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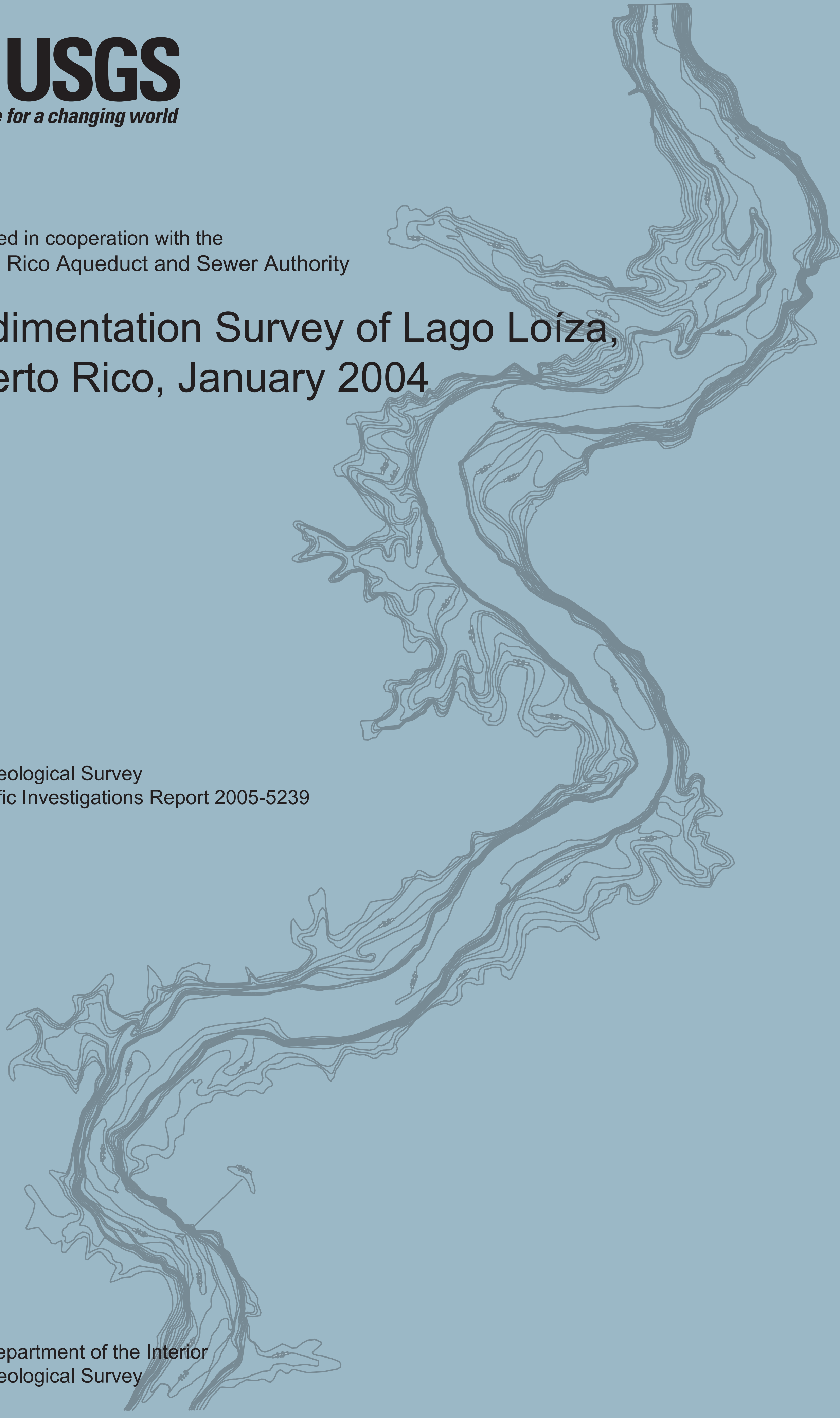
Sedimentation Survey of Lago Loíza, Puerto Rico, January 2004



U.S. Geological Survey
Scientific Investigations Report 2005-5239

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

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By Luis R. Soler-López and Fernando Gómez-Gómez

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

U.S. Department of the Interior
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[Plates are in pocket]

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Tables

Conversion Factors and Datum, Acronyms, and Translations

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Flow rate	
cubic meter per year (m^3/yr)	0.000811	acre-foot per year (acre-ft/yr)
cubic meter per day (m^3/d)	35.31	cubic foot per day (ft^3/d)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram (Mg)	0.9842	ton, long (2,240 lb)
metric ton per day	1.102	ton per day (ton/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Datum:

Horizontal Datum - Puerto Rico Datum, 1940 Adjustment

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929) - a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called "Sea Level Datum of 1929".

Acronyms used in this report:

BLASS	Bathymetric/Land Survey System
DGPS	Differential Global Positioning System
GIS	Geographic Information System
GPS	Global Positioning System
PRASA	Puerto Rico Aqueduct and Sewer Authority
PRIFA	Puerto Rico Infrastructure Financing Authority
TIN	Triangulated Irregular Network
USGS	U.S. Geological Survey

Translations:

Spanish	**English**
Lago	Lake (in Puerto Rico, also reservoir)
Río	River
municipio	municipality

Sedimentation Survey of Lago Loíza, Puerto Rico, January 2004

By Luis R. Soler-López and Fernando Gómez-Gómez

Abstract

A sedimentation survey of Lago Loíza reservoir was conducted during January 2004 to determine the reservoir water-storage capacity. After a bathymetric survey performed on November 1994, the drainage basin was impacted by Hurricanes Hortense on September 10, 1996, and Georges on September 21, 1998. In addition, dredging was conducted between 1997 and 1999 to increase the storage capacity by about 5.8 million cubic meters to increase the public-supply water safe yield at the Sergio Cuevas Filtration Plant.

The results of the 2004 bathymetric survey indicate that the storage capacity of Lago Loíza reservoir was 17.53 million cubic meters or 3.34 million cubic meters greater than the November 1994 capacity. The long-term reservoir sedimentation rate is about 310,000 cubic meters per year; however, higher annual rates have occurred since the reservoir construction, but these rates are considered short-term, low occurrence, and principally associated with land-use disturbances and extreme runoff events.

The estimated sediment trapping efficiency of Lago Loíza was as follows: 72 percent in 1994, 78 percent in 1999, and 76 percent in 2004. The Lago Loíza drainage area sediment yield for the period 1994 to 2004 was 859 cubic meters per square kilometer per year, about one-and-a-half times higher than the previously (1990-1994) estimated value of 600 cubic meters per square kilometer per year.

Based on the 2004 bathymetric survey, the continued utility of Lago Loíza as a water-supply reservoir is about 56 more years. Based on the average long-term reservoir sedimentation rate of 310,000 cubic meters per year, however, the storage added by the dredging, which was conducted from 1997 to 1999, will be lost by 2018.

Introduction

The Lago Loíza reservoir has a drainage area of 538 square kilometers (km^2) and constitutes the principal source of public water supply to the eastern part of the San Juan metropolitan area. During 2003, the reservoir supplied an average of 394,000 cubic meters per day (m^3/d) to the Puerto Rico Aqueduct and Sewer Authority (PRASA) Sergio Cuevas Filtration Plant (W. Molina, U.S. Geological Survey, written commun., 2004). The ability to maintain this draft rate, however, is determined primarily by the available storage, which by 1994 on a long-term basis (1953-1994) was reduced, on average, by about 337,000 cubic meters per year (m^3/yr) by sedimentation, based on several sedimentation surveys conducted in the past (Webb and Soler-López, 1997). The effect of sedimentation became evident during the drought of 1994, when rainfall in northwestern Puerto Rico was about 30 percent below normal between August 1993 and September 1994. At the time of the drought, the available storage capacity in Lago Loíza was about 14.2 million m^3, which was about 7 million m^3 below the required storage capacity to have sustained a draft rate of about 360,000 m^3/d (Rodríguez-Martínez and others, 2002). In order to alleviate a future water supply short-fall, the Puerto Rico Infrastructure Financing Authority (PRIFA) authorized the dredging of Lago Loíza between 1997 and 1999, to increase the reservoir storage capacity by about 5.8 million m^3.

Between the drought of 1994 and the completion of the dredging in 1999, two hurricanes affected the island (Hurricane Hortense on September 10, 1996, and Hurricane Georges on September 21, 1998). Because of the high sediment loads associated with hurricanes (Gellis, 1993), Hurricanes Hortense and Georges negatively impacted the reservoir by sedimentation. Sedimentation surveys conducted at other reservoirs in Puerto Rico indicated that these hurricanes reduced the water-storage capacities of the reservoirs in excess of 10 percent of their original volumes (Soler-López, 2001a, 2001b). In order to determine the available storage in Lago Loíza, the PRASA requested the USGS to conduct a bathymetric survey. The purpose of this report is to document the results of the bathymetric survey and to provide the PRASA officials with the necessary information to effectively manage the reservoir.

The bathymetric survey was conducted using a global positioning system (GPS) interfaced to a depth sounder. The field data were then transferred into a geographic information system (GIS), which was used to determine the existing storage capacity, the sedimentation rates, sediment distribution, and to anticipate the useful life of the reservoir as a major public water-supply source. Data from the 2004 bathymetric survey were compared with the 1999 post-dredge storage capacity of Lago Loíza derived from information provided by the PRIFA, and with the previous USGS 1994 bathymetric survey of Lago Loíza.

From the 1994, 1999, and 2004 data sets, longitudinal bottom profiles along the central portion of Lago Loíza, as well as transverse cross sections representing the reservoir's bottom from shore to shore, were generated and overlaid to locate areas of sediment accumulation from 1999 to 2004. In addition, the reservoir pool elevation and storage capacity relation were generated at 1-meter (m) elevation intervals for each year to generate a graph representing the reservoir volume at different elevations and to show the volume variations during these surveys.

Dam, Reservoir, and Basin Characteristics

The Río Grande de Loíza was impounded in March 1953 with the completion of the Carraízo Dam, 21.7 kilometers (km) upstream from the river's outlet to the Atlantic Ocean. The reservoir is located between the municipios of Caguas , Gurabo, and Trujillo Alto in northeastern Puerto Rico, and the dam structure is about 10 km north of Caguas, about 9 km northwest of Gurabo, and about 3 km south of Trujillo Alto (fig. 1).

The dam is a concrete gravity structure located in a shallow valley with a gently sloping left abutment and a 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 dam was modified in 1977 with eight radial gates installed above the spillway, each 11.88 m wide by 9.14 m high. The gates had a 10.67-m radius skinplate of riveted fabrication with upper and lower arms at each side supported by pin bearings on the downstream portion of the piers. In 1977, flash boards were added to raise the maximum pool elevation from 40.14 to 41.14 m above mean sea level. The additional storage capacity provided by the flash boards was in the range of about 2.7 million m^3 (Webb and Soler-López, 1997). Recently (2001-2002), as part of a major maintenance and safety overhaul, all radial gates were replaced with new structures having the same dimensions. The principal dam and reservoir characteristics are given on table 1.

The reservoir was built to provide a storage capacity of 26.80 million m^3 of water at an elevation of 41.14 m above mean sea level for the Sergio Cuevas Filtration Plant, serving the San Juan metropolitan area. Although penstocks and turbines for power generation were originally included to provide an independent source of power for dam operations, hydroelectric power generation was later abandoned due to the infrequency of reservoir water releases (Ivari, 1981).

The reservoir has a drainage area of 538 km^2 making it the largest drainage basin of any reservoir in Puerto Rico. Mean annual rainfall in the Lago Loíza Basin ranges from 1,600 millimeters (mm) in Juncos and Caguas (which lie in the rain shadow of the mountain range) to as much as 5,000 millimeters per year (mm/yr) on the slopes of the Sierra de Luquillo mountains (Calvesbert, 1970) (fig. 2). The principal streams draining into Lago Loíza are the Río Grande de Loíza, Río Gurabo, and Río Cañas. Two other rivers, the Río Bairoa and Río Cagüitas 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 period of record from 1960 to 2002 is 305 million m^3. Flow from these streams constitute about 84 percent of the total mean annual inflow of 363 million m^3 to the reservoir (Díaz and others, 2002).

The Lago Loíza basin is underlain primarily by granodiorite of the San Lorenzo Batholith, volcanic rocks, and alluvium (Briggs and Akers 1965; Cox and Briggs, 1973; Bawiec, 2001; Gellis and others, 1999). The basin is composed mainly of the Mucara-Caguabo soils series, followed by the Mabi-Río Arriba soil series, and of the Pandura-Lirios soil series. These soils have slopes that range from 0 to 60 percent with the flat lands containing the Mabi-Río Arriba series, which is the portion of the Río Gurabo valley (Boccheciamp, 1978).

The 1987 land use within the basin was classified as pasture (50 percent), forested areas (20 percent), rural areas (11 percent), croplands (10 percent), and urban areas (6 percent). The rest of the areas (constituting about 3 percent) were classified as disturbed ground and other uses (Birdsey and Weaver, 1987). These land-use classifications and percentages could have changed as a result of new urban developments that have taken place during the past 17 to 18 years.

Method of Survey

The 2004 bathymetric survey of Lago Loíza involved planning, data collection, data processing, and analysis. An Arc/Info GIS was used to establish the survey lines and to analyze the collected data. The survey lines were planned at a spacing of 50 m, starting at the dam and continuing upstream along the two branches of Lago Loíza (fig. 3). The bathymetric data were collected during January 26 to 28, 2004, using a depth sounder coupled to a GPS that recorded the horizontal position of the survey boat. A geo-referenced digital map of the reservoir shoreline and planned survey lines were loaded into a portable computer and served as a guide for the bathymetric data collection.

The reservoir pool elevation was monitored at the continuous recording USGS lake-elevation station Lago Loíza at damsite near Trujillo Alto, Puerto Rico (station number 50059000, fig. 1). The pool elevation of Lago Loíza was not at the crest top of the gates, therefore, the depth sounding data were adjusted using a time-elevation correction factor to represent depths at maximum pool elevation of 41.14 m above mean sea level.

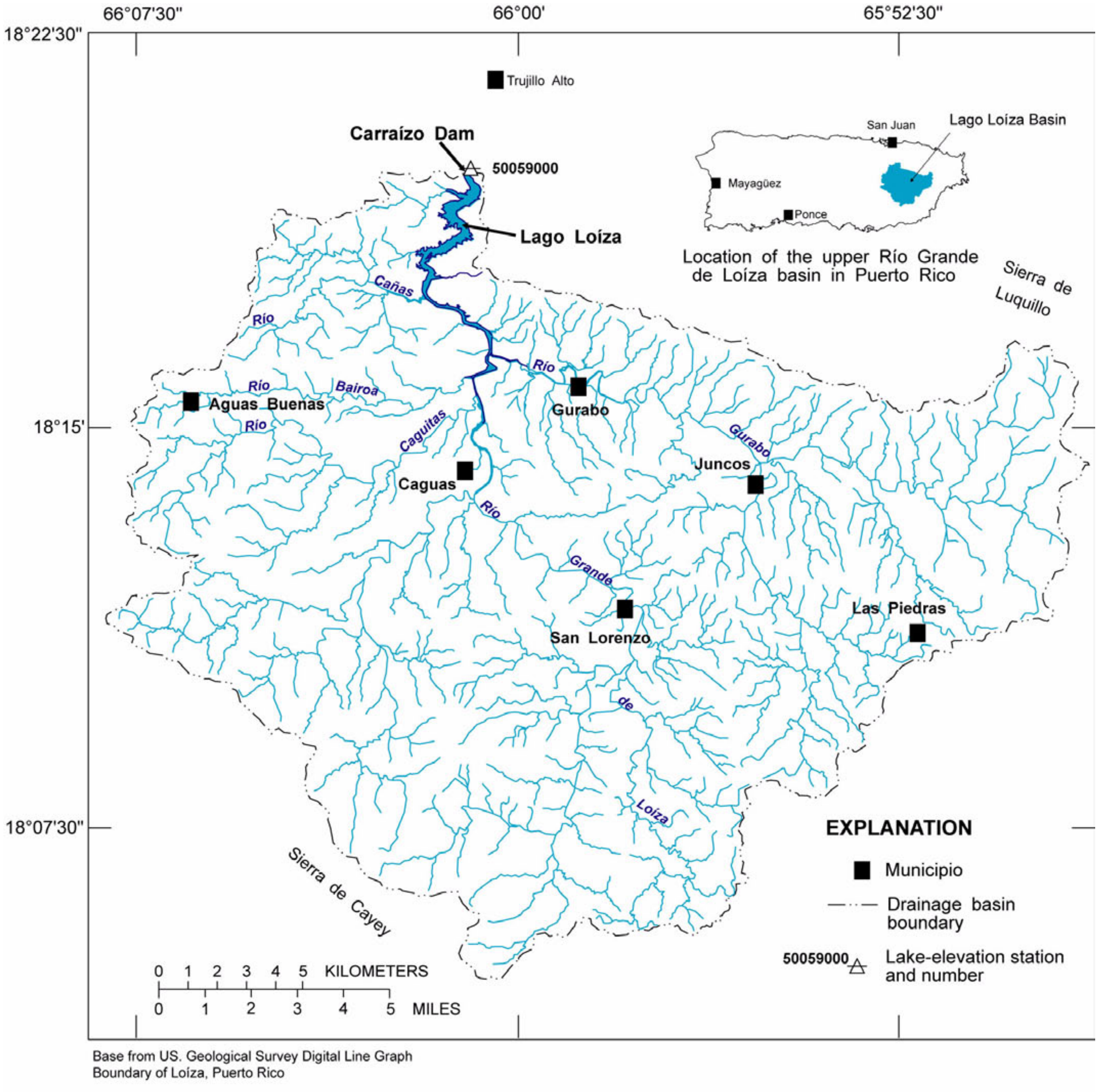


Figure 1. Location of Lago Loíza in the Río Grande de Loíza Basin, Puerto Rico.

Table 1. Principal characteristics of Lago Loíza and structures (modified from Sheda and Legas, 1968; Puerto Rico Electric Power Authority, 1980).

[amsl, above mean sea level; TIN, Triangulated Irregular Network; GIS, Geographic Information System]

Total length of dam at top (spillway and non-overflow sections)	210 meters
Length of spillway section	95.1 meters
Elevations (above mean sea level):	
Top of dam (maximum flooded elevation)	44.0 meters
Top of gates (maximum pool elevation)	41.14 meters
Spillway crest	31.0 meters
Crown of water intake	30.0 meters
Invert of water intake	28.0 meters
Maximum width at base	30.0 meters
Diameter of penstocks	1.67 meters
Installed power-generating capacity	3,000 kilowatts
Discharges with gates completely open	
Maximum pool elevation (41.14 meters amsl)	6,590 cubic meters per second
Maximum design elevation (43.0 meters amsl)	8,835 cubic meters per second
Top of dam (44.0 meters amsl)	9,970 cubic meters per second
Maximum discharge recorded at dam site (September 10, 1996)	6,314 cubic meters per second
Original storage at pool elevation of 41.14 meters amsl from the 1947 TIN	26.80 million cubic meters
Surcharge storage for flood control (from 41.14 to 43.0 meters amsl)	8.0 million cubic meters
Drainage area at dam site	538 square kilometers
Flooded area at elevation of 41.14 meters (derived from GIS)	2.67 square kilometers
Maximum original depth at pool elevation of 41.14 meters amsl	25 meters
Maximum depth during 1999 post-dredge survey	18 meters
Maximum depth during 2004 survey	15 meters
Maximum length of normal pool (to the confluence of the Río Grande de Loíza and the Río Gurabo)	10 kilometers

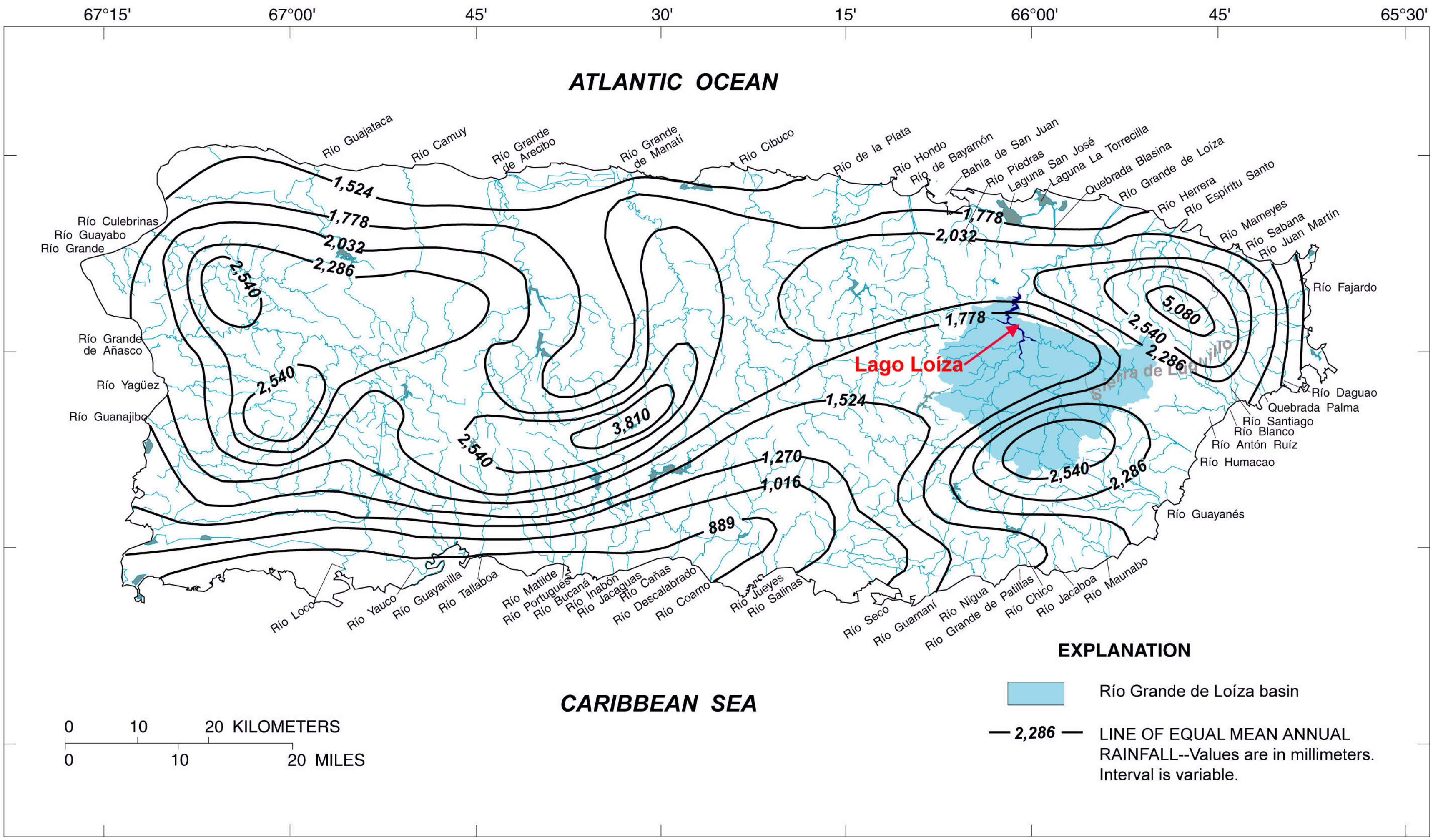


Figure 2. Mean annual rainfall distribution in Puerto Rico (modified from Calvesbert, 1970).

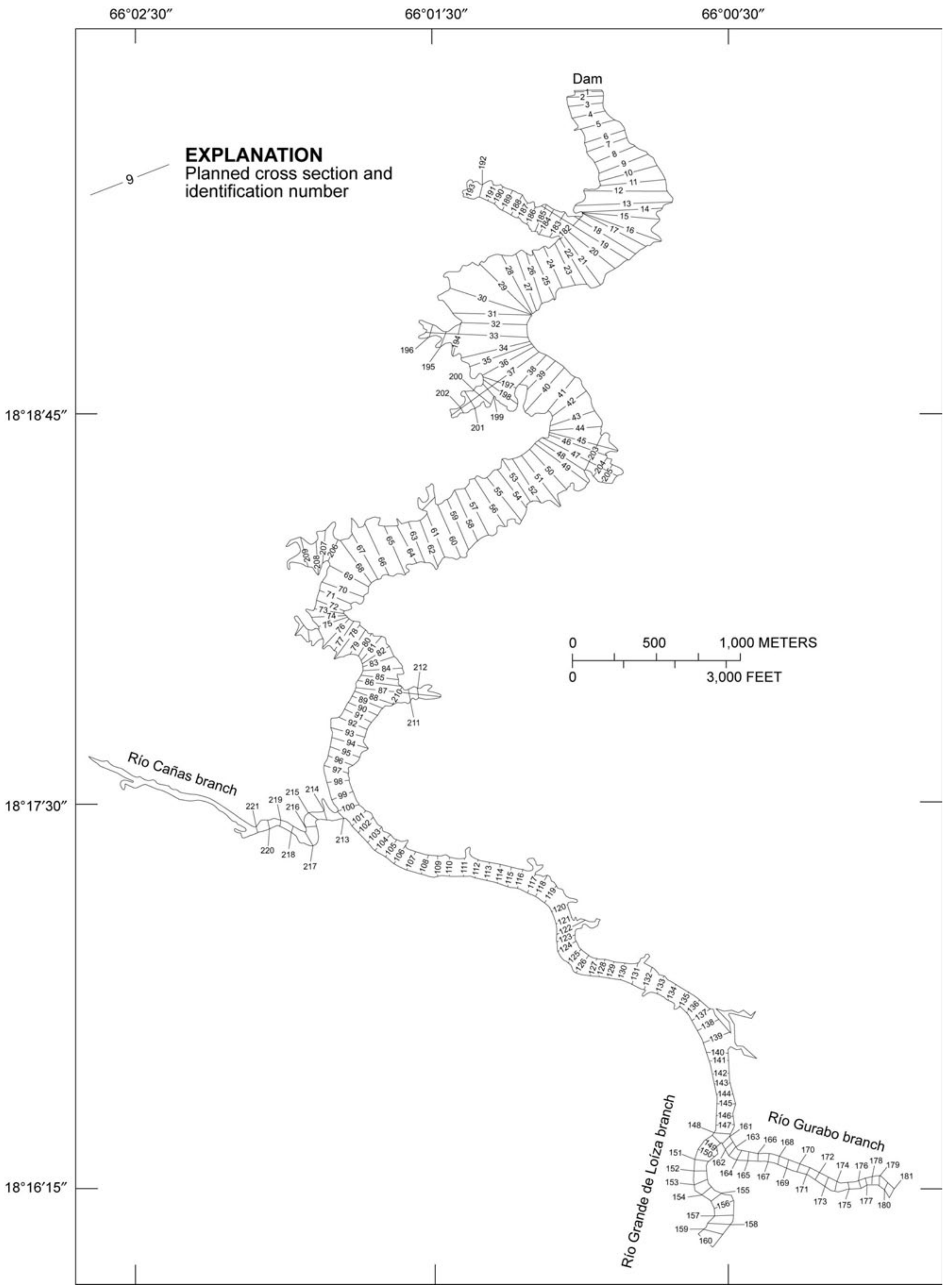


Figure 3. Planned cross-section locations for the January 2004 bathymetric survey of Lago Loíza, Puerto Rico.

A total of 19,442 data points (depth soundings) were collected over the entire reservoir, while navigating along the planned survey lines (fig. 4, track lines). The depths along the cross sections were plotted and 1-m-interval contour lines of equal depth were drawn from the shoreline to the deepest parts of the reservoir (plates 1 and 2). The procedure used to contour the reservoir's bottom is explained in the data processing section of this report. These contour lines were then converted into a triangulated irregular network (TIN) describing the reservoir's bottom (fig. 5). The TIN represents the reservoir bottom surface model as thousands of adjoining triangles with x, y, and z coordinates assigned to all vertices (Environmental Systems Research Institute, Inc., 1992). The longitudinal distance of the reservoir along the thalweg is shown on figure 6. The GIS uses the TIN to calculate the storage capacity and thickness of sediment accumulation.

To obtain an estimate of the sediment accumulation rate between 1999 and 2004, and to estimate the useful life of the reservoir based on current data, the 1999 post-dredge storage capacity of Lago Loíza provided by the PRIFA was compared with the 2004 calculated storage capacity.

Selected cross sections depicting the reservoir's bottom from shore to shore, as well as longitudinal profiles of the reservoir's bottom along the thalweg of Lago Loíza were generated for 1994, 1999, and 2004 from their TIN surface models. The relation between pool elevation and water-storage capacity for 1994, 1999, and 2004 was generated by calculating the reservoir volume at 1-m elevation intervals and is shown in graphical form on figure 7.

Field Techniques

The bathymetric survey of Lago Loíza was conducted during January 26 to 28, 2004. Data were collected using the bathymetric/land survey system (BLASS) developed by Specialty Devices, Inc. Previous bathymetric surveys conducted by the USGS used a differential global positioning system (DGPS), which consisted of two GPS receivers that operated simultaneously in order to maintain the positional data accuracy within 2 m. For the bathymetric survey of Lago Loíza, however, the BLASS system was upgraded from a 12-channel satellite receiver to a 24-channel satellite receiver, which enabled for one stand-alone GPS unit to maintain the 2-m positional data accuracy. The system consists of a Novatel global GPS receiver coupled to a Depth Sounder model SDI-IDS Intelligent. The depth sounder vertical accuracy is 2 centimeters (cm) more or less 1 percent of the measured depth. The GPS receiver monitors the horizontal position of the survey boat, whereas the depth sounder measures water depths. To verify the accuracy of the system upgrade, the stand-alone GPS unit was placed at the known benchmark, USGS roof (latitude 18°25'N, longitude 66°06'W), which was calculated using the post-processing software, CENTIPOINT, giving a maximum error of 10 cm. The positional data were collected with the upgraded system for about 5 minutes and a total of 1,049 positional data points were analyzed and the standard deviation was determined. The resulting data were compared with the post-processed position coordinates and the outcome indicated that the minimum latitude difference was 1.65 m and the maximum difference was 2.05 m, for an average of 1.85 m. The minimum longitude difference was 2.11 m and the maximum difference was 2.48 m, averaging 2.29 m. The overall positional difference between the post-processed coordinates and the stand-alone coordinates average was 2.07 m, which is in very close agreement with the positional accuracy obtained using the DGPS.

The system upgrade resulted in a more effective data collection process, because it eliminated the need to have a base or reference GPS station deployed at several sites overlooking the reservoir. The reservoir water level varied less because of the reduced data collection time, therefore, the time spent collecting data was less and the time spent post-processing data was reduced.

The bathymetric survey software HYPACK was used to navigate and to collect data. The software integrates the position and depth data, storing the x, y (geographic locations), and z (depths) coordinates in a portable computer.

A total of 221 survey sounding lines were originally planned using the GIS (fig. 3); however, vegetation growth and water hyacinths (*Eichornia crassipes*) in some areas limited the data collection to only 118 cross sections (fig. 4). Nonetheless, the vast majority of the unsurveyed lines were located in areas where runoff is negligible, thus sediment influx is also minimal. It is reasonable to conclude that the bottom topography in these areas has changed little, if any, over the years. The bottom features at these areas were estimated by using previous surveys and the original Lago Loíza pre-impounded topography.

Data Processing

The initial editing of the 2004 data was performed using the HYPACK software. The positions were corrected to eliminate anomalies that occur when the satellite signal is lost, because of local topographic features or electromagnetic interference. The position errors were corrected by interpolating back to the middle point between the correct preceding and posterior position. The depth data were also corrected to eliminate incorrect depth readings that can result from insufficient signal gain or when floating debris interferes with the transducer face. Incorrect depth readings were interpolated between the correct preceding and posterior depth readings. The edited data were then transferred into the Arc/Info GIS database for further processing. The Arc/Info software was customized to produce color-coded depth data, according to different depth values. The data points of the same color were connected by adding a line between them, and a contour map of the reservoir's bottom depth was generated (plates 1 and 2).

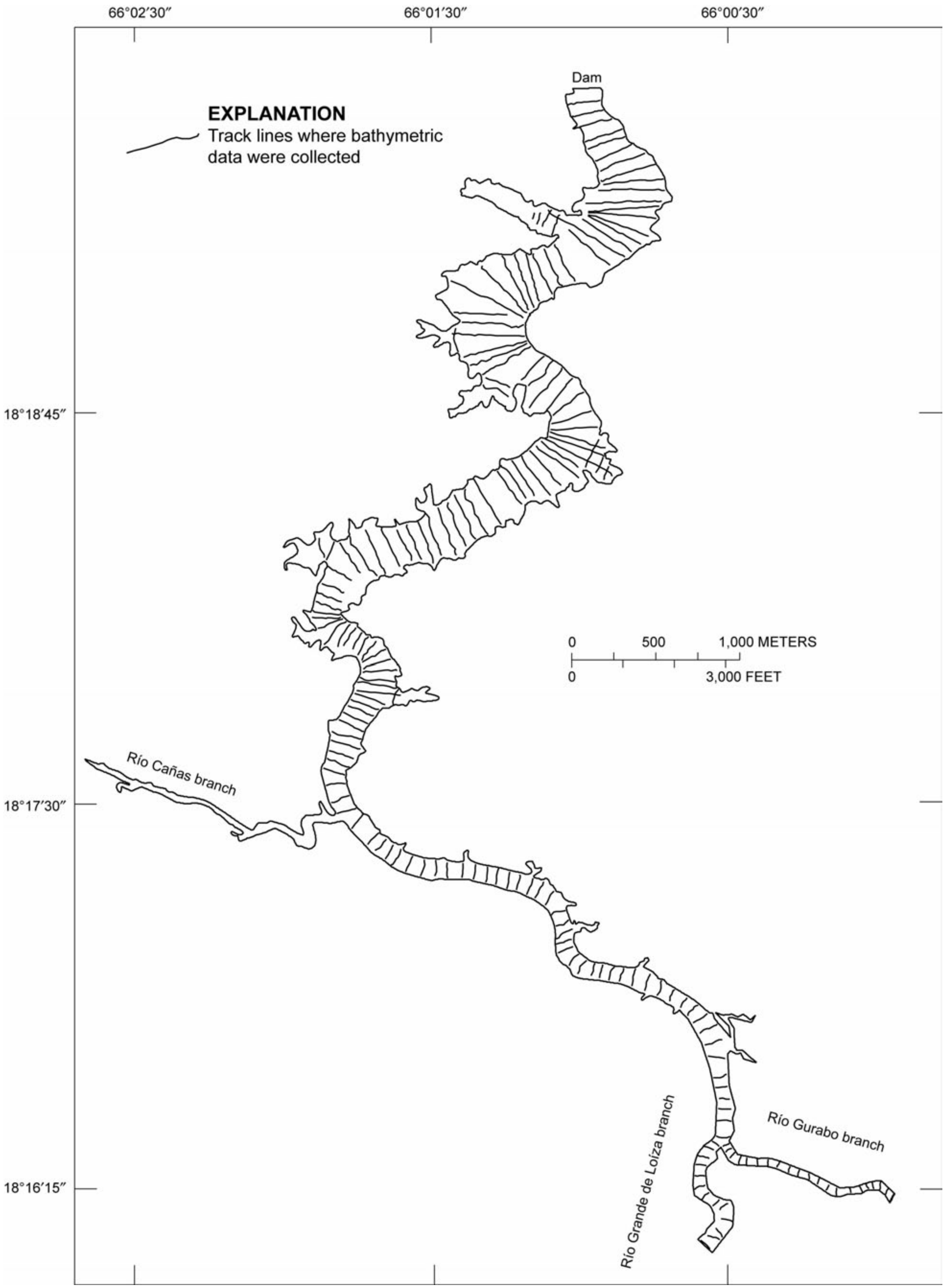


Figure 4. Actual track lines of the January 2004 bathymetric survey of Lago Loíza, Puerto Rico.

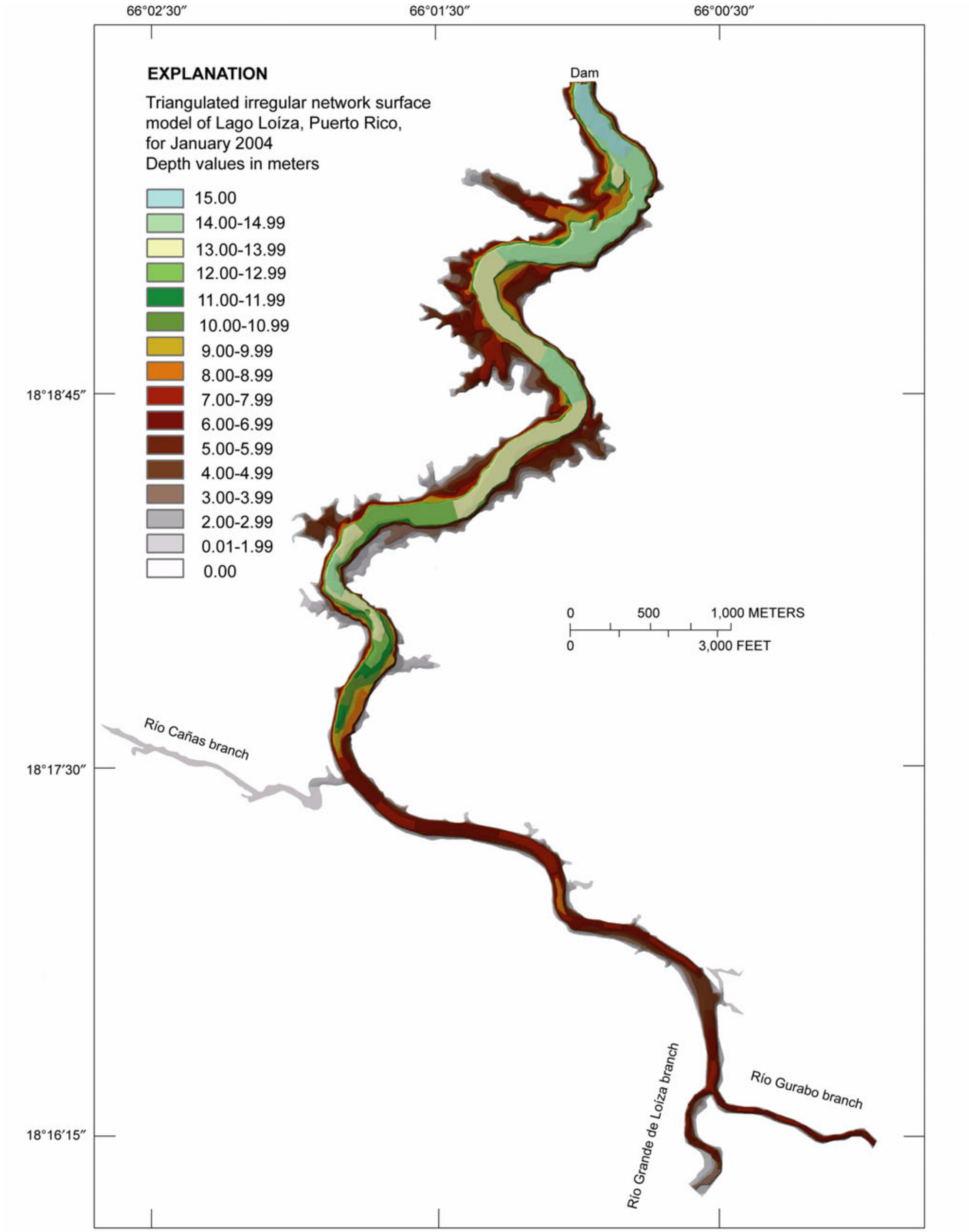


Figure 5. Triangulated irregular network surface model of Lago Loíza, Puerto Rico, for January 2004.

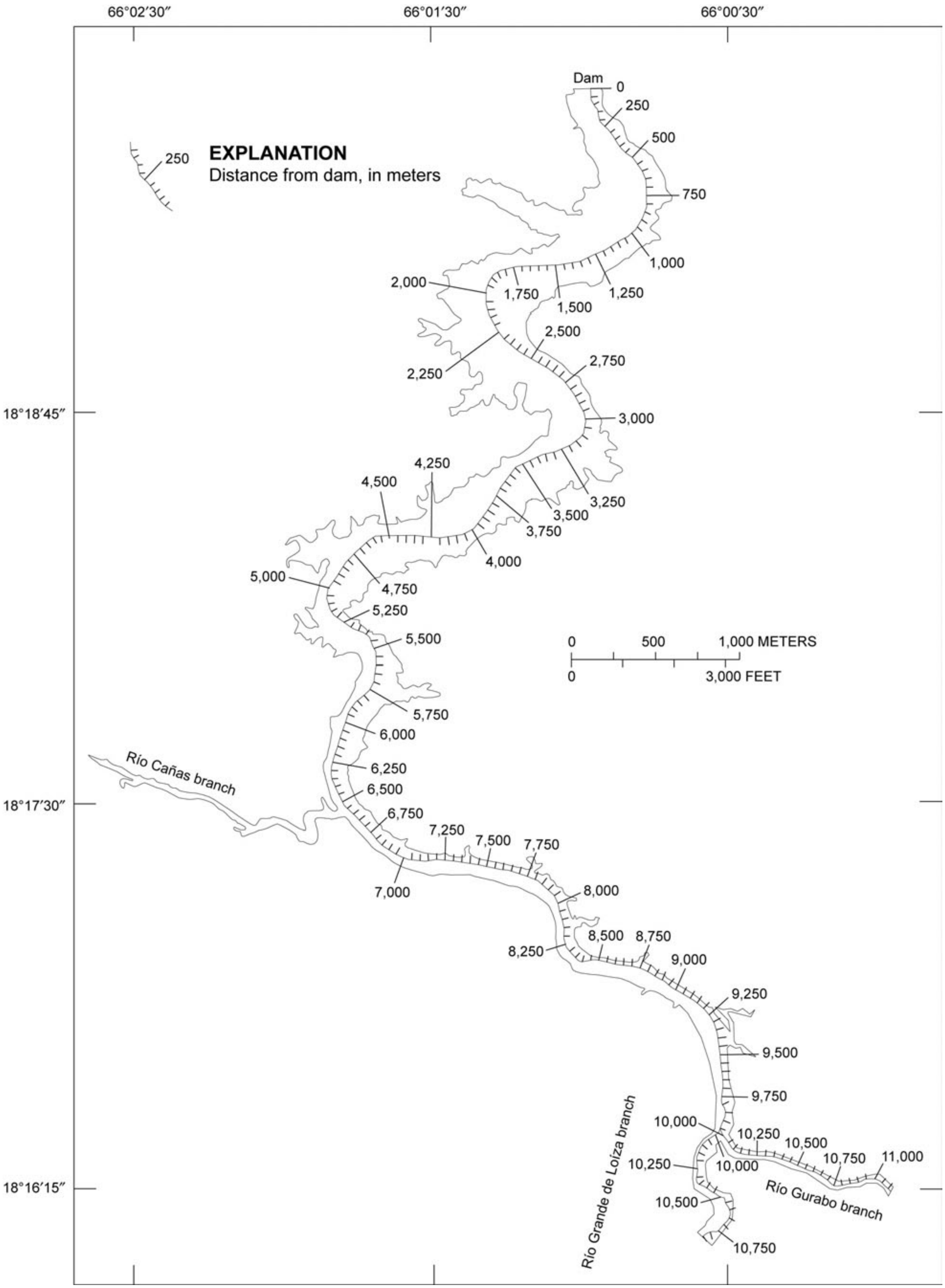


Figure 6. Reference longitudinal distance along the thalweg of Lago Loíza, Puerto Rico.

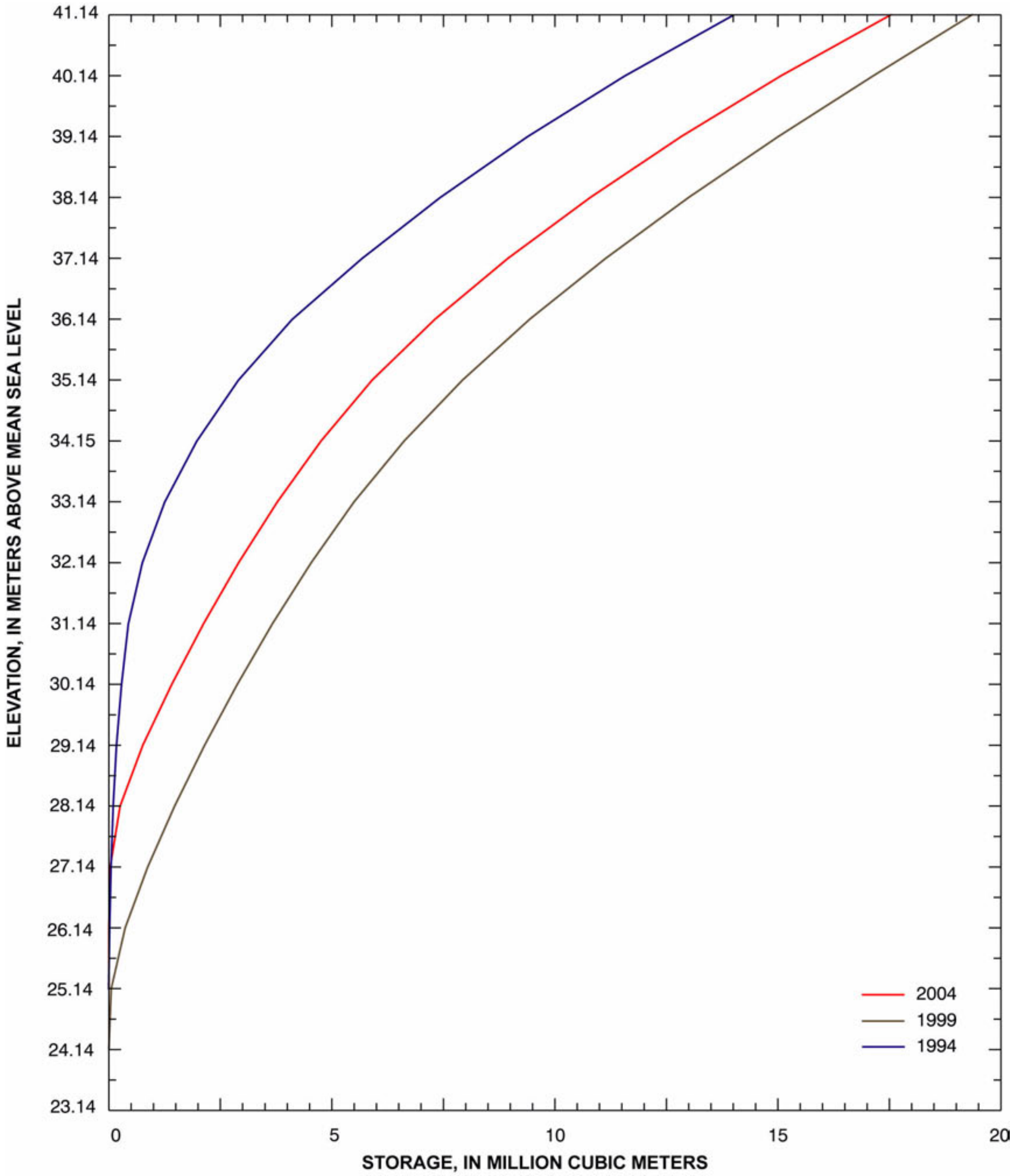


Figure 7. Relation between water-storage capacity and pool elevation of Lago Loíza, Puerto Rico, for 1994, 1999, and 2004.

The bathymetric contour map was used to create the TIN surface model of the reservoir bottom for 2004 (fig. 5). In addition, the 1994, 1999, and 2004 TIN surface models of Lago Loíza were used to generate transverse cross sections and longitudinal profiles of the reservoir's bottom. Sampling the TIN every 5 m along selected cross sections generated transverse cross sections representing the reservoir's bottom from shore to shore for 1994, 1999, and 2004 (fig. 8). The same procedure used in generating the selected cross sections was employed to generate the longitudinal profile along the thalweg of Lago Loíza for the same years (fig. 9). The selected cross sections were located to represent flooded areas of the reservoir, whereas the longitudinal profiles were located at the deepest part of the reservoir's bottom from the dam upstream to the confluence of the reservoir tributaries (Río Grande de Loíza and Río Gurabo).

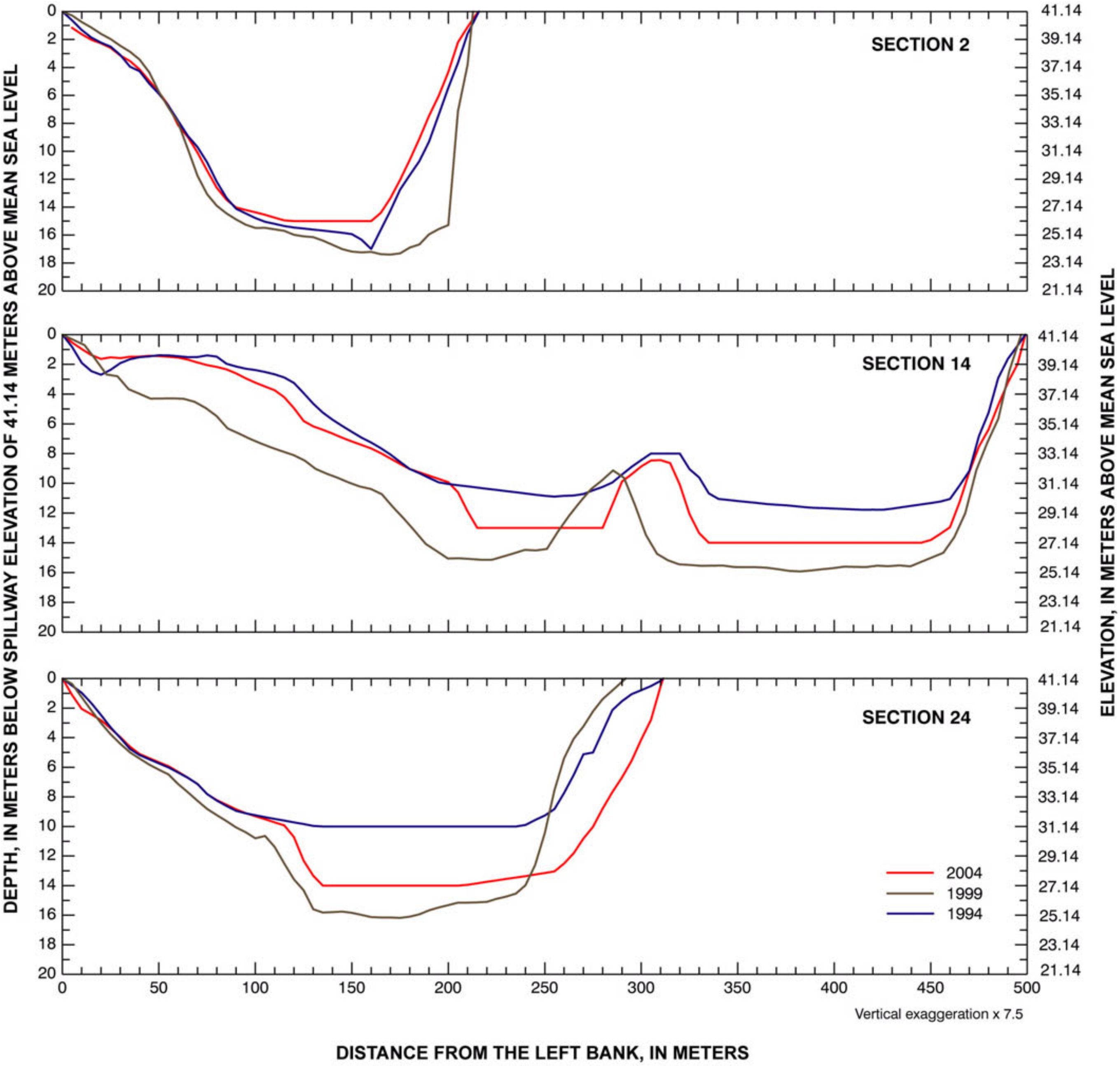
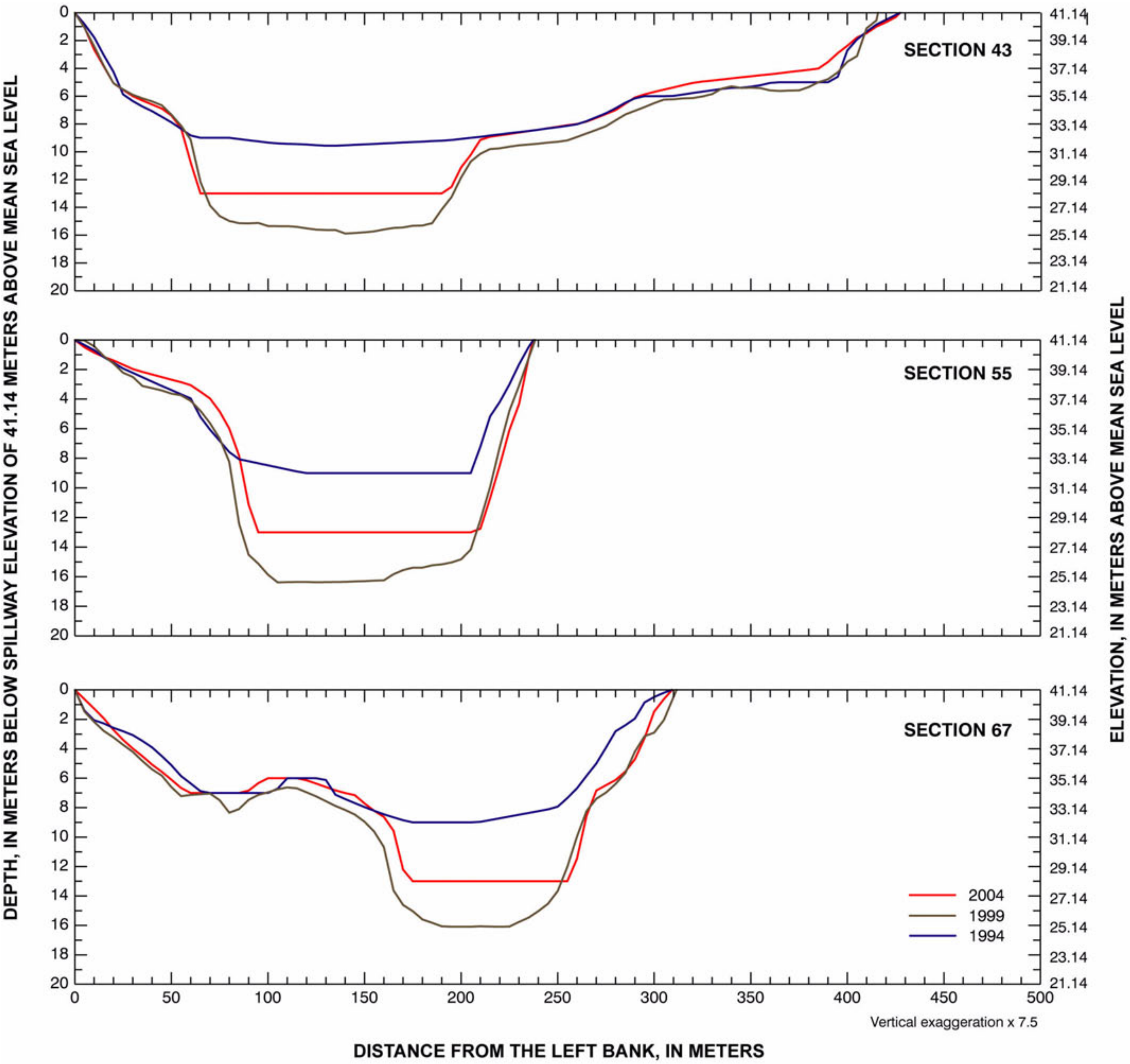


Figure 8. Selected cross sections generated from the TIN surface models of Lago Loíza, Puerto Rico, for 1994, 1999, and 2004. Refer to figure 3 for cross-section locations.



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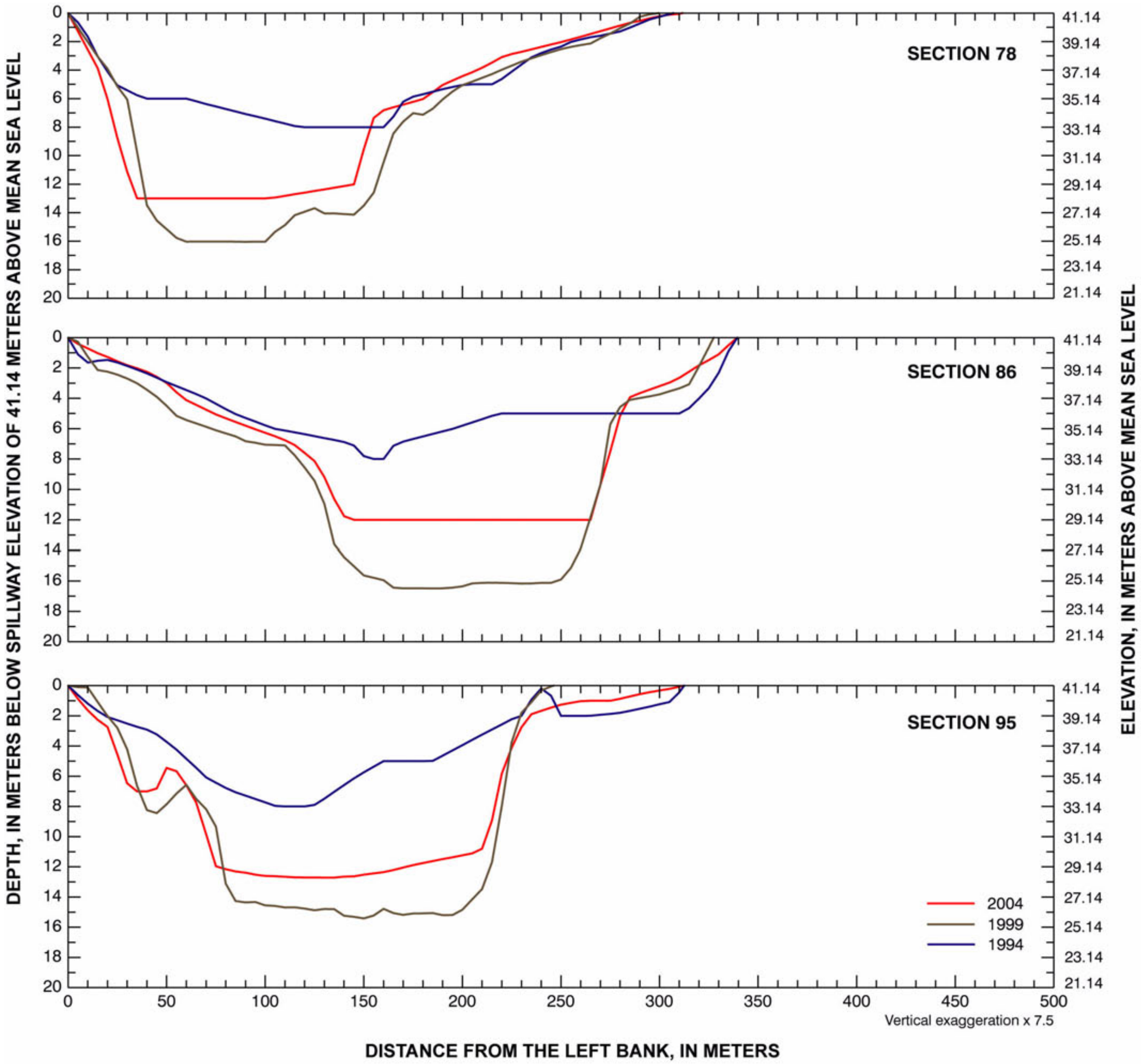

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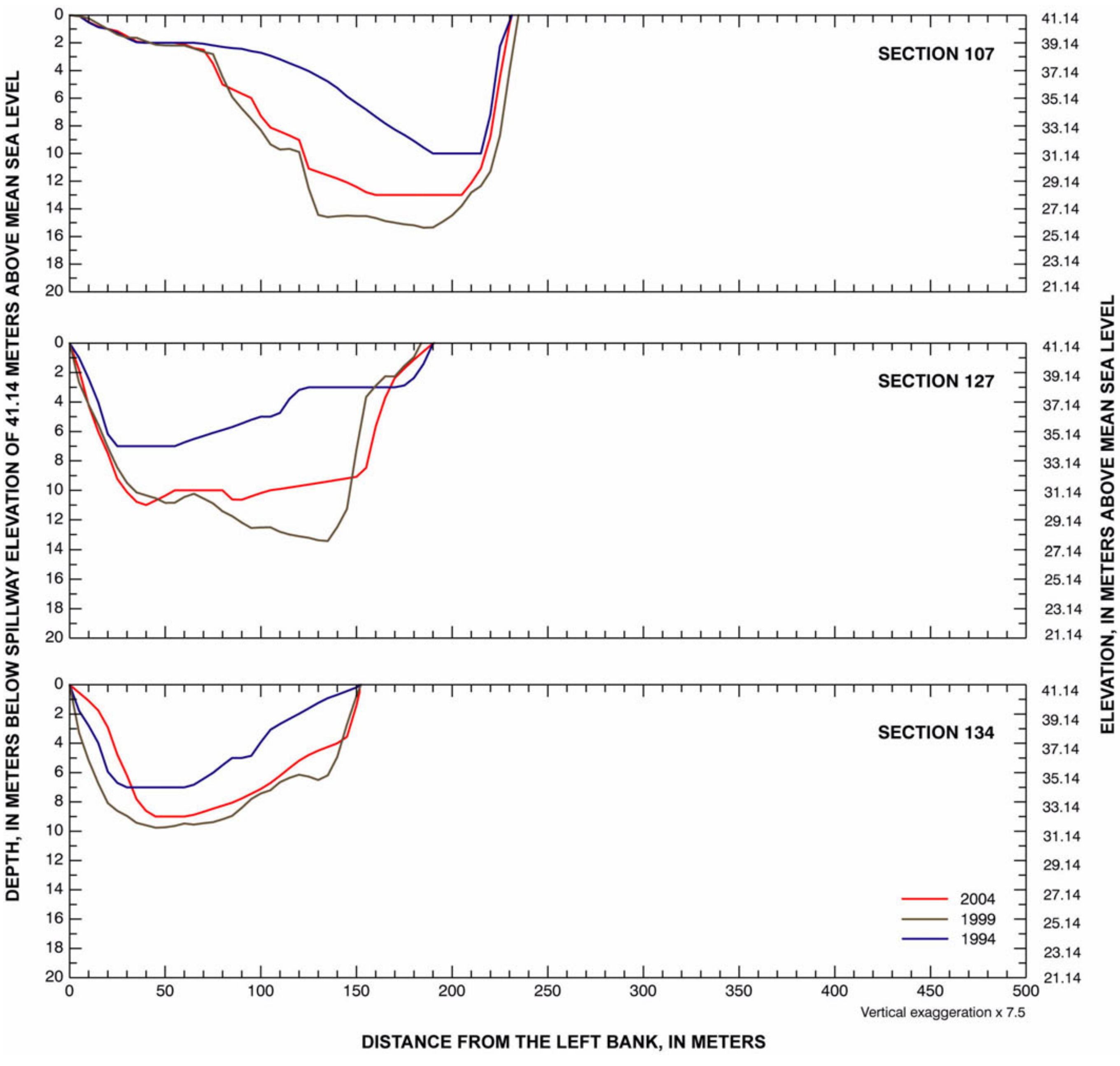

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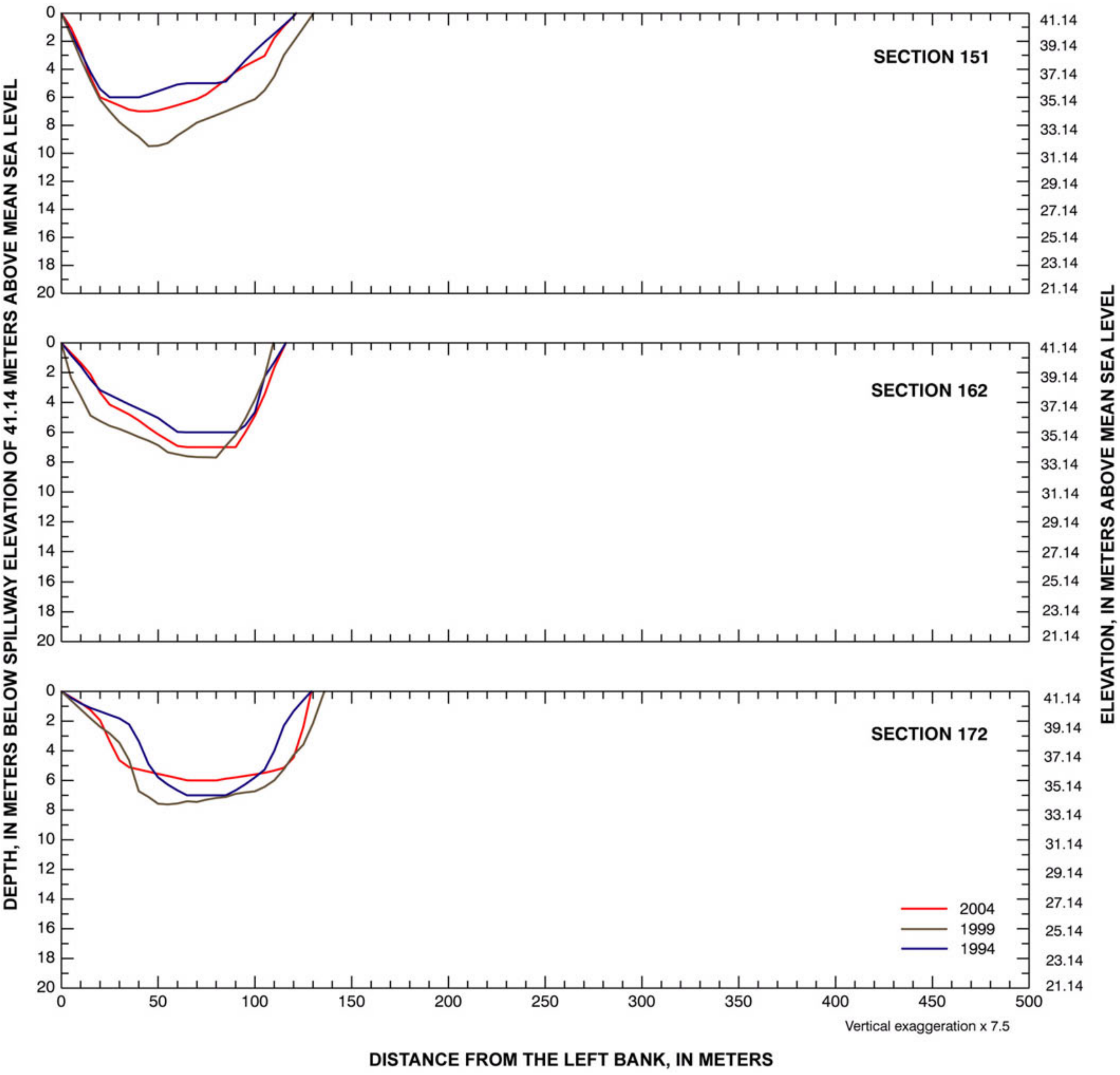

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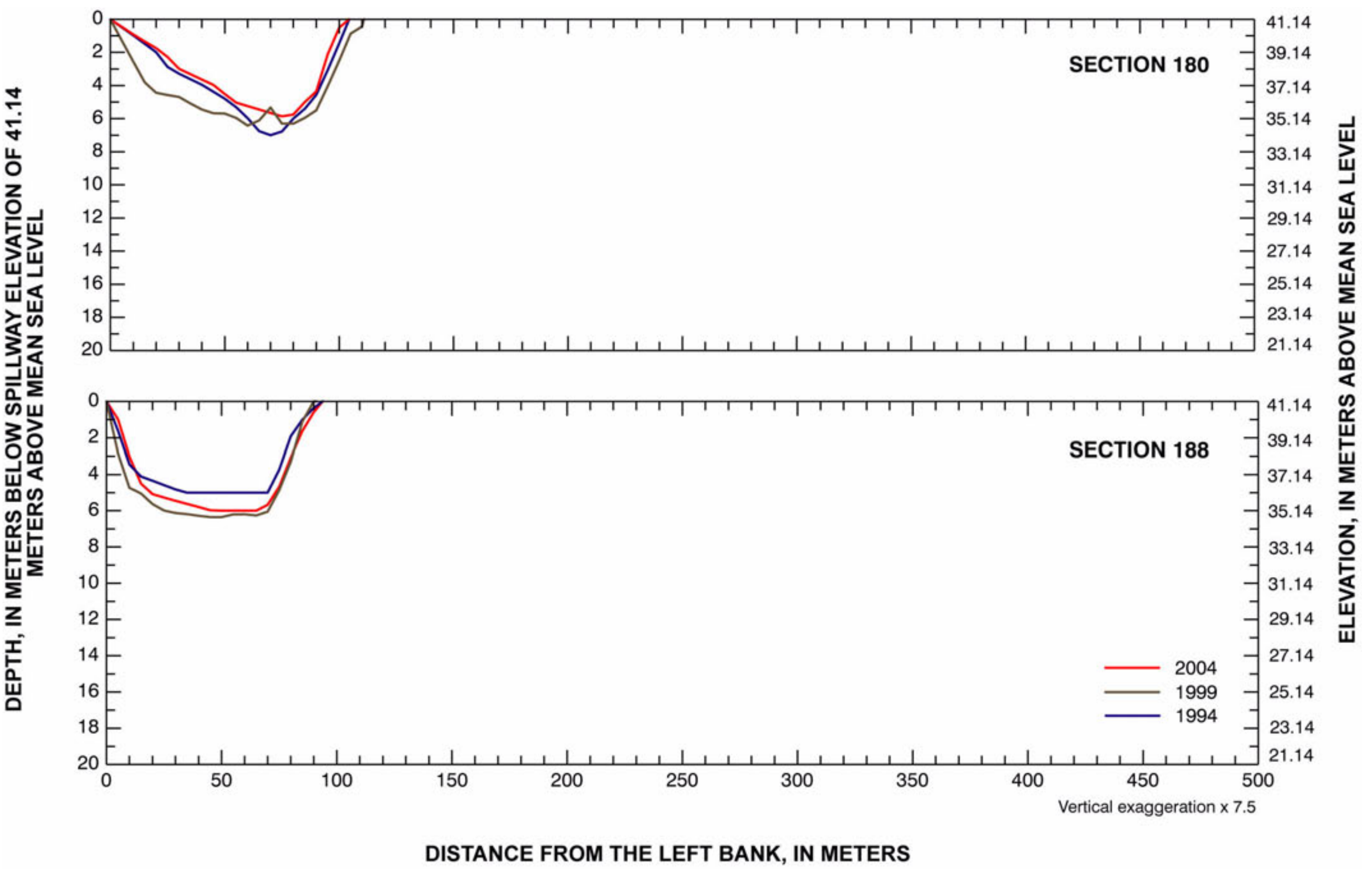

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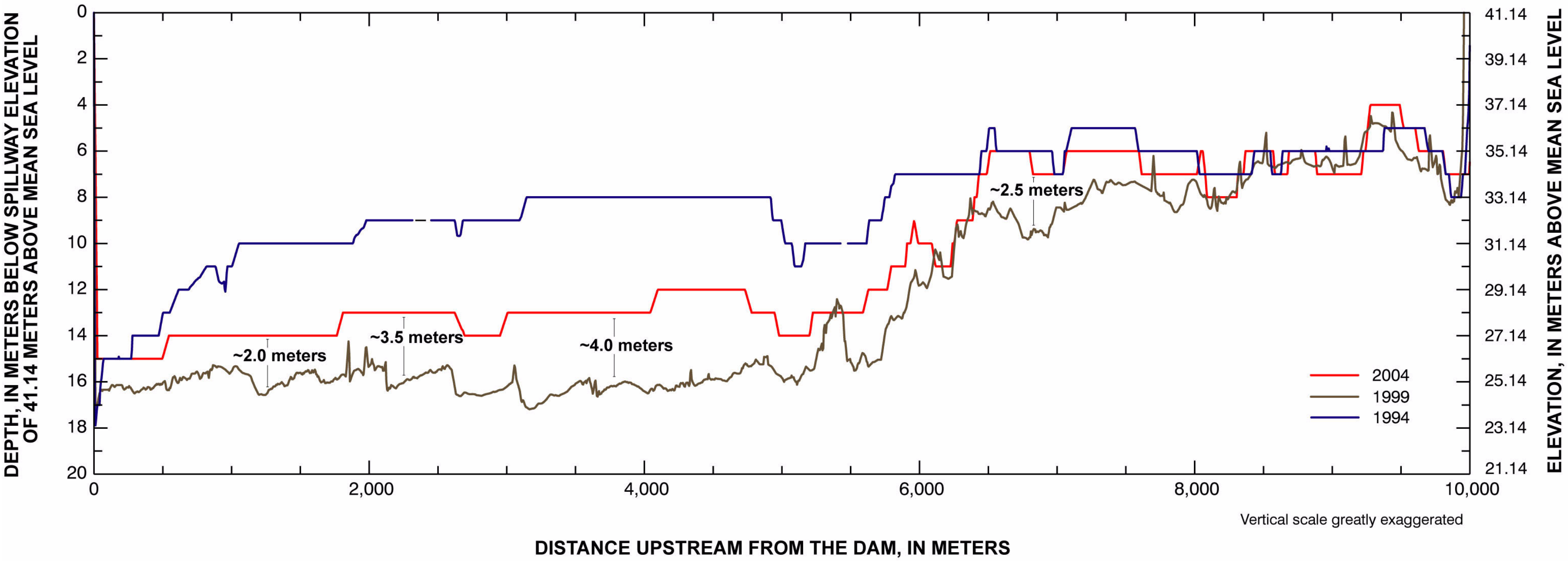

Figure 9. Longitudinal profiles along the thalweg of Lago Loíza, Puerto Rico, generated from the TIN surface models for 1994, 1999, and 2004.

Historical Sediment Accumulation and Effect on Reservoir Storage

The Lago Loíza reservoir has been affected by a relatively high sedimentation rate (compared to regional rates, Soler-López, 2001b), and the resulting storage-capacity loss since its construction in 1953. The original installed storage capacity was 26.80 million m^3 at 41.14 m above mean sea level in 1953, decreasing to 23.41 million m^3 by 1963 and to 20.00 million m^3 by 1971. The storage capacity continued decreasing to 16.38 million cubic meters in 1979, 15.20 million cubic meters in 1990, and to 14.19 million cubic meters in 1994 (Webb and Soler-López, 1997). The reservoir was dredged between 1997 and 1999 to augment the water-storage capacity, as a result of the reduced storage capacity of the reservoir, increase in draft rate to supply the Sergio Cuevas Filtration Plant and the drought of 1994, which led to water rationing during a 136-day period. The storage capacity of Lago Loíza before the dredging started in 1997, was estimated by applying the 1953-1997 sedimentation rate of about 310,000 m^3 for the period of 1994 to 1997, resulting in an estimated volume of about 13.26 million m^3.

The 1999 PRIFA reservoir storage capacity after dredging was reported as 19.35 million m^3 (Puerto Rico Infrastructure Financing Authority, written commun., 2004) or an increase of 36 percent compared with the 1994 storage capacity. Detailed information on the historical sedimentation trends of Lago Loíza from 1953 to 1994 was published in Webb and Soler-López (1997). Table 2 summarizes the 1994, 1999, and 2004 results of the respective sedimentation surveys of Lago Loíza.

The Lago Loíza storage capacity was increased by dredging from 14.19 million m^3 in 1994 to 19.35 million m^3 in 1999, for an increase of 36 percent compared with the 1994 volume. This 1999 storage capacity of Lago Loíza is about 72 percent of the original 1953 volume of 26.80 million m^3. Based on these values, the actual dredged-volume loss after the hurricanes is about 31 percent (1.82 out of 5.78 million m^3).

Table 2. Comparison between the 1994, 1999, and 2004 sedimentation surveys of Lago Loíza, Puerto Rico. All the 1994 data are derived from Webb and Soler-López (1997).

[---, undetermined or unavailable]

Year	1994	1999	2004
Reservoir surface area, in square kilometers	2.67	2.67	2.67
Storage capacity, in million cubic meters	14.19	19.35[1]	17.53
Live storage, in million cubic meters	14.15	17.80	17.28
Dead storage, in million cubic meters	0.04	1.55	0.25
Years since construction	41	46	51
Sediment accumulation since construction, in million cubic meters	12.61	14.30[2]	16.12[3]
Inter-survey sediment accumulation, in million cubic meters	1.01	1.69	1.82
Long-term storage capacity loss, in percent	47	53	60
Long-term annual storage capacity loss, in cubic meters	303,000	310,870	316,078
Inter-survey storage capacity loss, in percent	3.8	6	7
Inter-survey annual storage capacity loss, in percent	1.0	1.2	1.4
Inter-survey annual storage capacity loss, in cubic meters	242,000	338,000	364,000
Storage capacity added by dredging, in million cubic meters	---	5.78[4]	---
Dredged volume loss, in million cubic meters	---	---	1.82
Percent of dredged volume loss	---	---	31
Percent of annual dredge volume loss from 1999 to 2004	---	0	6.2

[1] Reported in storage-capacity table provided by the Puerto Rico Infrastructure Financing Authority.

[2] Sediment accumulation by 1994 (12.61 million cubic meters) plus the average annual sedimentation rate of about 337,000 cubic meters (as reported in Webb and Soler-López, 1997) applied from 1994 to 1999 (1.69 million cubic meters).

[3] Sediment accumulation by 1999 (14.30 million cubic meters) plus the loss between 1999 and 2004 (1.82 million cubic meters).

[4] Reported by the Puerto Rico Infrastructure Financing Authority.

This represents a dredged-volume loss of about 364,000 m^3/yr (6.2 percent per year) between 1999 and 2004. Figure 10 summarizes the Lago Loíza storage capacity variations and sedimentation rates from 1953 to 2004. As indicated by figure 10, high sedimentation rates occurred for the period of 1971 to 1979. This particularly high sedimentation rate of about 452,000 m^3/yr occurred during the construction of Highway PR-52 and the subsequent passage of Hurricane David and Tropical Storm Frederic in 1979. These high sedimentation rates, however, are considered to be short-term, low-occurrence events associated with land-use disturbances and extreme runoff events.

The sedimentation rate between 1999 and 2004 of 364,000 m^3/yr is 17 percent higher than the average long-term rate of about 310,000 m^3/yr, indicating that dredging activities alone may not be sufficient to increase substantially the life expectancy of Lago Loíza. Gellis (1991) documented the importance of land use in delivering sediment to Lago Loíza and, therefore, another alternative to reducing the sediment transport to Lago Loíza is upland erosion-control strategies.

Based on the data presented, it is uncertain that the existing sedimentation rate of Lago Loíza can be reduced substantially in the foreseeable future. The increased sedimentation rate after 1999 (0.36 million m^3/yr) probably reflects the sediment load transported into Lago Loíza by the flooding caused by Hurricane Georges on September 21, 1998. It is important to understand that the net effect of major floods may not be completely observed at the reservoirs until several years after the event occurred, as soil eroded by these extreme events tends to remain stored in the river channels upstream from the reservoir with the potential of rapid mobilization even with runoff events of minor intensity (Soler-López, 2001a, 2001b). The greater mass of sediment mobilization and deposition occurs primarily during rainfall-runoff events of substantial magnitude capable of mobilizing sand and coarse-grained streambed sediments, which make up the bed material in all inflowing tributaries. In the Lago Loíza basin, the source of sand and coarse material is the extensive granodiorite intrusive rock outcrop, which covers about 50 percent of the basin (Gellis, 1991).

It is reasonable to conclude that sediment accumulation in Lago Loíza tends towards an equilibrium state in which the reservoir loses storage capacity to a rate close to the historical long-term average sedimentation rate of about 310,000 m^3/yr. Higher sedimentation rates, however, can be induced by extreme rainfall-runoff events and land-use disturbances as shown on figure 10.

The Lago Loíza reservoir water-intake structure used for public-supply water withdrawals is located at an invert elevation of 28.0 m above mean sea level. The volume of water contained above the elevation of the intake structure is referred to as the live (useful) storage, and the volume below it is referred to as the dead storage (the dead storage is designed to accommodate sediment without disabling reservoir structures). The 2004 bathymetric data indicate that the reservoir's bottom in the vicinity of the water intake tower was at an approximate elevation of 26.0 m above mean sea level. This indicates that the reservoir's bottom is about 2 m below the invert (lower) elevation of the structure. Using the intake structure invert elevation of 28.0 m above mean sea level, the 2004 live storage of Lago Loíza is about 17.28 million m^3 and the dead storage is about 0.25 million m^3. The 2004 storage capacity of Lago Loíza at 1-m elevation intervals is listed on table 3.

The sediment deposition and distribution pattern in Lago Loíza, although appreciable in selected cross sections (fig. 8), is more distinguishable in the longitudinal bottom profiles of the reservoir (fig. 9). Sediment accumulation along the thalweg from the dam to the Río Grande de Loíza and Río Gurabo confluence since 1999 can be summarized as follows: a 1-m-thick layer of sediment has accumulated in the immediate vicinity of the dam; a 2-m-thick layer of sediment has accumulated slightly upstream from the dam to about 1,250 m upstream; a more uniform (overall elevation) sediment layer ranging from 3.5 to 4.0 m thick extends from about 1,750 to about 5,000 m upstream from the dam; and, a sediment layer of 2.5 m thick extends from about 6,500 to 7,000 m upstream from the dam. The sediment deposition rates in these specific areas from 1999 to 2004 are equivalent to 20, 40, 70, 80, and 50 centimeters per year (cm/yr), respectively. Sediment deposition rates increase with distance from the dam because coarse sediment settles in the bottom faster than finer sediment as sediment-laden water loses velocity. The relatively lower deposition rate of 50 cm/yr for the portion, about 7,000 m upstream from the dam, could be the effect of the narrow, relatively shallow reservoir morphology, which tends to maintain water velocities similar to the tributary rivers during high runoff events. It is precisely at about 5,000 to 6,000 m upstream from the dam that deposition rates are higher, where the reservoir morphology transforms from a narrow, relatively shallow channel to a wider, deeper channel.

Based on the sediment deposition rate of 20 cm/yr near the dam, the reservoir's bottom of Lago Loíza could reach the public-supply water intake structure in about 10 years, thus affecting the normal water withdrawals. The inflow towards the intake structure of about 4.38 cubic meters per second (m^3/s), however, makes the sediment deposition and settling improbable.

Based on the mean annual inflow to Lago Loíza of 363 million cubic meters and the 2004 water-storage capacity of 17.53 million m^3, the Lago Loíza drainage area provides enough water to completely fill the reservoir about 21 times per year. Therefore, Lago Loíza can store only about 5 percent of the mean annual inflow, and the percentage of basin runoff storage will continue to decrease as the water-storage capacity decreases, owing to sedimentation.

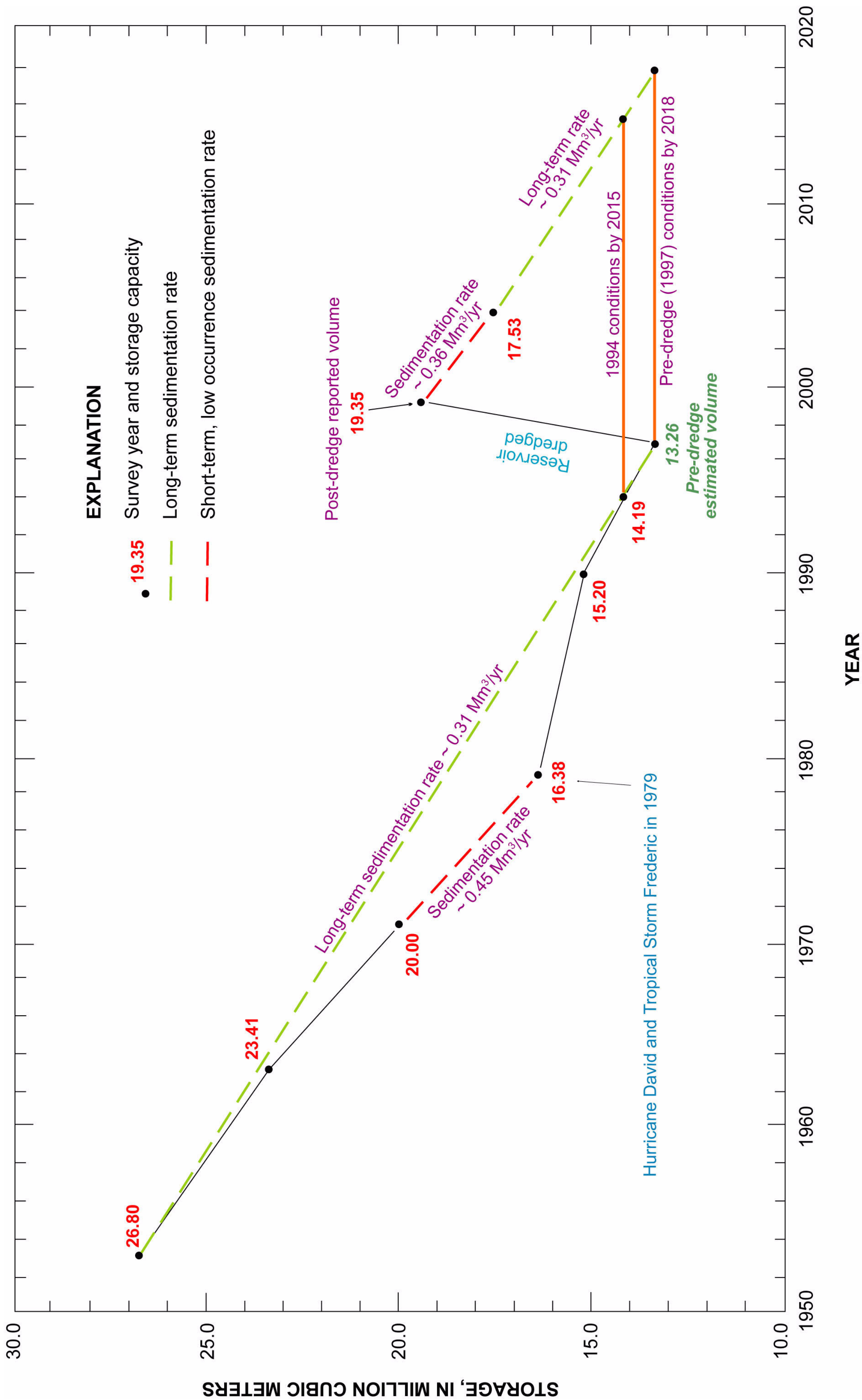

Figure 10. Lago Loíza storage capacities and sediment accumulation rates from 1953 to 2004.

Table 3. Storage capacity for Lago Loíza, Puerto Rico, January 2004.

Pool elevation, in meters above mean sea level	Storage capacity, in million cubic meters
41.14	17.53
40.14	15.07
39.14	12.84
38.14	10.80
37.14	9.95
36.14	7.31
35.14	5.90
34.14	4.76
33.14	3.78
32.14	2.91
31.14	2.12
30.14	1.41
29.14	0.76
28.14	0.25
27.14	0.03
26.14	0.00

Sediment Trapping Efficiency

Heinemann (1981) considered trapping efficiency to be the most informative descriptor of a reservoir, because it basically provides information on the useful life of a reservoir based on the mean annual sediment influx and the amount that is actually deposited in the reservoir. This value is the proportion of the incoming sediment that is deposited or trapped in a pond, reservoir, or lake. The trapping efficiency is dependent on several properties, including sediment particle-size distribution, the time and rate of water inflow to the reservoir, the reservoir size and shape, the location of the outlet structure, and the location and discharge schedules (Verstraeten and Poesen, 2000).

Many empirical studies showing the relation between reservoir storage capacity, water inflow, and trapping efficiency have been conducted in the past, of which Brune's (1953) is the most widely used and accepted. Brune developed a curve (fig. 11) that estimates the trapping efficiency of a reservoir based on the ratio of storage capacity to annual water inflow volume. The trapping efficiency of Lago Loíza was estimated using the relation established by Brune (1953). In addition, a suspended-sediment budget for Lago Loíza was estimated for the period of 1996 to 2002, using the USGS suspended-sediment stations network and compared with the estimate derived from Brune's curve.

Based on historical data, the estimated long-term mean annual runoff for the entire Lago Loíza drainage area is 363 million m^3, and the 2004 reservoir storage capacity is 17.53 million m^3. Therefore, the ratio of capacity to inflow (C/I) of Lago Loíza is 0.048 (17.53/363). Using the median curve of Brune's relation, the Lago Loíza sediment trapping efficiency was estimated to be 72 percent for 1994, 78 percent for 1999, and 76 percent for 2004. The increase in sediment trapping efficiency recorded from 1994 and 1999 is the result of the increased reservoir storage resulting from reservoir dredging operations between 1997 and 1999. Conversely, the sediment trapping efficiency decreased from 1999 to 2004, as a result of the reservoir storage-capacity decrease.

Streamflow and suspended sediment have been monitored at each of the five tributaries draining into the reservoir. Table 4 summarizes the total suspended-sediment load for each water year from 1996 to 2002.

The data presented on table 4 indicate that two major suspended-sediment loads entered the reservoir, when Hurricanes Hortense (1996) and Georges (1998) made landfall in Puerto Rico. For water year 1996, about 78 percent (753,508 metric tons) of the total suspended-sediment load of all tributaries were generated during the passage of Hurricane Hortense on September 10, 1996 (Díaz and others, 1996-2002). For water year 1998, about 61 percent (512,523 metric tons) of the total suspended-sediment load was generated during the passage of Hurricane Georges on September 20-21, 1998 (Díaz and others, 1997-2004). These suspended sediment loads represent 144 and 98 percent, respectively, of the average suspended-sediment load of 524,585 metric tons for a 5-year period (1996-2000).

Sediment Yield and Reservoir Life Expectancy

Sediment yield has been defined by the American Society of Civil Engineers as the total sediment outflow measurable at a point of reference, for a specified period of time, per unit of surface area contributing to the point of reference (McManus and Duck, 1993). For the period of 1994 to 1999, the total estimated volume of sediment contributed to Lago Loíza from a drainage area of 538 km^2 is estimated at 2.17 million cubic meters. This volume is estimated by dividing 1.69 million cubic meters of sediment accumulation from 1994 to 1999 (table 2) by the estimated sediment trapping efficiency of 78 percent for 1999. This estimated rate of sediment influx (2.17 million cubic meters) divided by the number of years between 1994 and 1999 (5 years), results in an average of about 434,000 cubic meters per year. This sediment volume eroded from the Lago Loíza drainage area divided by the net sediment contributing area of 535 km^2, (the total drainage area of 538 km^2 minus the 2.67 km^2 surface area of the reservoir) results in an average basin sediment yield, or area-normalized reservoir storage loss of 811 cubic meters per square kilometer per year ($m^3/km^2/yr$). The sediment yield from 1999 to 2004 is about 907 $m^3/km^2/yr$. The average drainage area sediment yield for the period 1994-2004 is about 859 $m^3/km^2/yr$.

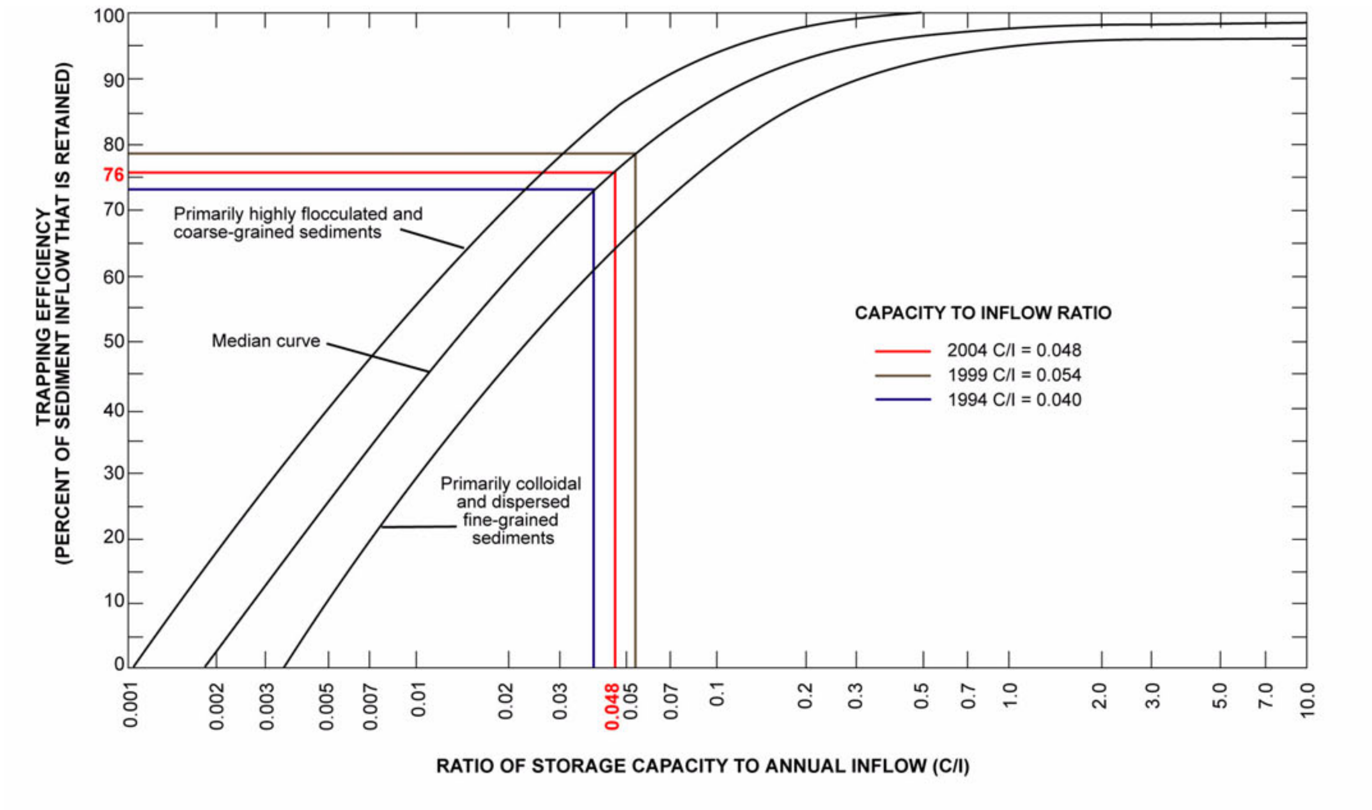

Figure 11. Reservoir trapping efficiency as a function of the ratio between water-storage capacity and annual water inflow volume (Brune, 1953).

Table 4. Suspended-sediment loads at tributary streams to Lago Loíza for water years 1996 to 2002, in metric tons per year (Díaz and others, 1997-2004).

[---, no data available; N/A, not applicable]

Tributary	1996	1997	1998	1999	2000	2001	2002	Total for the period 1996-2000
Río Grande de Loíza	494,992	68,745	548,820	159,086	131,140	87,124	71,567	1,402,783
Río Gurabo	276,172	23,215	182,983	100,431	64,236	37,274	7,201	647,037
Río Cagüitas	38,801	3,625	68,262	49,537	114,326	---	---	274,551
Río Bairoa	36,720	358	5,475	19,459	13,807	1,887	---	75,819
Río Cañas	116,414	9,193	33,731	31,496	31,902	6,676	---	222,736
Total for the year	963,099	105,136	839,271	360,009	355,411	N/A	N/A	Average 524,585

These sediment yields are about one-and-a-half times higher than the value of 600 $m^3/km^2/yr$ reported for the period from 1990 to 1994, possibly reflecting the impact of Hurricanes Hortense in 1996 and Georges in 1998 as evidenced by the suspended-sediment loads calculated for these years.

Sediment cores of about 2 m in depth were collected from four locations in Lago Loíza in December 1990, as part of a study conducted by the USGS on the effects of land use in the Lago Loíza basin on upland erosion, sediment transport, and reservoir sedimentation (Gellis and others, 1999). These cores were taken for the determination of many properties and characteristics, but for the published report, the sediment dry-bulk density data were not published. The average dry-bulk density of the cores was roughly 1 gram per cubic centimeter. Therefore, an estimate of the sediment yield from the drainage area of Lago Loíza on a mass basis was estimated by using the sediment dry-bulk density of 1 gram per cubic centimeter determined for that study. Thus, the Lago Loíza sediment yield on a mass basis is equivalent to 859 and 907 megagrams per square kilometer per year for 1994-2004, and 1999-2004, respectively. These drainage area-normalized storage-capacity loses of Lago Loíza are about half the average of 1,578 $m^3/km^2/yr$ for14 reservoirs studied in Puerto Rico (Soler-López, 2001b).

The life expectancy of Lago Loíza or any other reservoir can be estimated by dividing the remaining storage capacity by the annual storage-capacity loss. Using the average long-term (1953-1997) reservoir storage loss rate of 310,000 m^3/yr as previously indicated, the reservoir would completely fill in about 56 years or by the year 2060. More important, however, is the fact that the gain in storage remaining from the dredging operations between 1997 and 1999 could be lost to sedimentation in about 13 years (3.96 million m^3 [amount of remaining water storage] divided by 0.31 million m^3 [the long-term sedimentation rate]). This dredging operation was conducted to augment the “safe yield” of Lago Loíza as the public-water supply source of the Sergio Cuevas Filtration Plant serving the eastern part of the San Juan metropolitan area. At the time of the drought in 1994, the filtration plant was unable to maintain a production rate of 340,000 m^3/d (90 million gallons per day) leading to water rationing during a 136-day period (Rodríguez-Martínez and others, 2002).

Summary and Conclusions

The Carraízo Dam was constructed in 1953 and constitutes a major public-supply water source for the San Juan metropolitan area. In 1977, as a result of loss to sediment accumulation, flash boards were installed to increase the storage capacity to about 2.7 million cubic meters and increase the “safe yield” of the reservoir. The reservoir storage capacity, however, continued to decrease as documented by several subsequent sedimentation surveys. The consequences of lost storage became evident during 1994, when a major drought resulting from a rainfall deficit of about 30 percent between August 1993 and September 1994 led to a 136-day water rationing schedule affecting the eastern part of the San Juan metropolitan area.

Prompted by this water-supply shortfall, the reservoir was dredged between 1997 and 1999, to increase the storage capacity by about 5.8 million cubic meters. Prior to initiating the dredging project, however, Hurricane Hortense impacted the Lago Loíza watershed in 1996 and Hurricane Georges in 1998. Both of these hurricanes caused major flooding in the basin and undoubtedly contributed to reservoir storage depletion through sedimentation.

During January 2004, the U.S. Geological Survey in cooperation with the Puerto Rico Aqueduct and Sewer Authority conducted a bathymetric survey of Lago Loíza reservoir to assess the impact of these two storms on the water-storage capacity of the reservoir and to investigate the possible impact on dredging performed from 1997 to 1999.

The bathymetric survey results indicate that (1) the storage capacity of Lago Loíza in 2004 was 17.53 or 3.34 million cubic meters greater than that calculated in 1994 (14.19 million cubic meters); (2) the sedimentation rate of the reservoir on a long-term basis (1953-1997) is about 310,000 cubic meters per year, (3) the sedimentation rate between 1999 and 2004 was estimated at about 364,000 cubic meters per year, and (4) based on this sedimentation rate, the reservoir storage could reach the volume of 1994 by about the year 2015 and to pre-dredge conditions (1997) by the year 2018.

The long-term sedimentation rate of Lago Loíza of about 310,000 cubic meters per year may be increased by major land-use changes and rainfall-runoff events of the magnitudes generated by hurricanes. Between 1994 and 1999, the sedimentation rate was estimated at 338,000 cubic meters per year and it is likely that this sediment loading rate increased as a result of the impact of Hurricane Hortense in 1996 and Georges in 1998. Also the high rate of 364,000 cubic meters per year from 1999 to 2004 could be the repercussion of these storms. Considering that about 50 percent of the drainage basin lies within a granodiorite intrusive rock outcrop, the sand portion of the sediment eroded from the stream banks or land surface by major storm events can remain stored longer than finer sediment in the river channels upstream from the reservoir with the potential of being mobilized by subsequent high runoff events. Therefore, the full impact of a major storm on the reservoir may not be completely observed until a few years after. As an example, the 1990 to 1994 drainage area sediment yield was in the range of 600 cubic meters per square kilometer per year. The yield increased, however, to about 811 cubic meters per square kilometer per year during the period from 1994 to 1999, and to 907 cubic meters per square kilometer per year for the period from 1999 to 2004, possibly reflecting the impact of Hurricanes Hortense and Georges. Other possible causes that could contribute to the increase in annual sediment yields could be land-use disturbances.

According to the 2004 bathymetric survey, Lago Loíza would be completely silted by the year 2060. The life expectancy of Lago Loíza was about 50 years, based on the 1994 sedimentation survey, and continues to be close to that (56 years) according to recent data. Dredging had the net effect of providing additional water for periods of low runoff and increased the reservoir life expectancy by about 18 years; however, the fact remains that the reservoir storage will likely reach the 1994 volume (when water rationing plans were implemented) by about 2015, cancelling out the safe-yield increase resulting from the dredging operations between 1997 and 1999.

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