaining storage of Lago Patillas is projected to be 161 years, ending in 2180.

The new vertical datum referenced to PRVD02 was established at Lago Patillas by conducting a Global Navigation Satellite System static observation in March 2019, which indicated that the spillway elevation is 67.55 meters. The new spillway elevation datum supersedes the previous datum (mean sea level) used on the island of Puerto Rico.

Introduction

Lago Patillas is a reservoir located in the municipality of Patillas about 8 kilometers northeast of the town of Arroyo (fig. 1). The reservoir impounds waters from Río Grande de Patillas at Lago Patillas Dam (hereafter called Río Grande de Patillas) and Río Marín Basins and was constructed for the irrigation of croplands in the southern coastal plains of Puerto Rico. The reservoir has a drainage area of about 66.56 square kilometers (km^2) and a conservation pool elevation of 67.55 meters (m) above the Puerto Rico Vertical Datum of 2002 (PRVD02). The semihydraulic earthfill dam was constructed in 1914 and is owned by the Puerto Rico Electric Power Authority (PREPA). The spillway structure consists of three radial arm gates, an open chute, and an approach channel with a crest elevation of 58.09 m above PRVD02.

Although the reservoir was constructed in 1914, no information regarding its storage capacity was available until 1961. As stated in Soler-López (2010), the storage capacity was 17.64 million cubic meters (Mm^3) in 1961 and 13.84 Mm^3 in 1997 (Soler-López, 1999) at an elevation of 67.55 m above PRVD02 (official vertical datum established after the last survey in 2007), which represents a reduction in volume of about 22 percent during that period. The last bathymetric survey of Lago Patillas was conducted in 2007, and the results showed that Lago Patillas' storage capacity had decreased by 0.27 Mm^3 since the previous survey in 1997. In 2015–16, PREPA established a new conservation pool elevation for Lago Patillas at 63.88 m above PRVD02, and since then, buildup of vegetation has been observed in the reservoir branches.

The U.S Geological Survey (USGS), in cooperation with PREPA, conducted a bathymetric survey in August 2019 to provide an updated stage-volume relation for Lago Patillas. PREPA will use this new information for decision making relating to flood control, water supply, and the assessment of potential sediment influx caused by heavy rainfall events. For example, Hurricane Maria made landfall on the island of Puerto Rico on September 20, 2017, and brought torrential rainfall and floods. Heavy rainfall events are known to transport large quantities of sediment to reservoirs and can contribute to the reduction of reservoir storage capacity (Nagles and others, 1999).

In 2018 and 2019, the USGS ran several field campaigns to update elevations at streamgages, groundwater wells, rain gages, and reservoir stages to the PRVD02 datum. In 2018, the USGS released high-resolution digital elevation maps generated using light detection and ranging (lidar) data based on topographic data collected in 2016 and 2017 (accessible at https://viewer.nationalmap.gov/basic/). This new dataset provides more accurate information on the topography of Puerto Rico than was available previously and was collected using the PRVD02 datum. This report documents the results of the bathymetric survey and new vertical control at the reservoir and describes the methods used for the sedimentation analysis of Lago Patillas in August 2019.

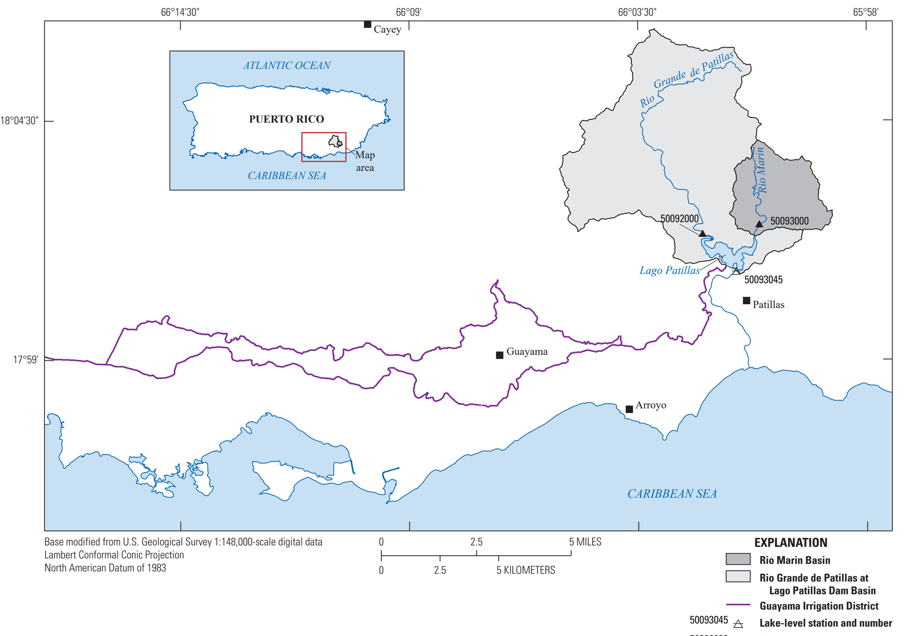

Figure 1. Location of Lago Patillas, Puerto Rico, within the Río Grande de Patillas at Lago Patillas Dam and Río Marín Basins.

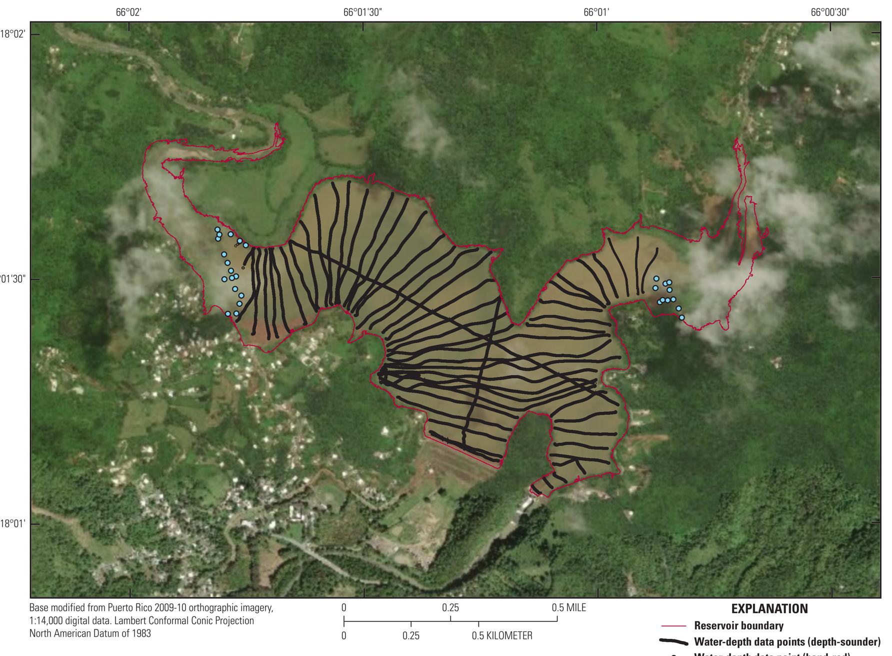

Figure 2. Location of collected water-depth data points at Lago Patillas, Puerto Rico, August 2019. Aerial orthoimagery courtesy of U.S. Army Corps of Engineers, Jacksonville, Florida, Geomatics Section.

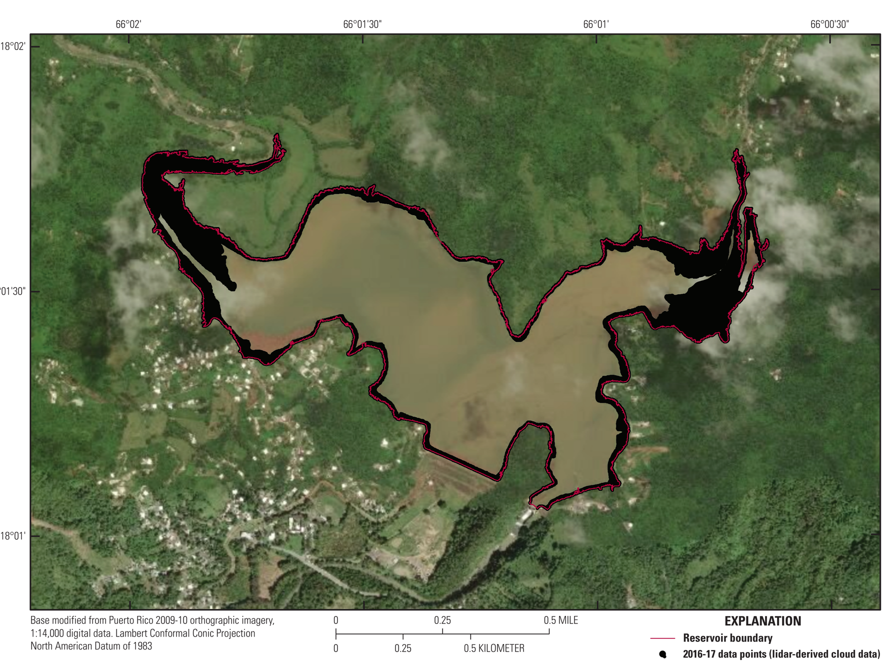

Figure 3. Map showing 2016–17 light detection and ranging (lidar) data points between the new conservation pool elevation and spillway elevation for Lago Patillas, Puerto Rico. Aerial orthoimagery courtesy of U.S. Army Corps of Engineers, Jacksonville, Florida, Geomatics Section.

Methods of Survey and Analysis

On August 14–16, 2019, a bathymetric survey was completed at Lago Patillas using field procedures established by the USGS (Wilson and Richards, 2006). The workflow used for the study involved (1) survey planning, including the establishment of a new vertical datum at the reservoir; (2) collection of water-depth data points across the reservoir; and (3) data postprocessing to generate the stage-volume curve and bathymetric mapping. Major tasks completed during planning for the bathymetric survey included the reestablishment of the transect lines used for the 2007 survey and compilation of spatial data, review of USGS topographic maps, and lidar point-cloud data to redefine the reservoir shoreline. Previous bathymetric surveys of Lago Patillas were vertically referenced to mean sea level, also referred to as the Puerto Rico Datum. This local vertical datum was used on the islands of Puerto Rico, Vieques, and Culebra before the new official vertical datum was implemented in 2012 (National Geodetic Survey, 2018). Survey-grade Global Navigation Satellite System (GNSS) technology was used to establish the new vertical datum, PRVD02, at Lago Patillas in March 2019. The USGS made a GNSS static observation at Lago Patillas to collect measurements of ellipsoid heights, which were later converted to orthometric height using a geoid model (GEOID12B). GNSS static observation involves setting up a fixed-base station and an antenna receiver over a single point to collect measurements during a given time period (Rydlund and Densmore, 2012). The GNSS static observation is the recommended survey method to obtain high-accuracy data at new control points, and surveyed elevations must be adjusted or postprocessed using other nearby control points. The measurements were made at one fixed point at Lago Patillas dam and processed through the National Oceanic and Atmospheric Administration (NOAA) Online Positioning User Service (OPUS). This new elevation, referenced to PRVD02, was tied to the mean sea-level datum using traditional surveying methods in July 2019. Compilation of data needed for the bathymetric survey of Lago Patillas also included delineation of a new reservoir shoreline from 2016–17 lidar-derived elevations released in 2018.

Data were collected by boat, and no terrestrial data were collected to delineate the shoreline. Survey transects were completed using an interval spacing of 50 m, which was the same spacing used in the 2007 survey; however, several areas could not be accessed because of the below-conservation pool elevation that was established in 2015–16. Water-depth data were collected using a bathymetric data collection system that couples a digital depth sounder (single-beam fathometer) and high-quality Differential Global Positioning System (DGPS) antenna. This system enables the measurement of water depths along predefined transect lines through the DGPS. The DGPS antenna was mounted on the depth sounder, and the collected water-depth data were horizontally referenced to the North American Datum of 1983 (NAD 83). The single-beam fathometer was calibrated each day prior to data collection by using the bar-check method (Wilson and Richards, 2006); the accuracy of the single-beam fathometer is 1 centimeter, ±1 percent of the measured depth. Manufacturer specifications for the equipment and the calibration process are presented in Gómez-Fragoso and Rosario (2021). The bathymetric survey of Lago Patillas included a total of 58 planned transect lines and over 239,000 water-depth measurements across the reservoir (fig. 2). Navigation at the reservoir branches was limited by debris and low water levels, making single-beam fathometer use difficult. In order to compensate for these difficulties, several shallow areas were surveyed using a graduated hand-held rod and DGPS antenna at intervals of approximately 3 m to an accuracy of ±0.03 m.

Water-depth data collected in August 2019 were referenced to the water-surface elevation during the reservoir survey, which varied between 3.76 and 3.78 m below the spillway elevation of 67.55 m above PRVD02. After the new elevation in PRVD02 for the spillway was established (previous studies provided an elevation of 67.67 m, referenced to mean sea level), based on the March 2019 GNSS static observation and GEOID12B, hydrographic software (HYPACK/XYLEM Inc, 2019) was used to convert water depth to bathymetric elevation referenced to PRVD02. The adjustment was made using a "tide time" correction file containing continuously monitored stage recorded at USGS lake-level station 50093045 at the Lago Patillas spillway (fig. 1). Stage data are available in the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2019) and were converted to represent the water-surface elevation at the reservoir, referenced to PRVD02. Hydrographic software was also used to eliminate noise data (spikes) in adjusted water-depth data prior to transferring the reported elevations into the Esri ArcMap 10.5 (Esri, 2016). The data generated during this study are available as a USGS data release (Gómez-Fragoso and Rosario, 2021).

To determine the stage-volume relation and create the bathymetric map for Lago Patillas, editing and postprocessing of the data collected across the reservoir were completed using the ArcGIS software developed by Esri (2016). The analysis included three types of survey datasets: (1) 2019 bathymetric survey data, (2) hand-rod measurements of water depth near reservoir branches (also measured in 2019), and (3) 2016 and 2017 lidar point-cloud data, used also to delineate a new reservoir shoreline. Single-beam fathometer data and hand-rod measurement data were adjusted to represent elevations in PRVD02 prior to being merged with lidar data. As stated earlier, a new reservoir shoreline was delineated for Lago Patillas, based on the 2016 and 2017 lidar point-cloud data at the spillway elevation of 67.55 m above PRVD02. Lidar point-cloud data were used to generate the bathymetric map because the data collected were considered reasonable when looking at lidar-derived ground points at the range of elevations between the new conservation pool elevation of 63.88 m above PRVD02 (64 m above mean sea level) and the spillway elevation of 67.55 m. In addition, lidar data were collected shortly after the new conservation pool elevation was established for Lago Patillas (fig. 3). Lidar point-cloud data were used to fill gaps between the new conservation pool elevation and spillway elevation (63.88 m to 67.55 m). To do this, the lidar data were clipped using the ArcGIS tool Extract LAS by setting the new reservoir shoreline at an elevation of 67.55 m above PRVD02 as the boundary feature. To generate the reservoir bathymetry surface, the aforementioned datasets (Gómez-Fragoso and Rosario, 2021) were combined in ArcGIS and a surface model was generated. The reservoir capacity was calculated at 1.0-m stage intervals from the bathymetric surface to generate a stage-volume curve from the 2019 survey using the data in table 1. In addition, the 2019 results were compared to those of previous USGS surveys completed in 2007 as part of the sedimentation analysis.

The sedimentation analysis for Lago Patillas also included the estimation of trapping efficiency, a term that describes the volume of accumulated sediments in reservoirs. This is an important element in sedimentation analysis and is used to determine sediment yield (Gómez-Fragoso, 2020). 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 describes the total sediment outflow measurable at the catchment outlet per unit area during a given period of time (Dutta, 2016; Griffiths and others, 2006), often defined as the amount of sediment load deposited in reservoirs. Sediment yield was calculated by dividing the volume of sediment accumulated in the reservoir by the average long-term trapping efficiency of the reservoir, the contributing drainage area of the basin, and the number of years between the first determination of capacity in 1961 and the 2019 survey:

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

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 Estimated Time to Zero Reservoir Storage

The storage capacity of Lago Patillas in 2019 was 12.96 Mm^3 at an elevation of 67.55 m above PRVD02, as reflected by the bathymetric survey data collected in August 2019. A comparison of the 2007 and 2019 survey results indicates that sediment influx is slowly decreasing the storage capacity of Lago Patillas (table 2). In 12 years, the storage capacity has been reduced by 0.61 Mm^3, and the intersurvey capacity loss is 0.05 million cubic meters per year (Mm^3/yr). The 2007–19 annual capacity loss is slightly greater than the 1997–2007 capacity loss of 0.03 Mm^3/yr reported in Soler-López (2010). The increase can probably be attributed to sediments carried by rivers during heavy rainfall events that were related to Hurricane Maria, which made landfall on the island in 2017 and brought torrential rainfall to the region. Figure 4 shows the stage-volume curves for the 2007 and 2019 surveys of Lago Patillas.

The loss of storage capacity at Lago Patillas is estimated to be 4.68 Mm^3, or about 27 percent, since 1961. Table 1 shows the stage-volume table for the 2019 survey at Lago Patillas at a 1-m intervals, which ranges in elevation (referenced to PRVD02) from 45.55 m to the spillway elevation of 67.55 m. As stated in Soler-López (2010), the sediment accumulation from 1961 to 2007 was estimated to be 4.07 Mm^3, with the mean, annual loss of capacity being 0.09 Mm^3/yr. The 2019 survey showed that the annual loss of capacity at Lago Patillas from 1961 to 2019 was 0.08 Mm^3, a value that has not substantially changed since the previous 2007 survey (table 2). Based on the most recent sedimentation rate of 0.08 Mm^3/yr, Lago Patillas is projected to be 100 percent full of sediment in 161 years, by 2180. The estimate is slightly longer than the previous estimate made following the 2007 survey. The storage capacity of Lago Patillas was also calculated to be 8.99 Mm^3 at the new conservation pool elevation of 63.88 m above PRVD02 established for the reservoir. During the 2019 survey, the water level at the reservoir varied from 0.09 to 0.11 m below the new conservation pool elevation. Figure 5 shows the bathymetric map of Lago Patillas generated from data collected in August 2019.

The long-term sediment yield for Lago Patillas from 1961 to 2019 is estimated to be about 1,330 cubic meters per square kilometer per year. Sediment yield was calculated using equation 1, where SA = 4.68 Mm^3, TE = 0.93, DA = 66.56 km^2 minus the water-surface area of 1.20 km^2, and T = 58 years (the number of years between the 1961 survey when the capacity was first computed and the 2019 survey). The sediment trapping efficiency of Lago Patillas was determined from the 2019 sediment analysis and calculated by using a storage capacity mean annual inflow ratio of 0.19. The mean annual inflow into Lago Patillas was calculated by averaging the annual mean runoff from 2014 to 2018 at two USGS streamgages: 50092000 Río Grande de Patillas near Patillas and 50093000 Río Marín near Patillas, Puerto Rico. The calculated annual mean runoff was 69.09 Mm^3/yr; of this amount, 55.72 Mm^3/yr was attributed to Río Grande de Patillas and 13.37 Mm^3/yr was attributed to Río Marín. This long-term sediment yield computed based on the 2019 survey is slightly smaller than the sediment yield computed for 1961–2007; however, the intersurvey sediment yield for 2007–19 is almost twice the value computed for 1997–2007 (table 2).

Table 1. Storage capacity table for Lago Patillas, Puerto Rico, August 2019.

[PRVD02, Puerto Rico Vertical Datum of 2002]

Pool elevation (meters above mean sea level	Pool elevation (meters above PRVD02)	Storage capacity (million cubic meters
67.67	67.55	12.96
66.67	66.55	11.79
65.67	65.55	10.68
64.67	64.55	9.64
63.67	63.55	8.70
64.00	[1]63.88	8.99
62.67	62.55	7.84
61.67	61.55	7.02
60.67	60.55	6.24
59.67	59.55	5.51
58.67	58.55	4.83
57.67	57.55	4.19
56.67	56.55	3.59
55.67	55.55	3.03
54.67	54.55	2.53
53.67	53.55	2.12
52.67	52.55	1.74
51.67	51.55	1.40
50.67	50.55	1.08
49.67	49.55	0.80
48.67	48.55	0.54
47.67	47.55	0.31
46.67	46.55	0.12
45.67	45.55	0.00

[1]New conservation pool elevation.

Table 2. Summary of the 2007 and 2019 sedimentation analyses of Lago Patillas, Puerto Rico.

[Sedimentation analysis data for 2007 are from Soler-Lopez (2010), except where noted]

Data descriptor	Year of survey	
	[1]2007	[1]2019
Total capacity, in million cubic meters	13.57	12.96
Years since first storage capacity was computed (1961)[1]	46	58
Years since construction	93	105
Sediment accumulation since 1961, in million cubic meters	4.07	4.68
Intersurvey sediment accumulation, in million cubic meters	0.27	0.61
Storage loss since 1961, in percent	23	27
Annual loss of capacity since 1961, in million cubic meters per year	0.09	0.08
Annual loss of capacity, in percent	0.50	0.46
Intersurvey annual loss of capacity, in million cubic meters per year	0.03	0.05
Sediment trapping efficiency, in percent	92	[2]93
Long-term sediment yield, in cubic meters per square kilometer per year	1,450	1,330
Intersurvey sediment yield, in cubic meters per square kilometer per square year	445	820
Estimated year the reservoir would fill completely with sediment (based on the annual loss of capacity since 1961)	[3]2160	2180

[1]No information is available for 1914 per Soler-López (2010); therefore, the calculations were made using the first storage capacity table computed in 1961.

[2]Using the capacity to inflow relation established by Brune (1953).

[3]Computed for the current study.

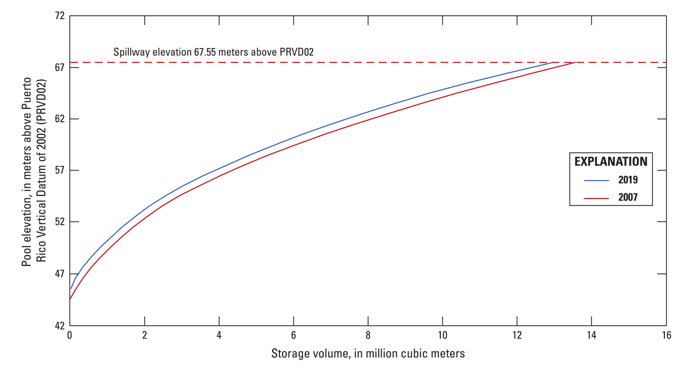

Figure 4. Stage-volume curves for the 2007 and 2019 bathymetric surveys of Lago Patillas, Puerto Rico.

Uncertainties in the Sedimentation Survey

The assessment of uncertainties in the sedimentation survey and quality-assurance (QA) checking for the estimation of volume and bathymetric contours was evaluated by comparing the bathymetric surface to the survey of additional transect lines. The location of each transect is shown in figure 6, and these transects were surveyed during the same period in which the data used for the volume calculation were collected. Each water-depth data point was converted to bathymetric elevation, referenced to PRVD02, and smoothed to remove noise, following the same processing used for the 2019 bathymetric survey. The comparison with the bathymetric surface was made by obtaining the bathymetric surface elevation at the same location as the surveyed point (QA transects). Figure 7 shows the comparison between QA-transect points and the 2019 bathymetric surface. The largest differences between the bathymetric surface and the quality-assurance points were mostly on the edges of the reservoir, and line 0089 showed the best match with the surface model. Results from the comparison between the bathymetric surface and the quality-assurance transects also indicated that the vertical accuracy of the bathymetric surface is 1.74 m at a 95-percent confidence level. The median absolute vertical error was about 0.13 m.

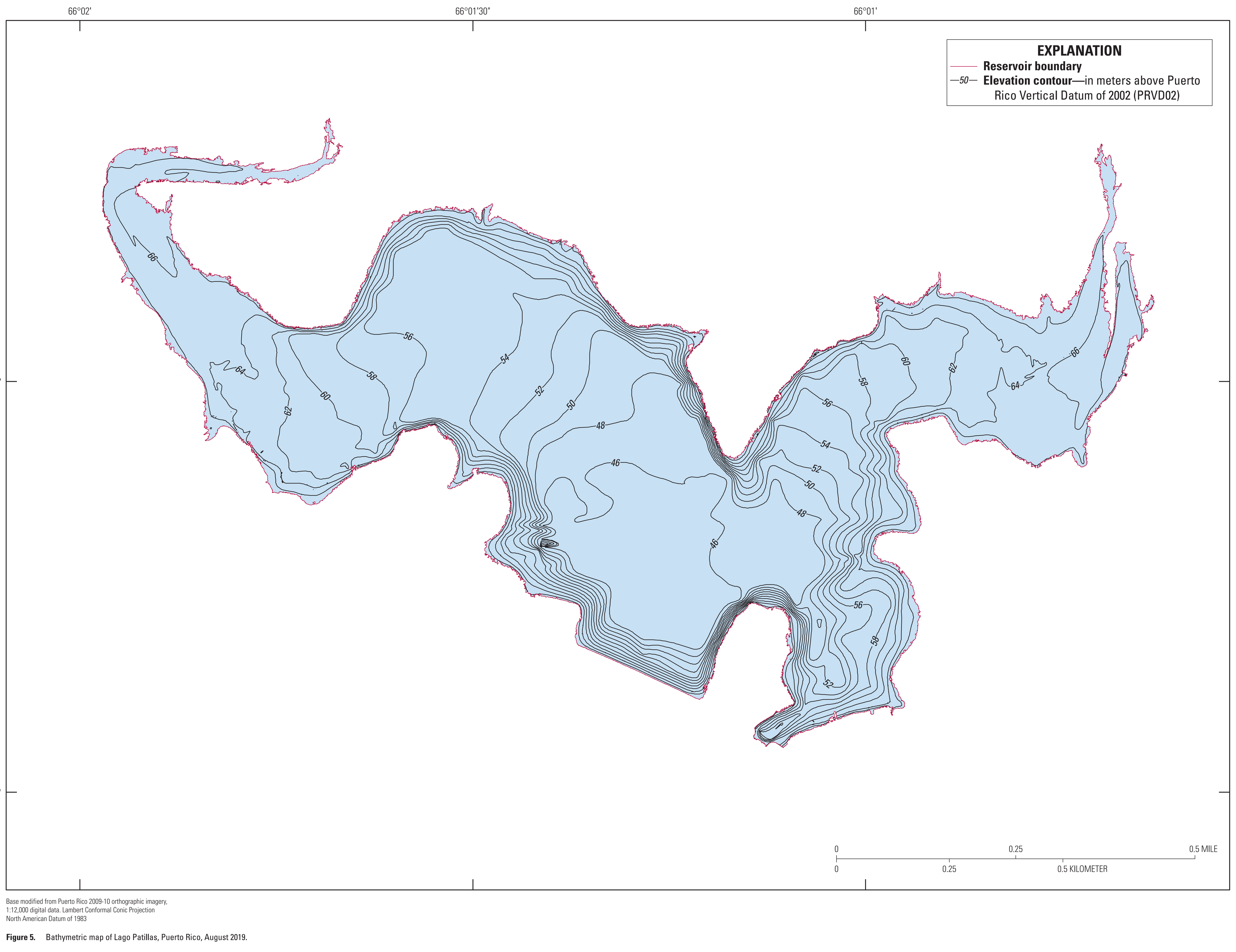

Figure 5. Bathymetric map of Lago Patillas, Puerto Rico, August 2019.

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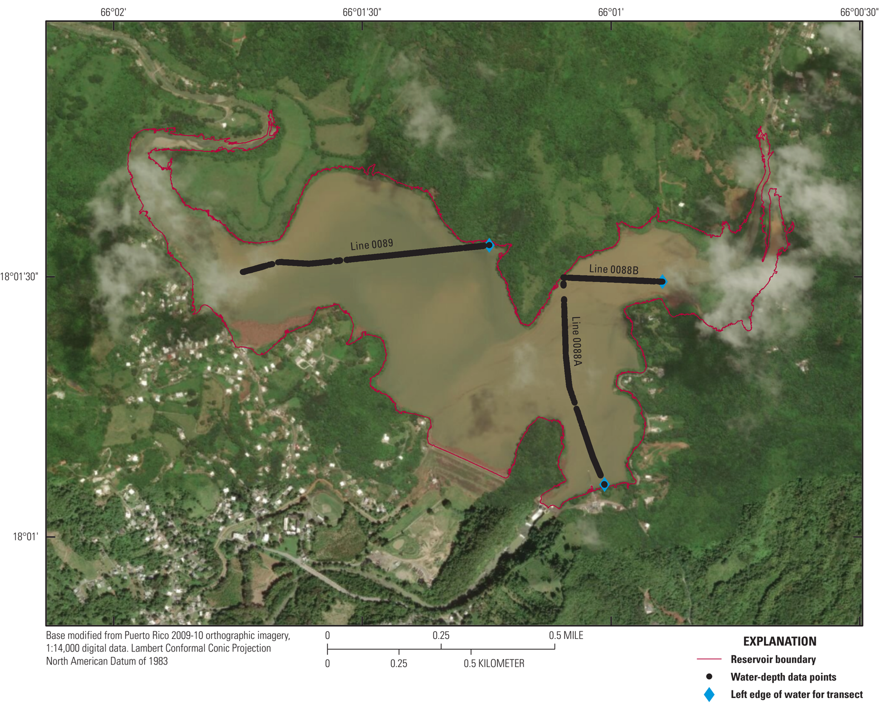

Figure 6. Water-depth data points collected at Lago Patillas, Puerto Rico, August 2019, used for the quality-assurance analysis. Aerial orthoimagery courtesy of U.S. Army Corps of Engineers, Jacksonville, Florida, Geomatics Section.

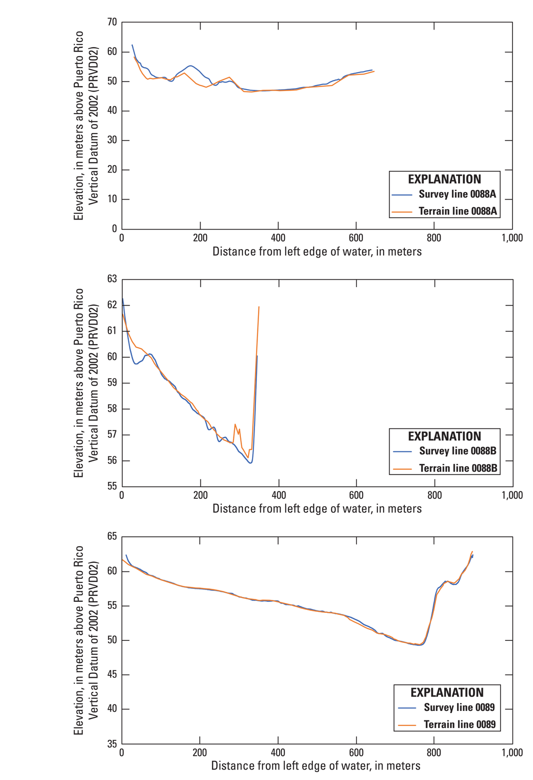

Figure 7. Elevation profiles for selected transects at Lago Patillas, Puerto Rico, from 2019 bathymetric surface and water-depth quality-assurance data points collected with a depth sounder (quality-assurance assessment). The term "terrain line" refers to the elevation taken from the bathymetric surface. A map of the transects, including the left edge of water for each, is shown in figure 6.

Digital files available at https://doi.org/10.3133/sim3471.

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Bathymetric Survey and Sedimentation Analysis of Lago Patillas, Puerto Rico, August 2019

By

Julieta M. Gómez-Fragoso

2021