

Figure 1. Location of Lago Loíza in the Rio Grande de Loíza Basin, Puerto Rico.

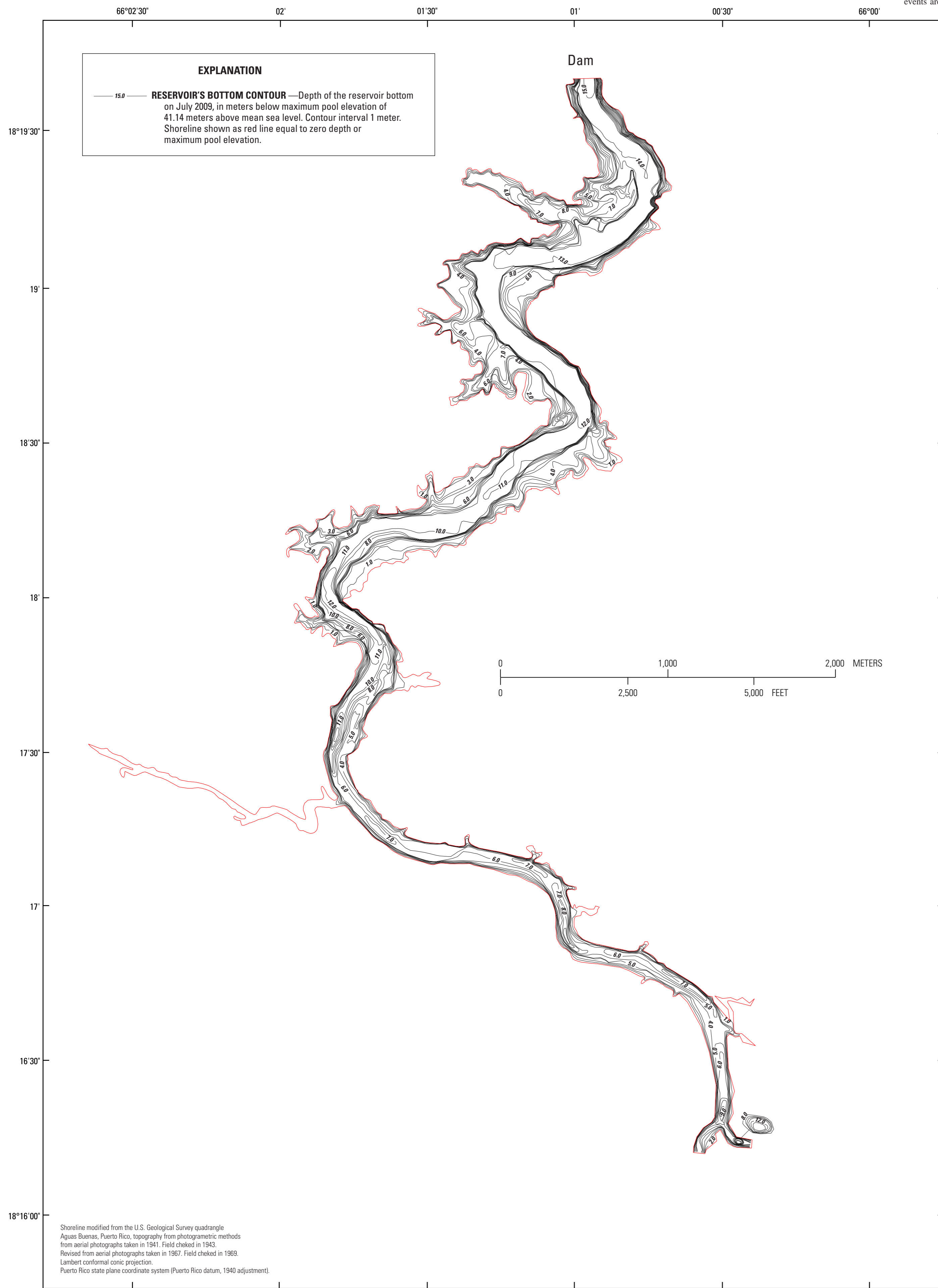


Figure 2. Bathymetric map of Lago Loíza, Puerto Rico, for July 2009.

**Introduction**

Lago Loíza is a reservoir formed at the confluence of Río Gurabo and Río Grande de Loíza in the municipality of Trujillo Alto in central Puerto Rico, about 10 kilometers (km) north of the town of Caguas, about 9 km northwest of Gurabo, and about 3 km south of Trujillo Alto (fig. 1). The Carraízo Dam is owned and operated by the Puerto Rico Aqueduct and Sewer Authority (PRASA), and was constructed in 1953 as a water-supply reservoir for the San Juan Metropolitan area. The dam is a concrete gravity structure that is located in a shallow valley and has a gently sloping left abutment and steep right abutment. Non-overflow sections flank the spillway section. Waterways include an intake structure for the pumping station and power plant, sluiceways, a trash sluice, and a spillway.

The reservoir was built to provide a storage capacity of 26.8 million cubic meters (Mm<sup>3</sup>) of water at the maximum pool elevation of 41.14 meters (m) above mean sea level (msl) for the Sergio Cuevas Filtration Plant that serves the San Juan metropolitan area. The reservoir has a drainage area of 538 square kilometers (km<sup>2</sup>) and receives an annual mean rainfall that ranges from 1,600 to 5,000 millimeters per year (mm/yr). The principal streams that drain into Lago Loíza are the Río Grande de Loíza, Río Gurabo, and Río Cañas. Two other rivers, the Río Bairoa and Río Caguas, discharge into the Río Grande de Loíza just before it enters the reservoir. The combined mean annual runoff of the Río Grande de Loíza and the Río Gurabo for the 1960-2009 period of record is 323 Mm<sup>3</sup>. Flow from these streams constitutes about 89 percent of the total mean annual inflow of 364 Mm<sup>3</sup> to the reservoir (U.S. Geological Survey, 2009). Detailed information about Lago Loíza reservoir structures, historical sediment accumulation, and a dredge conducted in 1999 are available in Soler-López and Gómez-Gómez (2005).

During July 8-15, 2009, the U.S. Geological Survey (USGS) Caribbean Water Science Center (CWSC), in cooperation with PRASA, conducted a bathymetric survey of Lago Loíza to update the reservoir storage capacity and estimate the reservoir sedimentation rate by comparing the 2009 data with the previous 2004 bathymetric survey data. The purpose of this report is to document the methods used to update and present the results of the reservoir storage capacity, sedimentation rates, and areas of substantial sediment accumulation since 2004.

**Method of Survey and Analysis**

The field techniques and bathymetric data reduction processes used for the 2009 survey were performed following procedures established by the CWSC, and described in the previous bathymetric survey report for Lago Loíza (Soler-López and Gómez-Gómez, 2005). The July 2009 bathymetric survey was conducted using a Bathymetric-Land Survey System, developed by Specialty Devices Inc., that consists of a global positioning system (GPS) coupled to a digital depth sounder similar to the setup used for the survey conducted in January 2004 (Soler-López and Gómez-Gómez, 2005). A total of 221 survey navigation lines were established at a spacing of about 50 m, beginning at the dam and continuing upstream along the different river branches of the reservoir. Geographic position (accurate to within 2 m) and water depths (accuracy of 2 centimeters +/- 1 percent of the measured depth) were acquired simultaneously using the GPS interfaced to the depth sounder. The pool elevation of the reservoir was recorded continuously at USGS lake-level station 50059000, Lago Loíza at Dam site near Trujillo Alto. The soundings were subsequently adjusted to represent water depths below the maximum pool elevation.

The 2009 data were stored and transferred into the USGS geographic information system (GIS) where final analysis and volume calculations were made following procedures similar to those used to develop the January 2004 bathymetric map of Lago Loíza (Soler-López and Gómez-Gómez, 2005). Data from the July 2009 survey were then used to generate a bathymetric map representing the reservoir bottom (fig. 2). Data points were color-coded according to their specific depths, and same-color points were connected with a line to draw depth contours. A triangulated irregular network (TIN) surface model of Lago Loíza was generated from the bathymetric map, and the reservoir volume was calculated using the GIS. The TIN surface model was used with the 2004-2009 digital data to generate a stage-storage table and curves as well as longitudinal bottom profiles along the thalweg of Lago Loíza (table 2, figs. 3 and 4).

**Storage Capacity, Sedimentation Rate, and Useful Life**

Bathymetric data indicate that the storage capacity of Lago Loíza decreased slightly from 17.53 Mm<sup>3</sup> in January 2004 (Soler-López and Gómez-Gómez, 2005) to 16.42 Mm<sup>3</sup> in July 2009 (table 1). This reduction of 1.11 Mm<sup>3</sup> between 2004 and 2009 (6.3 percent) is equivalent to an annual storage-capacity loss rate of about 222,000 cubic meters per year (m<sup>3</sup>/yr) for the period. Although the intersurvey sedimentation rate decreased by about 39 percent, the long-term rate has not changed substantially (table 1). As noted in Soler-López and Gómez-Gómez (2005), the long-term sedimentation rate of Lago Loíza has varied little over its history, this finding supports their conclusion that under normal rainfall conditions, the sedimentation rate of Lago Loíza has reached an equilibrium state in which the reservoir will continue to lose capacity at a rate of about 310,000 m<sup>3</sup>/yr. Intense rainfall events may exacerbate this process, however, as demonstrated in Soler-López (2001).

A comparison of longitudinal bottom profiles for 2004 and 2009 indicates that sediment accumulation in Lago Loíza for this period averaged about 1.5 m from 0 to 2,500 m upstream from the dam, and about 2.0 m from 2,800 to 5,600 m upstream (fig. 4). Sediment deposition from 5,600 m farther upstream was minimal.

The long-term sediment yield for the Lago Loíza drainage area has been calculated historically by dividing the sediment accumulation in the reservoir by the sediment trapping efficiency, reservoir drainage area, and years since the sediment accumulation began (typically the final construction date). The reservoir sediment trapping efficiency was usually determined by using the empirical relation established by Brune (1953), which uses the ratio of the reservoir water-storage capacity to the annual inflow volume (C/I). Heinemann (1981), however, associates a reservoir trapping efficiency to the following series of physical properties and operational procedures: (1) sediment particle-size distribution, (2) the time and rate of water inflow to the reservoir, (3) the reservoir size and shape, (4) the location of the outlet structure, and (5) the location and mechanism of discharge schedules. Of these, two are of primary importance in the sediment trapping efficiency of Lago Loíza: the reservoir size and shape, and the location and mechanism of water releases. Lago Loíza is a long and relatively shallow reservoir that resembles a natural river channel (fig. 5). This morphological characteristic imposes hydraulic conditions that increase water velocities during floods, preventing sediment particles from settling on the reservoir bottom. In addition, water discharges during these events are made through eight radial gates that open upwards. According to the 2009 bathymetry, the Lago Loíza bottom is at an elevation of about 26 m above msl. Based on the concrete spillway elevation of 31.0 m above msl, the Lago Loíza reservoir bottom is 5 m below the structure where water overflows during floods. These morphological and structural conditions probably prevent fine and mid-size sediment particles from being deposited, keeping them in suspension and facilitating sediment pass-through over the spillway during floods. If these assumptions are correct, the Lago Loíza sediment trapping efficiency may have been overestimated previously consequently underestimating the drainage area sediment yield.

Quiñones (2009) estimated empirically high sediment loads that could have entered Lago Loíza during September 21-24, 2008, when a trough (a low-pressure atmospheric system) affected most of Puerto Rico. The estimate was based on the previously published sediment trapping efficiency of 76 percent (Soler-López and Gómez-Gómez, 2005), historical USGS suspended sediment transport curves of the Río Grande de Loíza tributaries, and peak discharge data compiled from USGS streamflow records. It was estimated that for the aforementioned event, a total of 1.22 metric tonnes of sediment (suspended and bed load) were deposited in the reservoir; this sediment load was equivalent to 1.39 Mm<sup>3</sup> (Quiñones, 2009). In the paper (Quiñones, 2009), the USGS reported a long-term sedimentation rate of 0.31 million cubic meters per year (Mm<sup>3</sup>/yr) between 2004 and 2008 was applied to estimate a Lago Loíza storage capacity before the September 21-24 trough, of 16.29 Mm<sup>3</sup> [17.53 - (0.31 × 4) = 16.29]. By subtracting 1.39 Mm<sup>3</sup> from the prorated 2008 volume of 16.29 Mm<sup>3</sup>, the Lago Loíza storage capacity was reduced to 14.90 Mm<sup>3</sup> by the September 2008 trough according to Quiñones (2009).

The empirically estimated Lago Loíza storage capacity, however, is in disagreement with the 2009 bathymetric survey results by 1.52 Mm<sup>3</sup>. A possible explanation for the discrepancy between the estimated and the measured storage capacity of Lago Loíza is that the sediment trapping efficiency of the reservoir is lower than that estimated using the C/I ratio of Brune (1953), which does not take into account the findings of Heinemann (1981). For that reason, an adjusted sediment trapping efficiency of Lago Loíza was estimated for this study by dividing the 1.52 Mm<sup>3</sup> difference by 16.42 Mm<sup>3</sup> (1.52/16.42 = 0.09) and subtracting the result from the previously estimated trapping efficiency of 76 percent, yielding a new estimated sediment trapping efficiency of 67 percent (76 - 9 = 67). The estimate by Quiñones (2009), therefore, was useful for determining a more realistic sediment trapping efficiency for Lago Loíza, which reflects the newly considered morphological characteristics and location and mechanism of discharge schedules.

In addition to the corrections just described, the corrected sediment trapping efficiency of Lago Loíza also increases the reservoir-drainage-area sediment-yield by approximately 10 percent (table 1). The Lago Loíza sedimentation rate between 2004 and 2009 decreased from 364,000 m<sup>3</sup>/yr to 222,000 m<sup>3</sup>/yr (table 1, fig. 4), a 39 percent reduction. This trend in intersurvey drainage area sediment yield during the late 2000s has also been observed at nearby basins, such as the Lago Patillas and Lago de Cidra drainage areas where reductions ranged from 75 to 13 percent, respectively (Soler-López, 2010a, b). On a long-term basis the inter-survey drainage area sediment yield has remained nearly constant as has the reservoir sedimentation rate. The drainage area sediment yield was 882 cubic meters per square kilometer per year (m<sup>3</sup>/km<sup>2</sup>/yr) in 2004 and decreased slightly to 854 m<sup>3</sup>/km<sup>2</sup>/yr in 2009, a difference of only 3 percent, which is not statistically significant. Based on a long-term storage-capacity loss of about 310,000 m<sup>3</sup>/yr, the projected useful life of Lago Loíza is about 53 years, ending in 2062 (table 1).

**Summary and Conclusions**

During July 2009, the U.S. Geological Survey, in cooperation with the Puerto Rico Aqueduct and Sewer Authority, conducted a bathymetric survey of Lago Loíza to update the reservoir storage capacity and update the reservoir sedimentation rate by comparing 2009 bathymetric survey data with 2004 data.

The Lago Loíza storage capacity was 17.53 million cubic meters in January 2004, which decreased to 16.42 million cubic meters by July 2009. The inter-survey (2004-2009) storage capacity loss is about 6 percent, equivalent to a decrease of about 1.2 percent per year. This loss represents a reservoir sedimentation rate of about 222,000 cubic meters per year between 2004 and 2009. On a long-term basis (1953-2009), however, the sedimentation rate has remained constant at about 310,000 cubic meters per year.

Most of the storage capacity loss of Lago Loíza (averaging about 2 meters) occurred approximately 2,800 to 5,600 meters upstream from the dam. Sediment accumulation was observed to be 1.5 meters from approximately 0 to 2,500 meters upstream of the dam, however sediment deposition was practically unnoticeable from 5,600 meters to the lake headwaters. The long-term sediment yield of the Lago Loíza drainage area has remained nearly constant, totaling about 854 cubic meters per square kilometer per year. Based on a long-term storage capacity loss of about 310,000 m<sup>3</sup>/yr, the projected useful life of Lago Loíza is about 53 years, ending in 2062.

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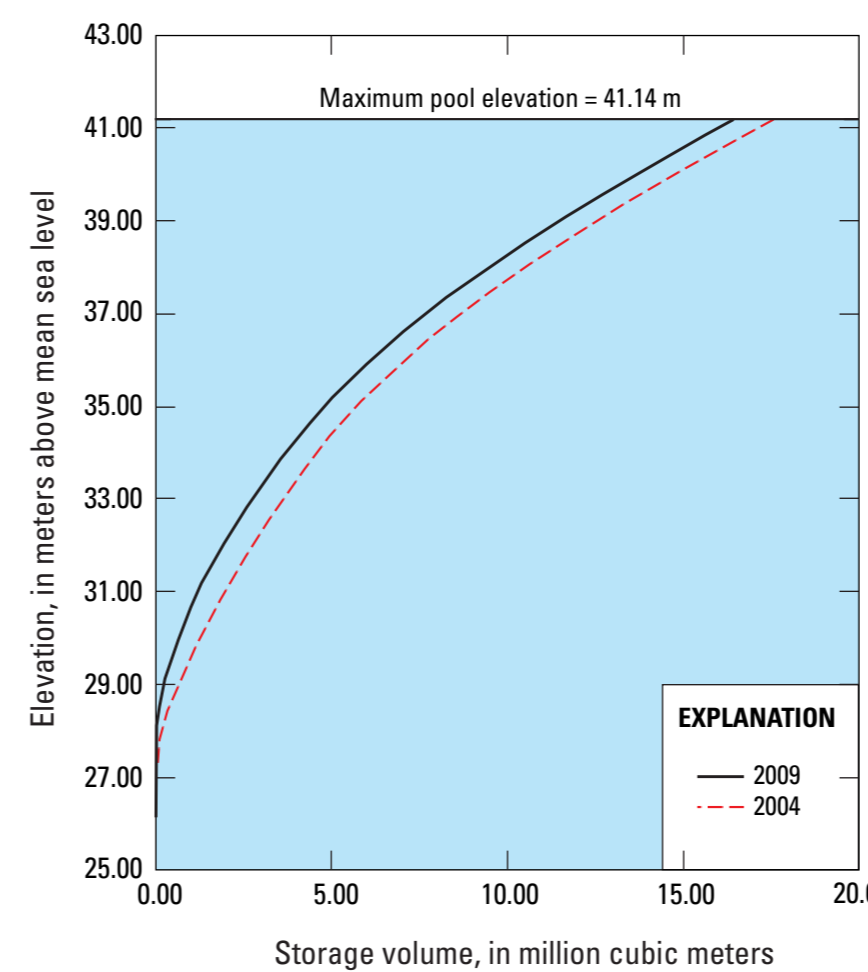


Figure 3. Relation between water-storage capacity and pool elevation of Lago Loíza for 2004 and 2009.

Soler-López, Luis R., and Gómez-Gómez, Fernando, 2005, Sedimentation survey of Lago Loíza, Puerto Rico, January 2004: U.S. Geological Survey Scientific Investigations Report 2005-5239, 26 p.

U.S. Geological Survey, 2009, Caribbean Water Science Center Water Data Report— Water year 2009: Accessed October 2010 at <http://wdr.water.usgs.gov/wy2009>.

Table 1. Comparison between the 2004 and the July 2009 sedimentation surveys of Lago Loíza, Puerto Rico. [—, not applicable].

Descriptor	Year of survey	
	2004	2009
Storage capacity, in million cubic meters	17.53	16.42
Live storage, in million cubic meters	17.28	16.34
Dead storage, in million cubic meters	.25	.08
Years since construction	51	56
Sediment accumulated, in million cubic meters	16.12	17.23
Inter-survey sediment accumulation, in million cubic meters	1.82	1.11
Long-term storage loss, in percent	60	64
Long-term annual loss of capacity, in cubic meters	316,078	307,679
Annual loss of capacity, in percent	1.4	.8
Inter-survey loss of capacity, in cubic meters per year	364,000	222,000
Storage capacity added by dredging, in million cubic meters	5.78	—
Inter-survey drainage area sediment yield, in cubic meters per square kilometer per year	1,015	616
Long-term sediment yield, in cubic meters per square kilometer per year	882	854
Dredged volume loss, in million cubic meters	1.82	2.93
Percent of dredge volume loss since 1999	31	51
Percent of annual dredge volume loss from 2004 to 2009	6.2	3.8
Year that the reservoir would fill with sediment	2060	2062

Table 2. Storage capacity for Lago Loíza, Puerto Rico, July 2009.

Pool elevation, in meters above mean sea level	Storage capacity, in million cubic meters
41.14	16.42
40.14	14.05
39.14	11.85
38.14	9.83
37.14	8.00
36.14	6.39
35.14	5.01
34.14	3.88
33.14	2.91
32.14	2.06
31.14	1.32
30.14	.74
29.14	.31
28.14	.08
28.14	.01
27.14	.01
26.14	.00

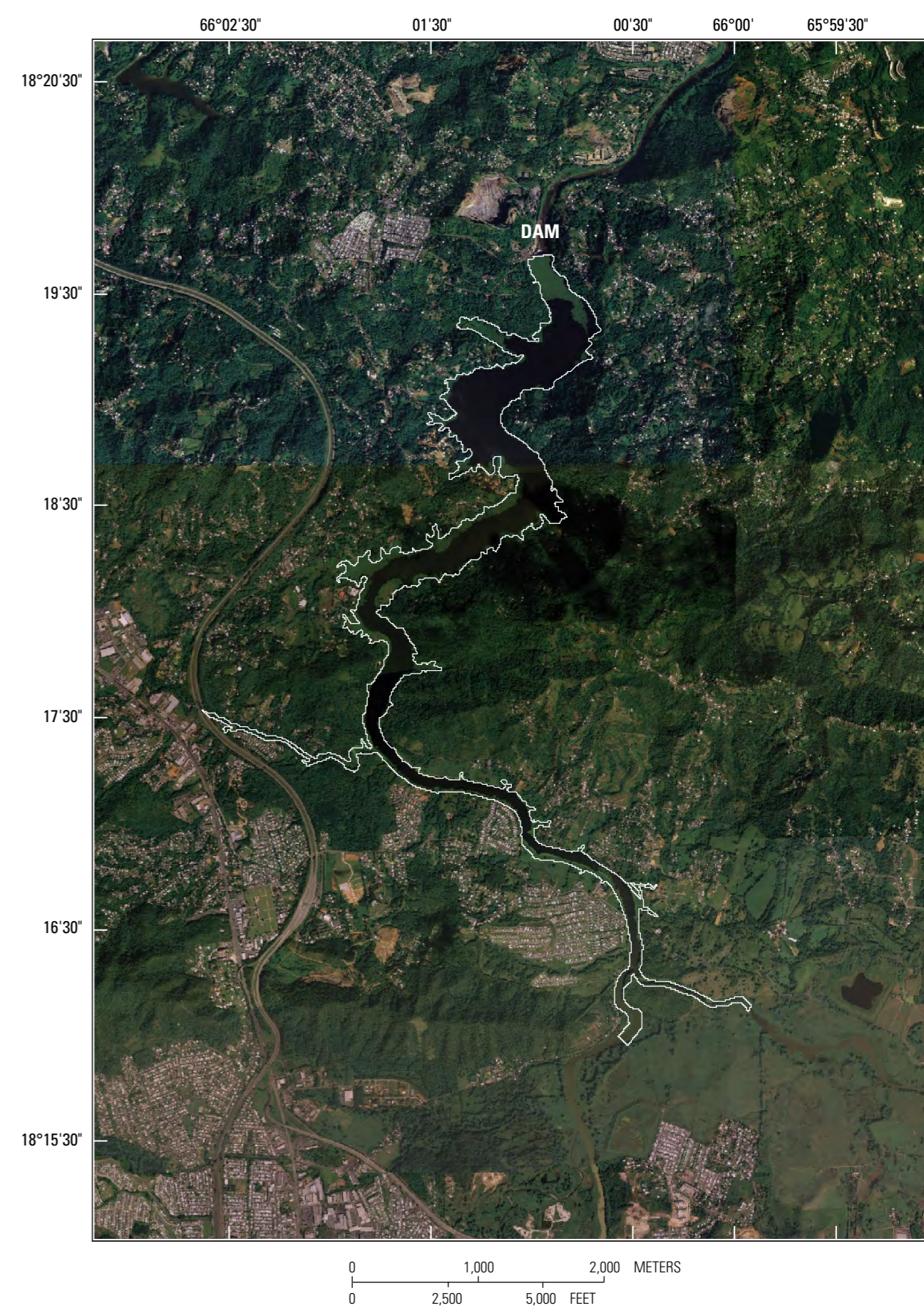


Figure 5. Aerial photograph of Lago Loíza showing its long geomorphology resembling a natural river channel. Photograph from the U.S. Army Corps of Engineers, Puerto Rico, 2007.

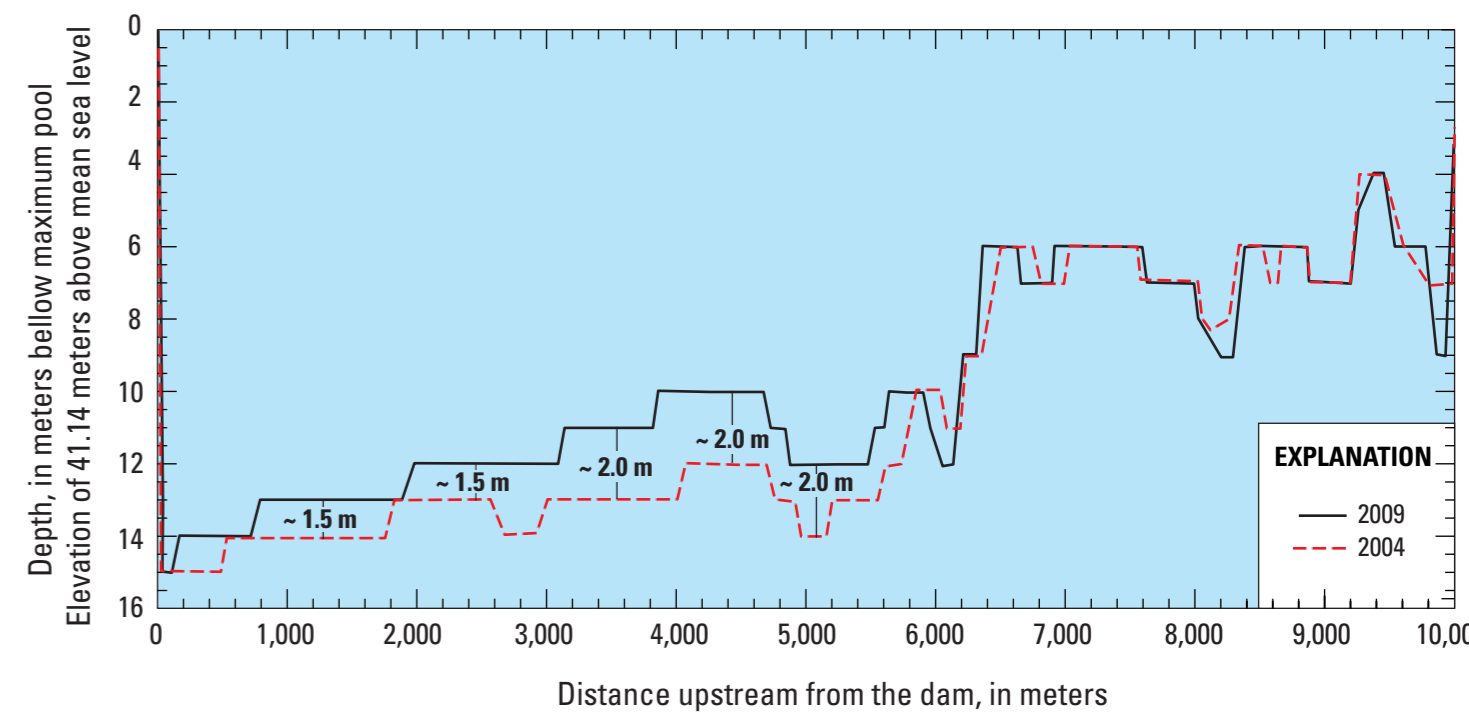


Figure 4. Longitudinal profiles along the thalweg of Lago Loíza, for 2004 and 2009.

**Sedimentation Survey of Lago Loíza, Puerto Rico, July 2009**

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