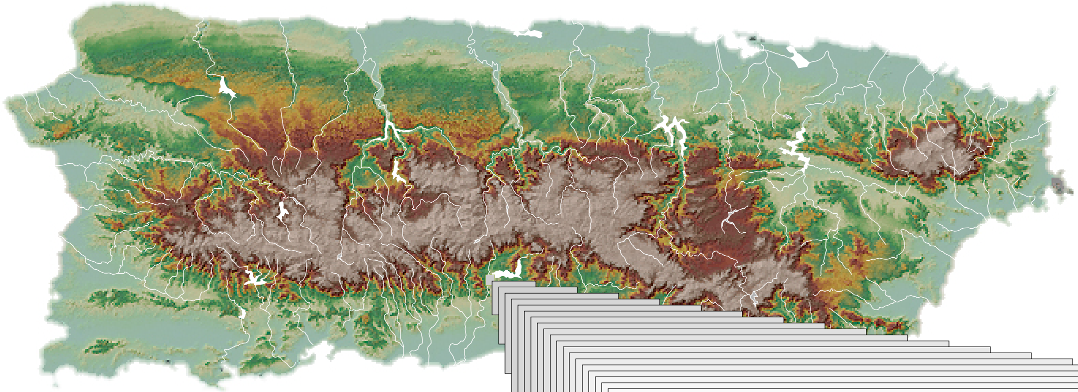
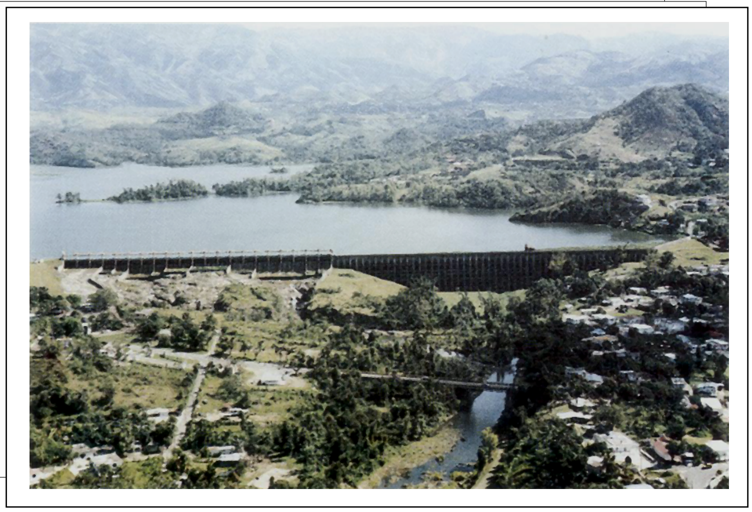
U.S. Department of the Interior
U.S. Geological Survey

Prepared in cooperation with the
PUERTO RICO ELECTRIC POWER AUTHORITY

Sedimentation History of Lago Guayabal, Puerto Rico, 1913-2001





Water-Resources Investigations
Report 03-4198

U.S. Department of the Interior
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Sedimentation History of Lago Guayabal, Puerto Rico, 1913-2001

By Luis R. Soler-López

Water-Resources Investigations Report 03-4198

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San Juan, Puerto Rico: 2003

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

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FIGURES

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CONVERSION FACTORS, DATUMS, ACRONYMS, and TRANSLATIONS

Multiply	By	To obtain
	Length	
millimeter	0.03937	inch
centimeter	0.03281	foot
meter	3.281	foot
kilometer	0.6214	mile
	Area	
square meter	10.76	square foot
square kilometer	0.3861	square mile
square kilometer	247.1	acre
	Volume	
cubic meter	35.31	cubic foot
cubic meter	0.0008107	acre-foot
million cubic meters	810.7	acre-foot
	Volume per unit time (includes flow)	
cubic meter per second	35.31	cubic feet per second
cubic meter per second	15,850	gallon per minute
cubic meter per second	22.83	million gallons per day
	Mass per area (includes sediment yield)	
megagram per square kilometer	2.855	ton per square mile

Datums

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 "Seal Level Datum of 1929".

Acronyms used in this report

BLASS	Bathymetric/Land Survey System
DGPS	Differential Global Positioning System
DOQ	Digital Orthophoto Quadrangle
GIS	Geographic Information System
GPS	Global Positioning System
PREPA	Puerto Rico Electric Power Authority
TIN	Triangulated Irregular Network
USGS	U.S. Geological Survey

Translations

Lago	Lake (in Puerto Rico, also reservoir)
Río	River

Sedimentation History of Lago Guayabal, Puerto Rico, 1913-2001

By **Luis R. Soler-López**

Abstract

The Lago Guayabal dam, located in the municipality of Villalba in southern Puerto Rico, was constructed in 1913 for irrigation of croplands in the southern coastal plains and is owned and operated by the Puerto Rico Electric Power Authority. The reservoir had an original storage capacity of 11.82 million cubic meters and a drainage area upstream of the dam of 112 square kilometers. Sedimentation has reduced the storage capacity to 6.12 million cubic meters in 2001, which represents a storage loss of about 48 percent. However, the actual sediment accumulation in the reservoir during the 88 years is greater, because some sediment removal was conducted between 1940 and 1948 by dredging and sluicing. This report summarizes the historical data from a 1913 land survey and eight bathymetric surveys conducted between 1914 and 2001, and the relation of high sedimentation to agricultural land practices within the Lago Guayabal basin and six major hurricanes which made landfall on the island.

The reservoir had an area-normalized sedimentation rate of about 1,863 cubic meters per square kilometer per year between 1913 and 1936 from a 112 square kilometer basin. In 1972, a new dam upstream along the Río Toa Vaca impounded runoff from 57.5 square kilometers, and sediment transport to Lago Guayabal was reduced. A comparison of bathymetric survey results between 1972 and 2001 indicates an area-normalized sedimentation rate of 1,120 cubic meters per square kilometer per year or about 60 percent of the rate between 1913 and 1936. The significant reduction (almost half) of the sedimentation rate after the Toa Vaca dam was built may indicate that erosion susceptibility of the Río Toa Vaca watershed is about twice that of the Río Jacaguas watershed impounded by Lago Guayabal.

INTRODUCTION

The Puerto Rico Power Electric Authority (PREPA) owns and operates the Lago Guayabal reservoir, located in southern Puerto Rico on the Río Jacaguas, about 5 kilometers north of the town of Juana Díaz and about 5 kilometers south of the town of Villalba (fig. 1). Because the south coast of Puerto Rico receives as little as 900 millimeters per year annual rainfall (Calvesbert, 1970), the reservoir was constructed as part of a major irrigation infrastructure project completed in 1914 to convey water for the cultivation of sugarcane along the southern coastal plains of the island.

Mean annual rainfall in the Lago Guayabal basin is about 1,800 millimeters, but can vary from less than 900 to more than 3,800 millimeters per year (Calvesbert, 1970) (fig. 2). These rainfall amounts, combined with the moderate erosion hazard of the Caguabo and Humatas soils that have slopes between 20 to 60 percent (Gierbolini, 1979) and the poor land-use management practices that have prevailed in the basin, have substantially impaired the reservoir storage capacity. Bathymetric surveys at Lago Guayabal have been conducted on a frequent basis given its importance as an irrigation source to the coastal plain which receives on average less than 1,150 millimeters of rainfall per year, with average pan evaporation rate of about 2,000 millimeters per year.

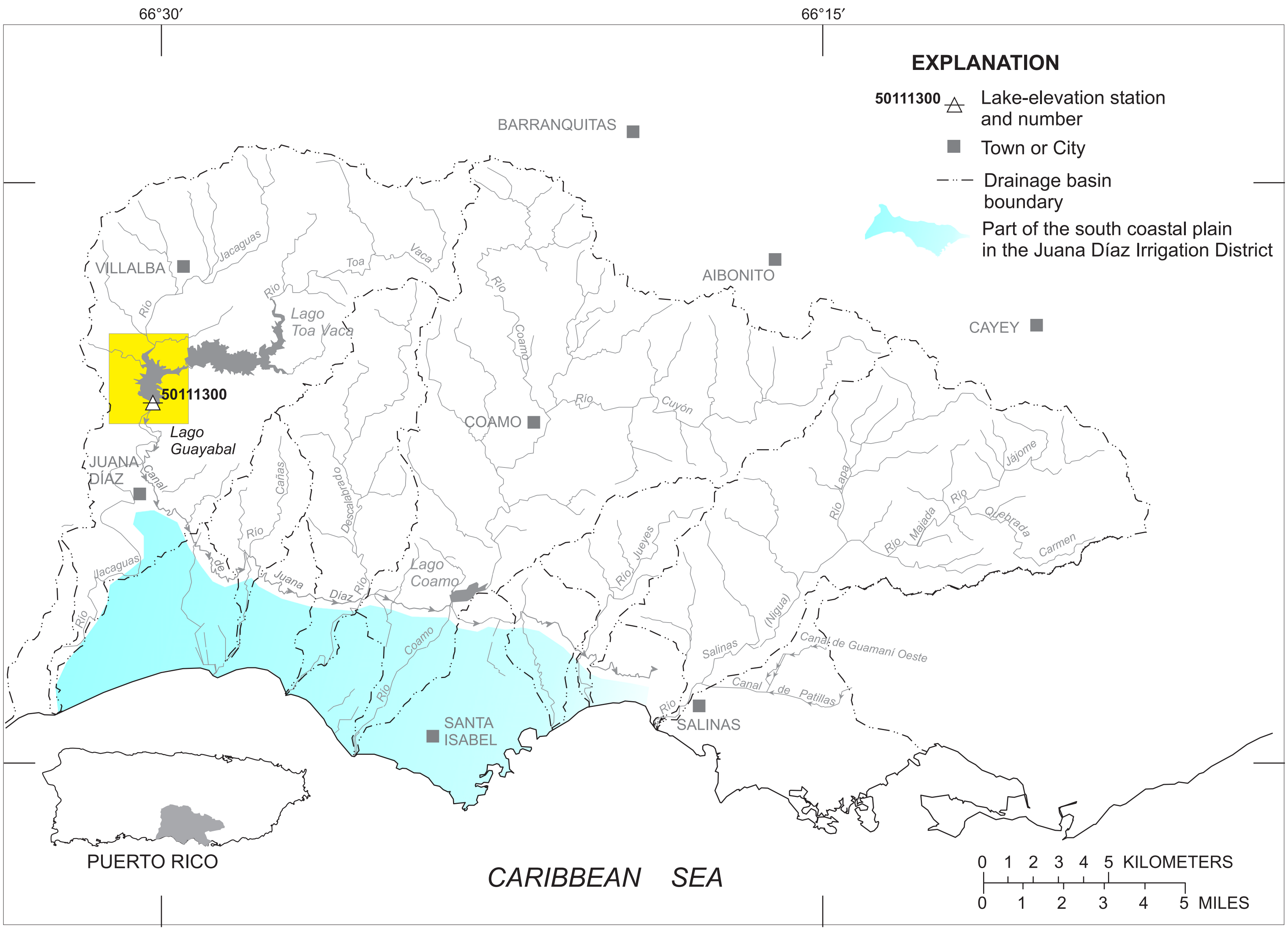


Figure 1. Location of Lago Guayabal in the Río Jacaguas basin and areas served by the Juana Díaz Irrigation District in southern Puerto Rico.

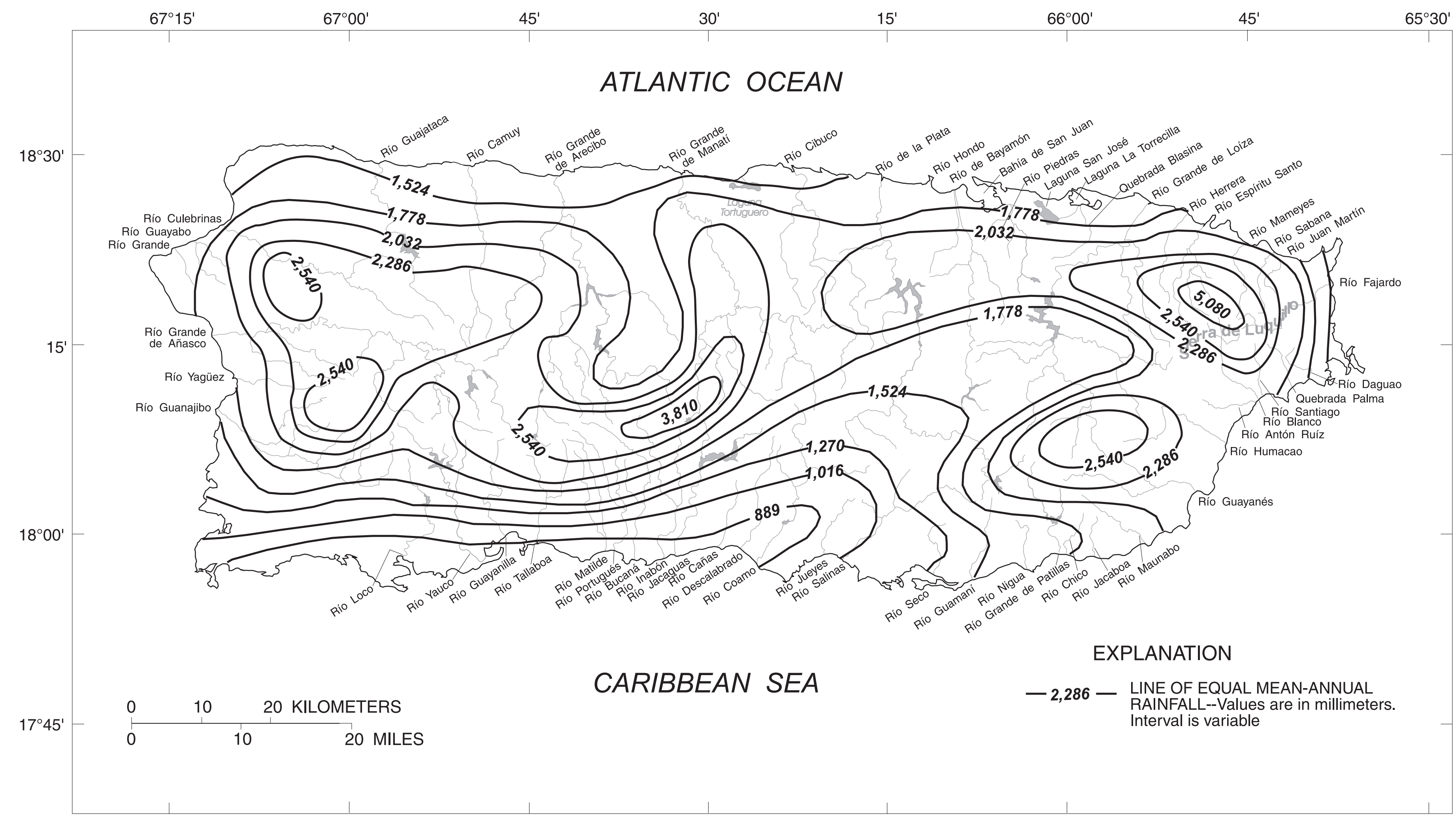


Figure 2. Isohyet map of the mean-annual rainfall distribution in Puerto Rico (modified from Calvesbert, 1970).

The U.S. Geological Survey (USGS), in cooperation with PREPA, conducted a bathymetric survey of Lago Guayabal during December 2001 using a differential global positioning system (DGPS) interfaced to a depth sounder. The field-collected data were then transferred into a geographic information system (GIS), which was used to determine the existing storage capacity, sedimentation rates, and sediment distribution, and to predict the useful life of the reservoir. This report provides the PREPA with the necessary information to more effectively manage the water resources in the Lago Guayabal Basin. Data from the December 2001 bathymetric survey were also compared with previous studies performed in 1914, 1936, 1950, 1951, and 1986 to define the historical long-term and inter-survey sedimentation rates, and the storage capacity loss, and to provide a current and accurate bathymetric contour map.

DAM, RESERVOIR, BASIN CHARACTERISTICS, AND GENERAL LAND-USE HISTORY

The Lago Guayabal dam structure was completed in 1913. It is located on the Río Jacaguas, in the municipality of Villalba in southern Puerto Rico, about 5 kilometers north of Juana Díaz and about 5 kilometers south of Villalba (fig. 1). The dam was designed to provide about 11.82 million cubic meters of storage for irrigation of sugarcane crops in southern Puerto Rico. When built, the spillway elevation was at 99.06 meters above mean sea level. However, the spillway was raised to 100.89 meters above mean sea level to allow the installation of flashboards during 1950-51 to compensate for the storage capacity loss as a result of high sediment influx to the reservoir. After the flashboards were installed, the normal pool elevation of Lago Guayabal was 103.94 meters above mean sea level. The reservoir drainage area was 112.0 square kilometers in 1913, however, the drainage area was artificially reduced when the Lago Toa Vaca dam was constructed on the eastern tributary of the reservoir (Río Toa Vaca) in 1972.

The dam is an Ambursen structure of slab and buttress construction with a structural height of 39.62 meters, and a length of 602.89 meters with buttresses at 5.49-meter centers (table 1). An earthfill structure with a concrete core extends from the left end of the non-overflow portion of the dam to the left abutment. The original 1913 spillway structure is located on the right abutment and had an elevation of 99.06 meters above mean sea level. Twenty intermediate piers, each 0.91 meter wide, separate the crest into 21 bays which are controlled by automatic flashboards 10.06 meters wide by 3.05 high in the fully raised position.

Irrigation releases from the reservoir are provided by an intake structure located on the upstream face of the non-overflow section of the dam between buttresses 20 and 21, and has an invert elevation (lower structure portion) of 87.17 meters above mean sea level. This information and other characteristics of Lago Guayabal dam are presented in table 1.

The Lago Guayabal basin is within the Caguabo and Humatas soil series in south central Puerto Rico (Gierbolini, 1979). These series generally consist of well drained, moderately steep to very steep, and moderately permeable soils, with a moderate erosion hazard. Hill slopes range from 20 to 60 percent. The solum of the Caguabo series is 36 to 61 centimeters thick, and the Humatas series solum is 76 to 132 centimeters thick. Surface runoff in these soils is rapid; thus, the moderate susceptibility to erosion.

The Caguabo soils for the most part have remained in pasture, brush, with some shallow-rooted crops, such as pigeon peas that can be cultivated without the need of irrigation and adapt well to local soils. For many years, the Humatas soils have been planted with a wide variety of crops, which include coffee, yams, plantains, and tanniers. In addition, some areas are covered with native pasture (Gierbolini, 1979).

Aerial photographs or topographic maps of the Lago Guayabal drainage area were not available at the time of construction or used over time as a tool for the comparison of the vegetation coverage and land use changes. However, by the early and mid-20th century, the Lago Guayabal drainage area was affected by an intensive use for agricultural purposes. During the first half of the 20th century, agriculture was primarily limited to the cultivation of export crops (coffee, tobacco and sugarcane) within large farmlands under private ownership. In 1941, the Puerto Rico Legislative Assembly created the Lands Authority with the purpose of re-distributing parcels of land among the predominantly rural population living as "agregados" or land-attached workers. This newly created authority had the power of expropriating lands in excess of 2 square kilometers from non-resident corporations, and selling the land to people who wished to cultivate it. The Lands Authority also played a major role in upgrading cultivation and harvest techniques to improve crops production. Figure 3 shows a 1959 map with the principal crops cultivated within the south-central portion of Puerto Rico, including the Lago Guayabal drainage area (Gaztambide-Vega and Arán, 1959). Coffee was the predominant crop cultivated in the basin, with sugar cane as the secondary crop principally within the Río Toa Vaca basin portion of the Lago Guayabal basin.

It is important to point out some facts about the cultivation of coffee, which enhances soil erosion. Coffee seedlings were planted in loose, unstable soil free of leaf litter below the forest canopy, during the rainy season, which is a sensitive period in terms of erosion susceptibility. Throughout most of the first half of the 20th century, the coffee variety planted required shade, thus a forest canopy was maintained. This coffee variety produced larger, healthier coffee plants, but the fruit production was smaller compared with a plant variety that thrived best exposed to direct sunlight. In general, the coffee production was about 10 times higher per unit of surface area when exposed to sunlight, as compared to plants requiring shade of a forest canopy (Picó, 1964). This finding encouraged clearing of large forested areas to plant coffee under sunlight. However, the coffee plants died sooner than those requiring shade. Therefore, additional land clearing was required for the planting of new seedlings to maintain coffee production. Figure 4 puts in perspective the importance of coffee planting throughout the upland eastern half of Puerto Rico. During the period 1913-1920, coffee production was high (fig. 4), thus erosion potential from the upper parts of the drainage area could have been at its maximum, and later it may have decreased considerably after mid-1920's.

Table 1. Principal characteristics of Lago Guayabal and Guayabal dam, Puerto Rico (modified from PREPA, 1988)

Total length of dam, in meters	602.89
Maximum height of dam, in meters	39.62
Invert elevation of intake structure, in meters above mean sea level	87.17
Original crest elevation of spillway structure, in meters above mean sea level	99.06
New crest elevation of spillway structure, in meters above mean sea level	100.89
Normal pool elevation after the installation of flashboards, in meters above mean sea level	103.94
Maximum discharge capacity, in cubic meters per second[1]	2,060.0
Original drainage area at damsite, in square kilometers[1]	112.0
New drainage area at damsite after the Toa Vaca dam construction, in square kilometers[2]	54.5
Original reservoir surface area at elevation of 99.06 meters above mean sea level, in square kilometers	1.19
Reservoir surface area after the installation of flashboards, in square kilometers[3]	1.44
Maximum depth during the December 2001 bathymetric survey, in meters	13.0

[1] From PREPA, 1988.
[2] Calculated using GIS and 1:20,000 scale topographic map.
[3] Calculated using GIS at normal pool elevation.

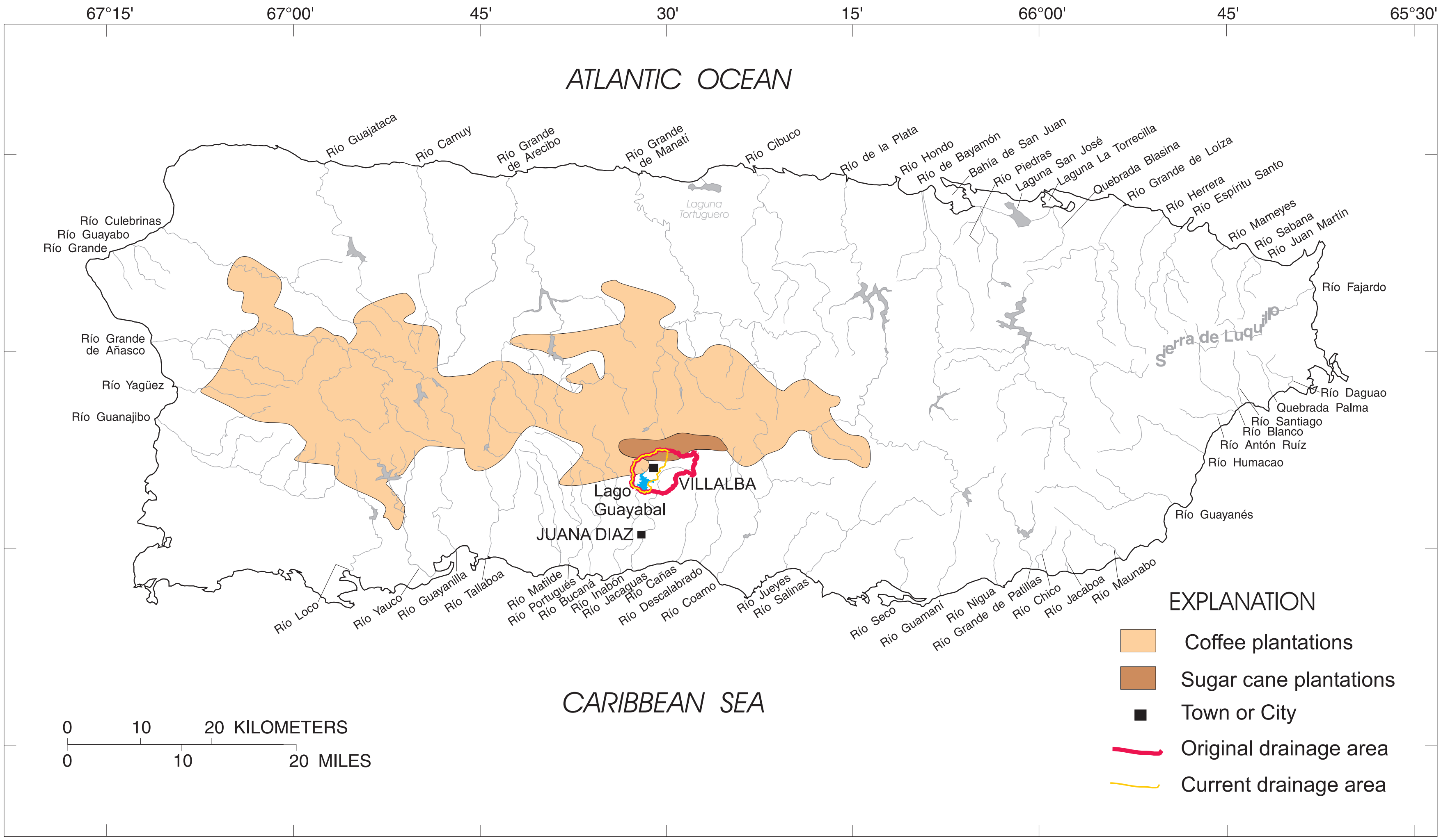


Figure 3. Predominant agricultural land use in the west-central mountainous areas of Puerto Rico during the mid-20th century (modified from Gaztambide-Vega and Arán, 1959).

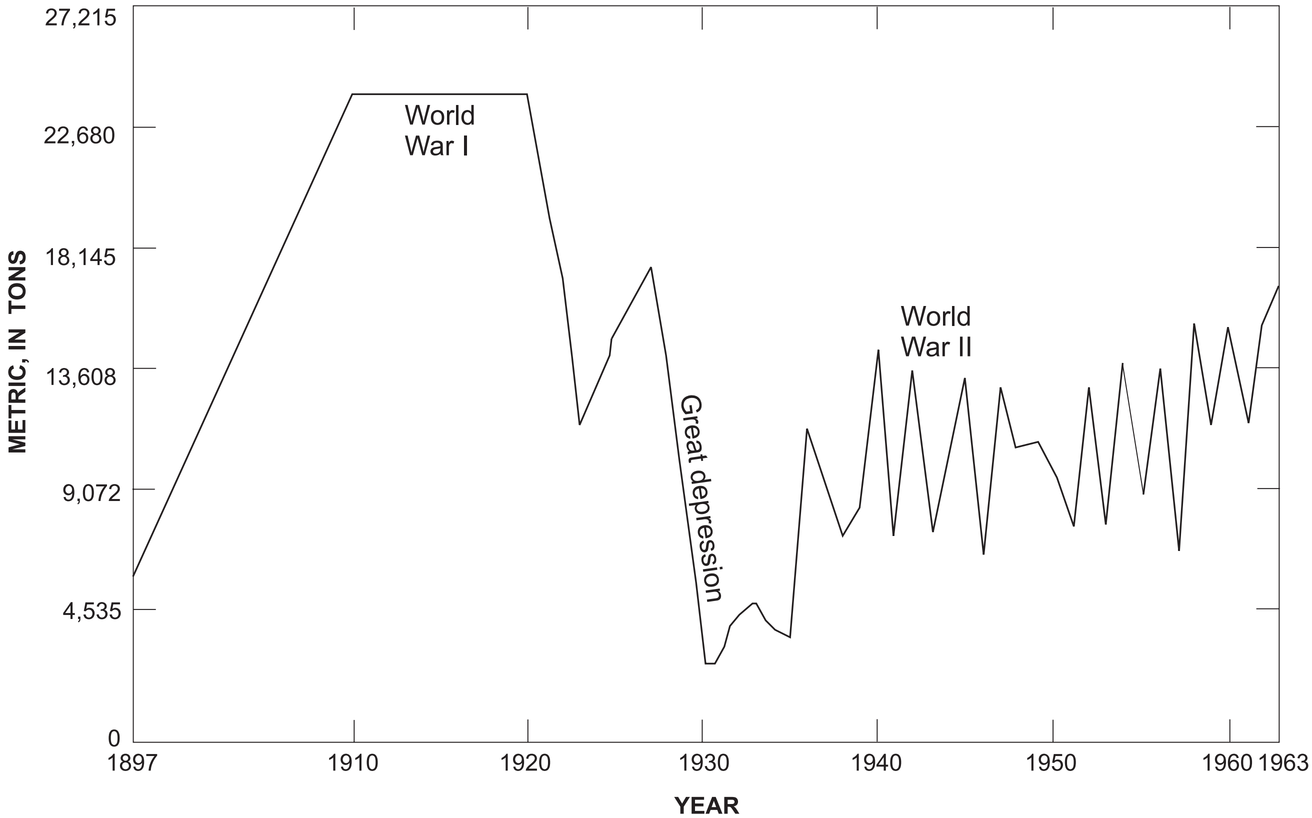


Figure 4. Puerto Rico coffee production from 1897 to 1963 (modified from the Puerto Rico Department of Agriculture, in Picó 1964).

Sugarcane, though a secondary crop cultivated in the past, also required land clearing and tilling. Although coffee and sugarcane were the principal crops within the basin, their cultivation has declined since, but have not completely disappeared. At present, the cultivation of pigeon peas is locally significant and this type of crop also requires land clearing and tilling.

In addition to the effect of agricultural land use, the Lago Guayabal drainage basin has been affected by six major hurricanes since construction of the Guayabal dam: Hurricane San Felipe in 1928, Hurricane San Nicolás in 1931, Hurricane San Ciprián in 1932, Hurricane Betsy in 1956, Hurricane Hortense in 1996, and Hurricane Georges in 1998. These historical climate events and crop cultivation methods presented an unfavorable scenario, which may have contributed in reducing the storage capacity of Lago Guayabal and thus, its safe yield for irrigation purposes.

Although agricultural practices, in general, enhance land erosion, the transport component from cultivated lands to streams is the most critical for the rapid mobilization of sediment. Figure 5 shows parts of digital orthophoto quadrangles (DOQ's) from aerial photographs taken between October 31, 1993, and November 13, 1995, showing the Lago Guayabal drainage area to the Río Jacaguas. From the photo mosaic, it is evident that within the Río Jacaguas basin above Lago Guayabal, the distance between any location to a perennial stream channel (as shown in the USGS, 1:20,000 scale topographic quadrangles) is generally on the order of hundreds of meters but not exceeding two kilometers. The high drainage density of tributaries plays a major role, particularly during major storms and rainfall events, which will be explained later in this report.

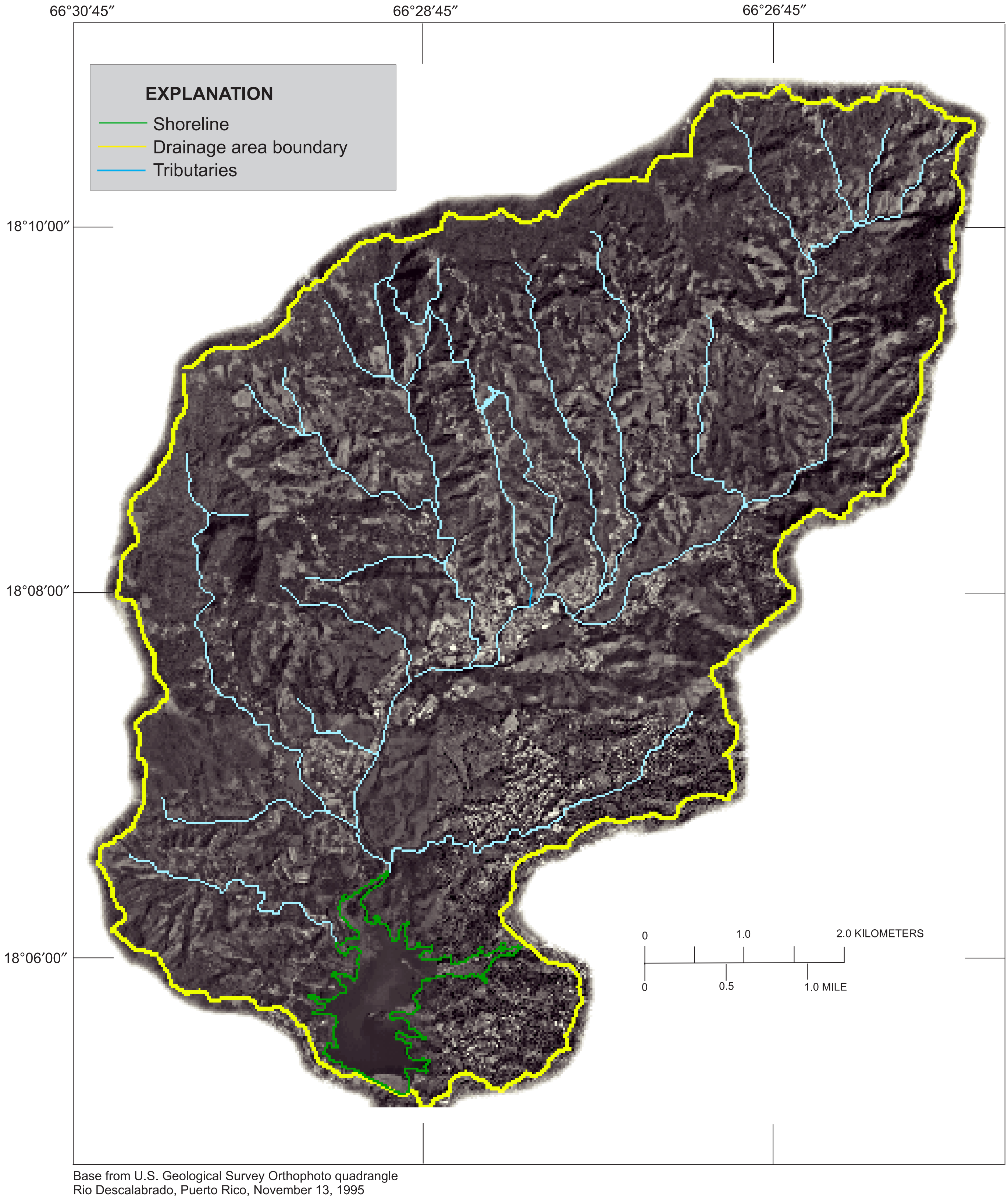


Figure 5. Current Lago Guayabal drainage area showing basin disruption, reservoir shoreline, and tributaries to the Río Jacaguas.

METHOD OF SURVEY

The 2001 bathymetric survey of Lago Guayabal 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. Survey lines were planned at a spacing of 50 meters, beginning at the dam and continuing upstream along the two branches of Lago Guayabal (fig. 6). Bathymetric data were collected during December 2001 using a depth sounder coupled to a DGPS to control the horizontal position of the survey boat. A geo-referenced digital map of the reservoir shoreline and the planned survey lines were loaded into a portable personal computer and served as the guide for bathymetric data collection. The reservoir pool elevation was monitored at the continuous-recording USGS lake-level station Lago Guayabal at damsite, near Juana Díaz Puerto Rico (station number 50111300 in fig. 1). The pool elevation of Lago Guayabal, although close to, was not at the crest of the top of the gates; therefore, the sounding data were adjusted using a time-elevation correction factor to represent depths at normal pool elevation of 103.94 meters above mean sea level.

A total of 10,456 data points (depth soundings) were collected over the entire reservoir (fig. 7) while navigating along the planned survey lines (fig. 6). The depths along the cross sections were plotted, and 1-meter interval contour lines of equal depth were drawn from the shoreline to the deepest parts of the reservoir (plate 1). The procedure used to contour the reservoir bottom is explained in a later section of this report. These contour lines were then converted into a triangulated irregular network (TIN) describing the surface model of the reservoir bottom (fig. 8). 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 9, and the original 1908 topography prior to the impoundment of the Lago Guayabal reservoir is shown on plate 2.

The GIS utilized the TIN to calculate the storage capacity (table 2) and thickness of sediment accumulation. The 1913 reservoir storage was compared with the 1914, 1936, 1950, 1951, 1964, 1972, 1986, and 2001 calculated storage capacities as reported by previous bathymetric surveys to obtain estimates of historical sediment accumulation rates, and to estimate the useful life of the reservoir based on historical data (table 3). Bathymetric or topographic maps were available only for 1913, 1950, and 1986. Therefore, selected cross sections depicting the reservoir bottom from shore to shore, as well as longitudinal profiles of the reservoir bottom along the thalweg of Lago Guayabal were generated for 1913, 1950, 1986, and 2001 from their TIN surface models (figs. 10 and 11). The relation between pool elevation and reservoir storage capacity for 1934 and for December 2001 was generated by calculating the reservoir volume at 1-meter elevation intervals (table 2) and is shown in graphical form on figure 12.

Table 2. Storage capacity table for Lago Guayabal, Puerto Rico, for December 2001

[all elevations in meters above mean sea level; all capacities in million cubic meters]

Pool elevation	Storage capacity
103.94	6.12
102.94	4.93
101.94	3.96
100.94	3.22
99.94	2.63
98.94	2.13
97.94	1.69
96.94	1.31
95.94	0.97
94.94	0.68
93.94	0.42
92.94	0.22
91.94	0.07
90.94	0.00

Table 3. Historical sedimentation trends of Lago Guayabal, Puerto Rico, 1913-2001

[--- undetermined]

Year	1913	1914	1936	1950	1951	1964	1972	1986	2001
Storage capacity, in million cubic meters	11.82	11.77	7.02	5.27	12.09	9.37	7.89	6.76	6.12
Live storage, in million cubic meters	11.32	---	---	4.61	11.93	9.37	7.89	6.76	6.12
Dead storage, in million cubic meters	0.50	---	---	[1]0.66	0.16	0	0	0	0
Years since construction	0	1	23	37	38	51	59	73	88
Sediment accumulated, in million cubic meters	0	0.05	4.80	6.55	[2]6.73	9.45	10.93	12.06	12.70
Long-term storage loss, in percent	0	0.4	41	55	57	80	93	102	107
Long-term annual loss of capacity, in cubic meters	0	50,000	208,696	177,027	177,105	185,294	185,254	165,205	144,318
Long-term annual loss of capacity, in percent	0	0.4	1.78	1.49	1.50	1.57	1.58	1.40	1.22
Inter-survey storage loss, in million cubic meters	0	0.05	4.75	1.75	0.18	2.72	1.48	1.13	0.64
Inter-survey annual loss of capacity, in cubic meters	0	50,000	215,909	125,000	180,000	209,231	185,000	80,714	42,667
Inter-survey annual loss of capacity, in percent	0	0.4	1.84	1.0	2.0	1.77	1.62	0.6	0.3
Sediment trapping efficiency, in percent	93	93	91	87	93	92	93	94	93
Drainage area sediment yield, in megagrams per square kilometers per year	0	485	2,070	1,836	1,719	1,818	1,795	[3]1,618	[3]1,235
Year that the reservoir would fill with sediment	---	2149	1970	1980	2019	2015	2015	[4]2070	[5]2101

[1] The increase in dead storage from 1913 to 1950 represents the sediment removal activities between 1940 to 1948.

[2] Sediment accumulation includes the sediment dredged and sluiced, plus the long-term sedimentation rate for the period 1950 to 1951 (PREPA, 1988). This accumulation is carried on after the flashboards installation.

[3] Sediment yield adjusted by the drainage area reduction in 1972.

[4] Using the 1972-86 inter-survey sedimentation rate because the sediment contributing drainage area was reduced in 1972.

[5] Using the sedimentation rate of 61,034 cubic meters per year from 1972 to 2001 because the sediment contributing drainage area was reduced in 1972.

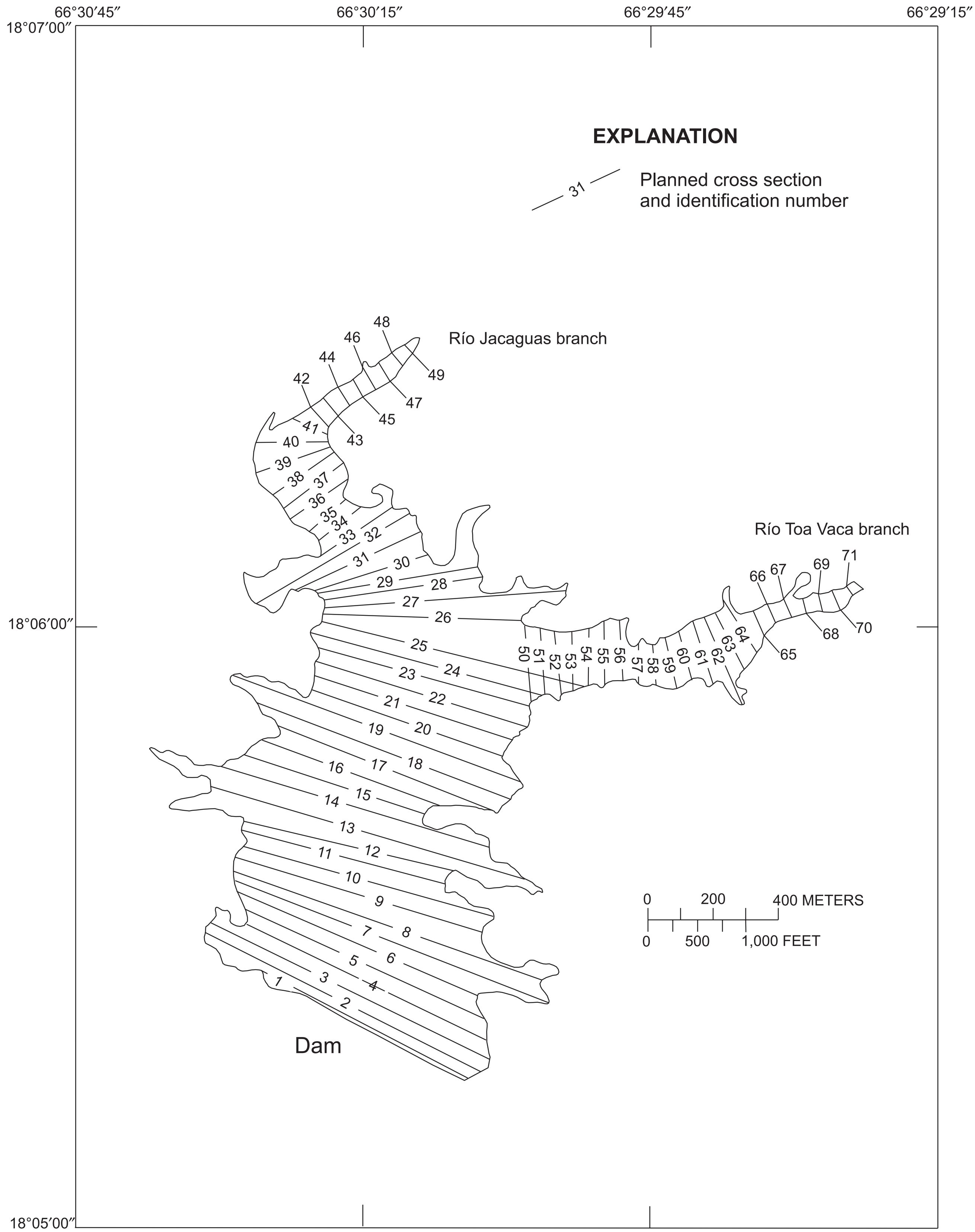


Figure 6. Planned cross-section locations for the December 2001 bathymetric survey of Lago Guayabal, Puerto Rico.

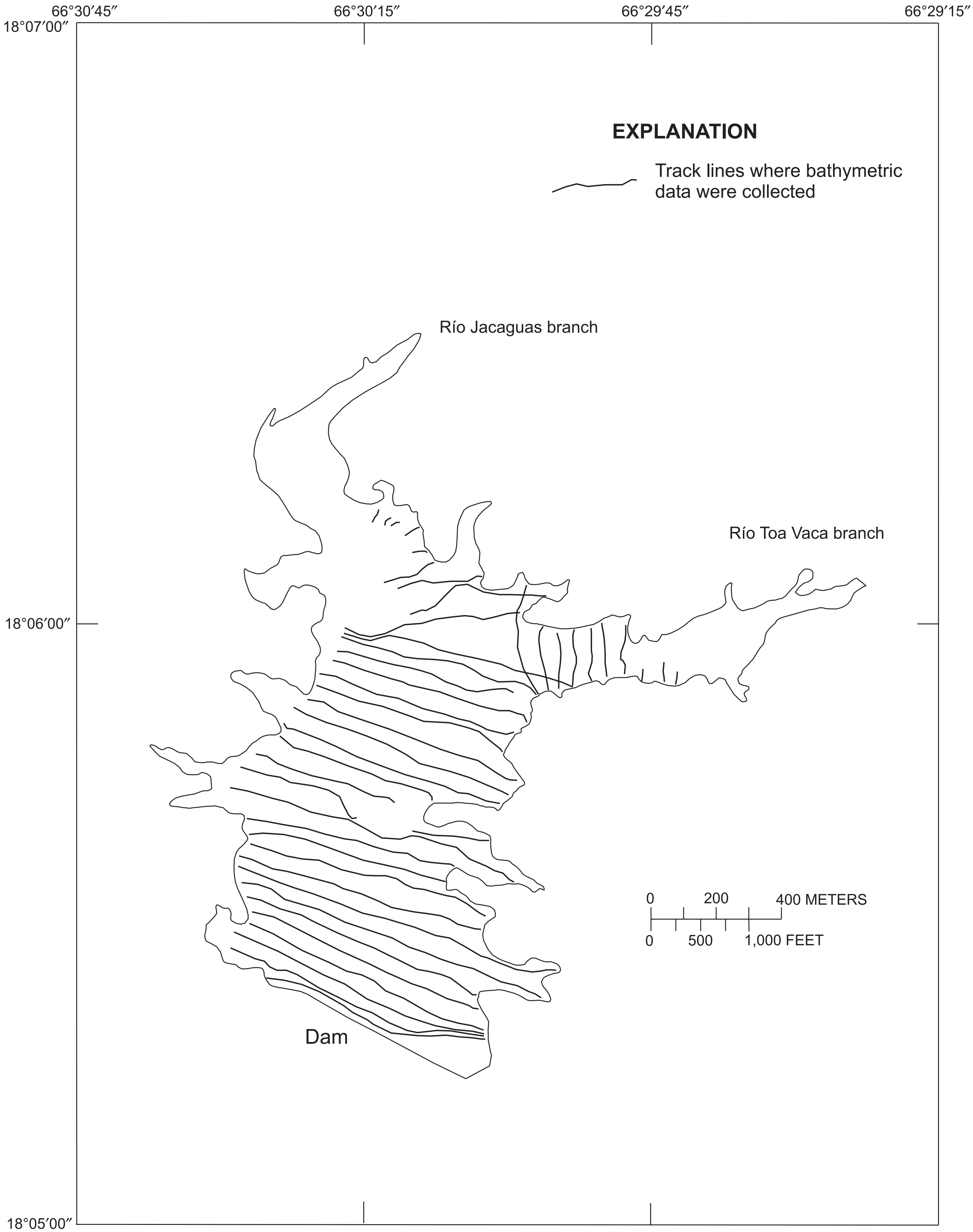


Figure 7. Actual track lines of the December 2001 bathymetric survey of Lago Guayabal, Puerto Rico.

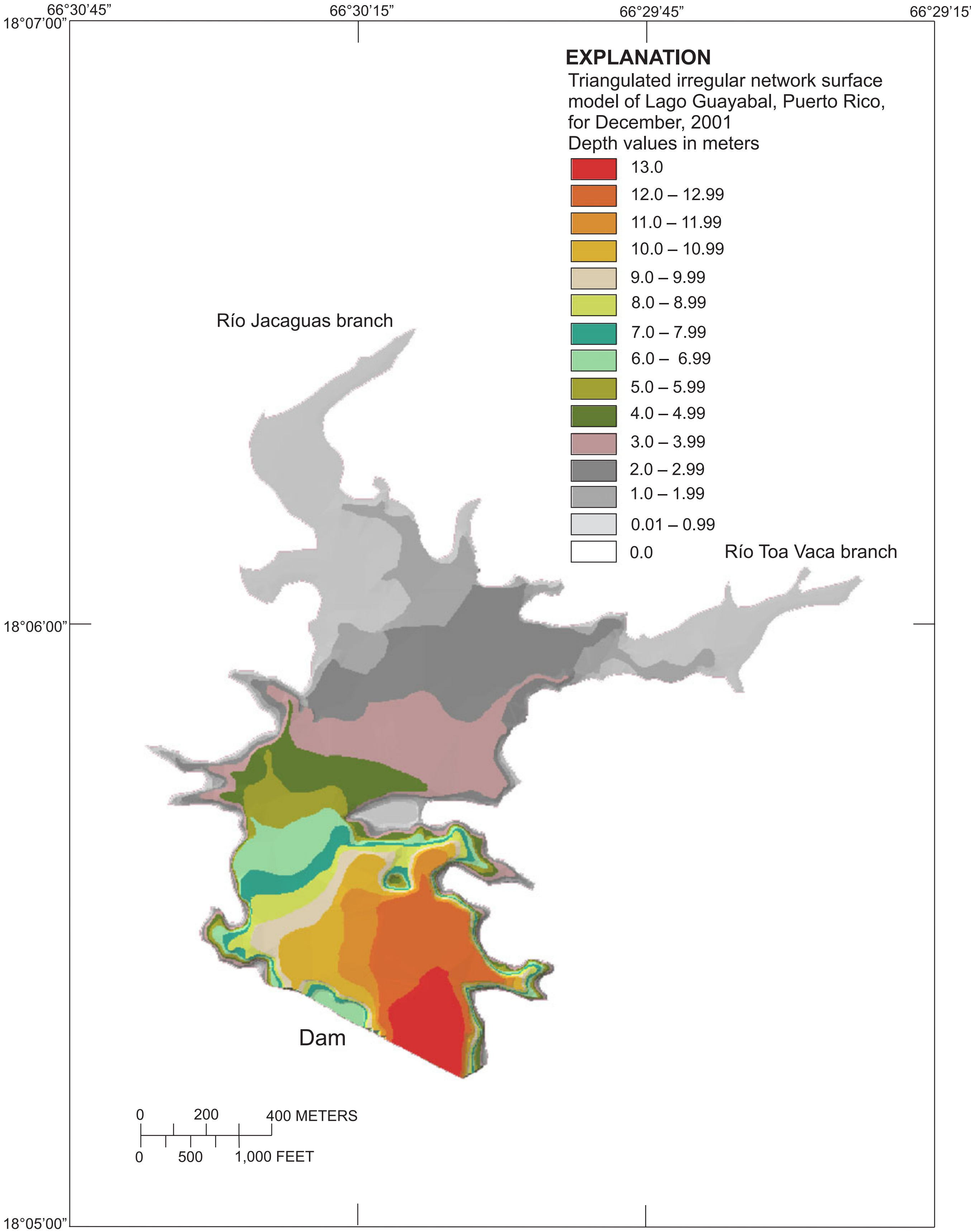


Figure 8. Triangulated irregular network (TIN) surface model of Lago Guayabal, Puerto Rico, for December 2001.

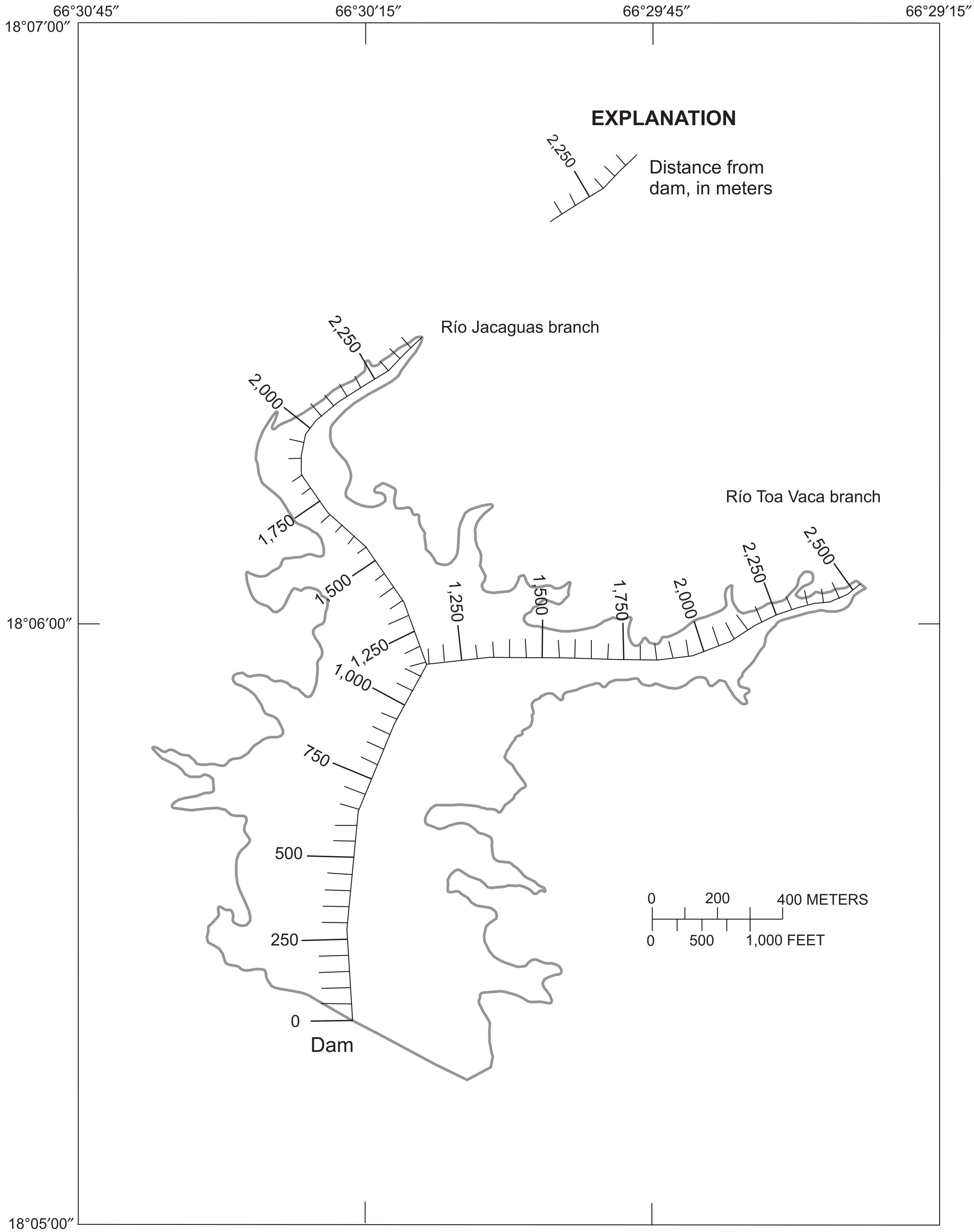


Figure 9. Reference longitudinal distance along the central portion of Lago Guayabal, Puerto Rico.

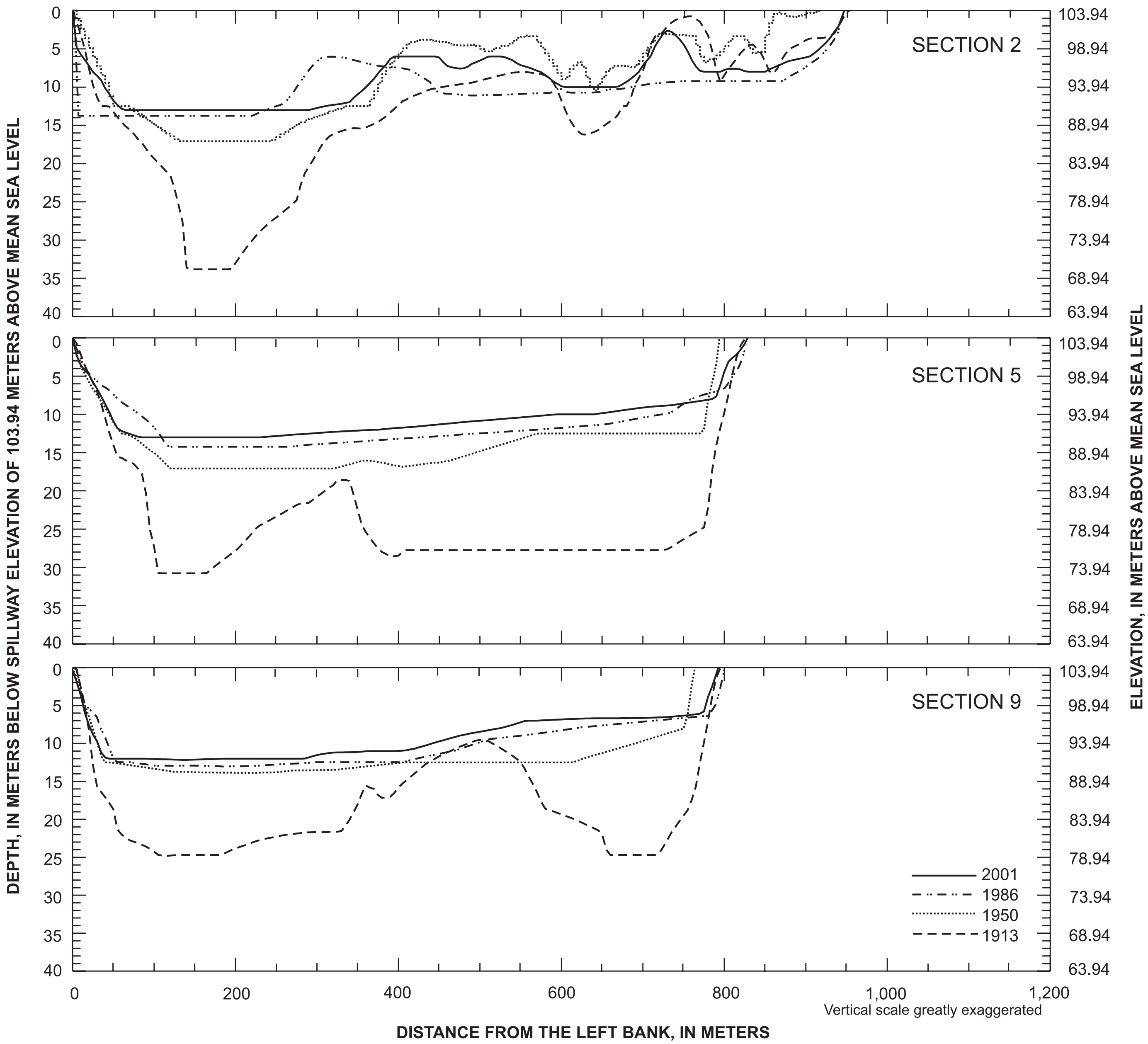


Figure 10. Selected cross sections generated from the TIN surface model of Lago Guayabal, Puerto Rico, for 1913, 1950, 1986, and December 2001. Refer to figure 6 for cross-section locations.

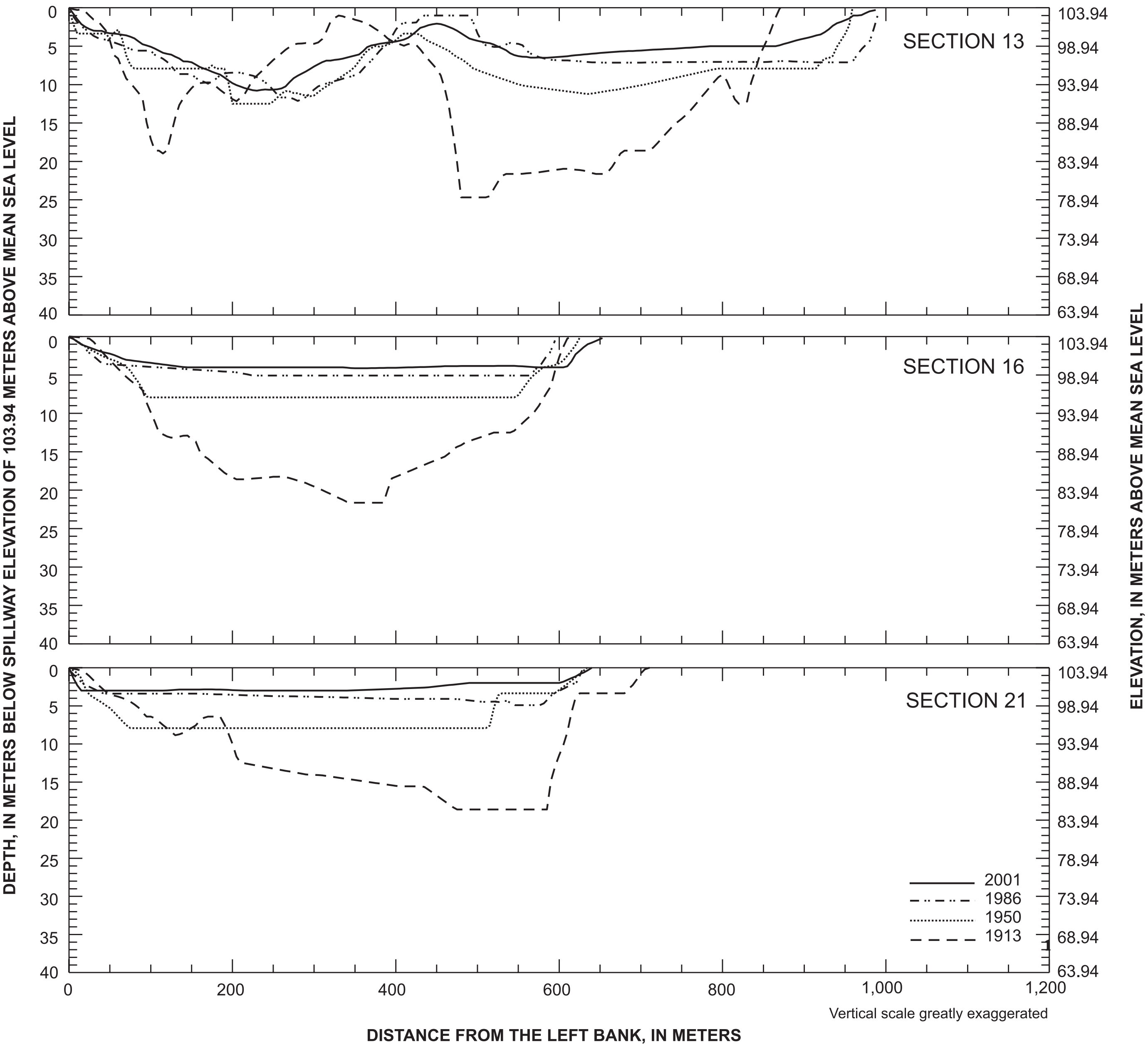
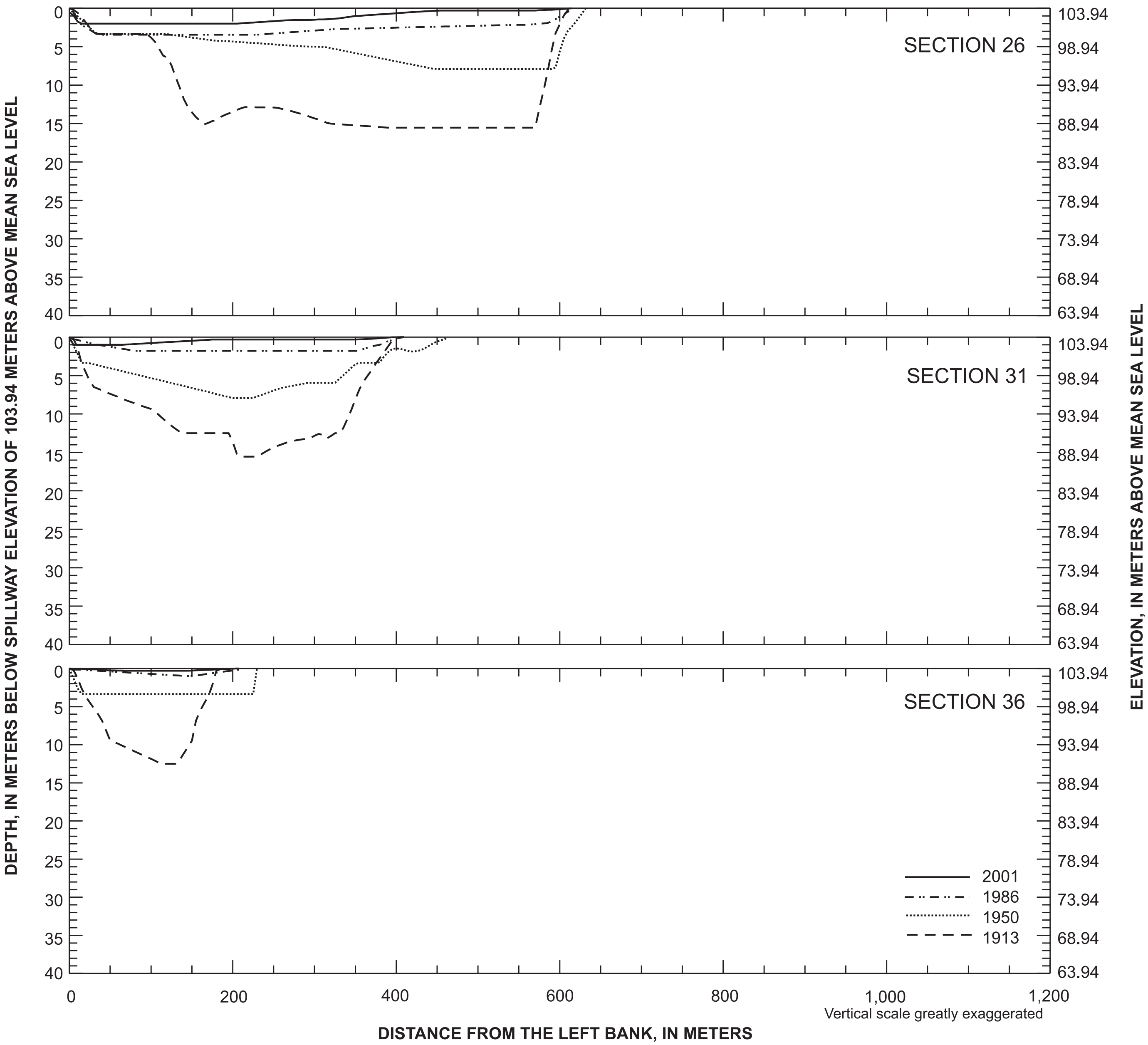


Figure 10. Selected cross sections generated from the TIN surface model of Lago Guayabal, Puerto Rico, for 1913, 1950, 1986, and December 2001—Continued. Refer to figure 6 for cross-section locations.



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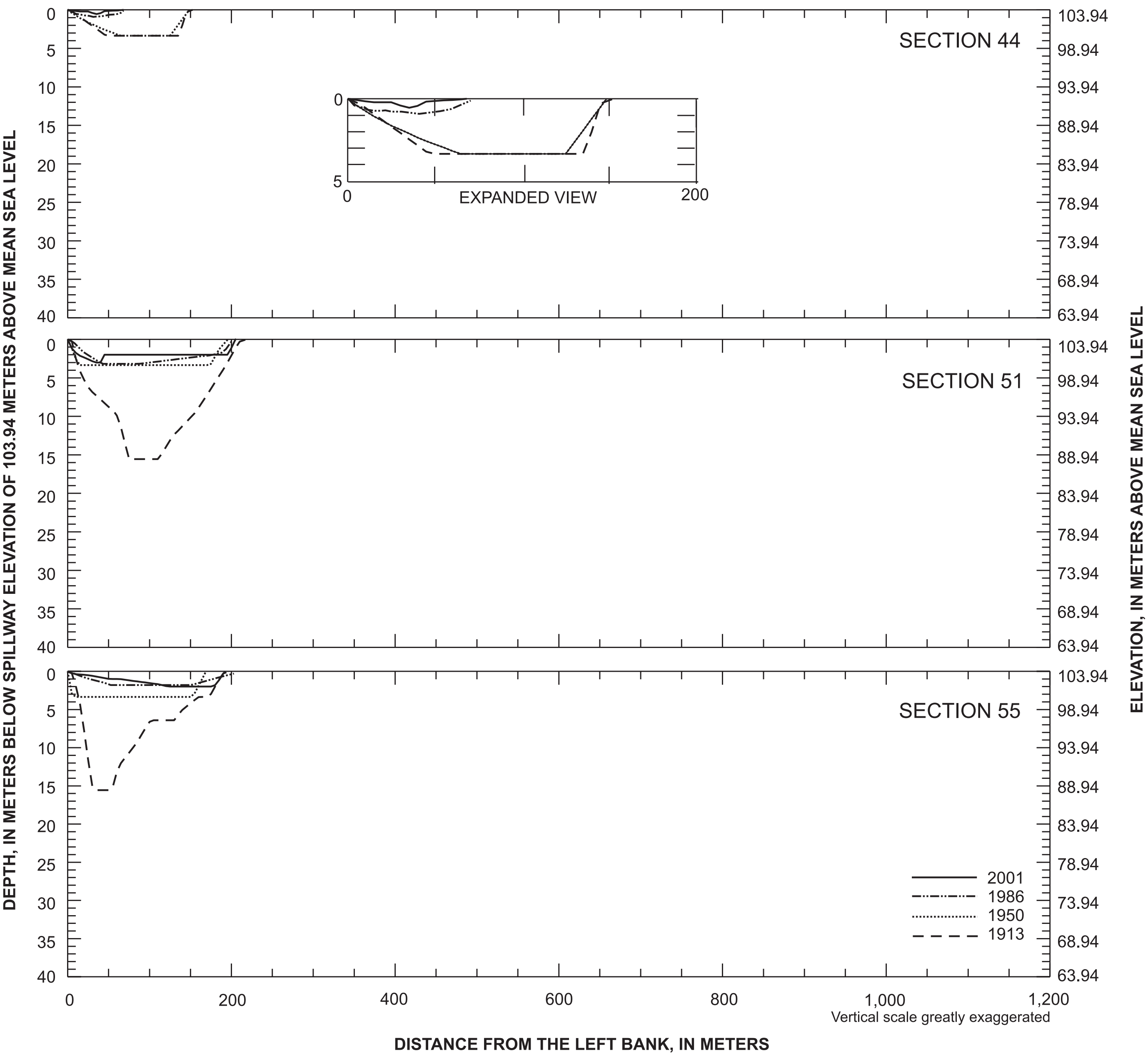

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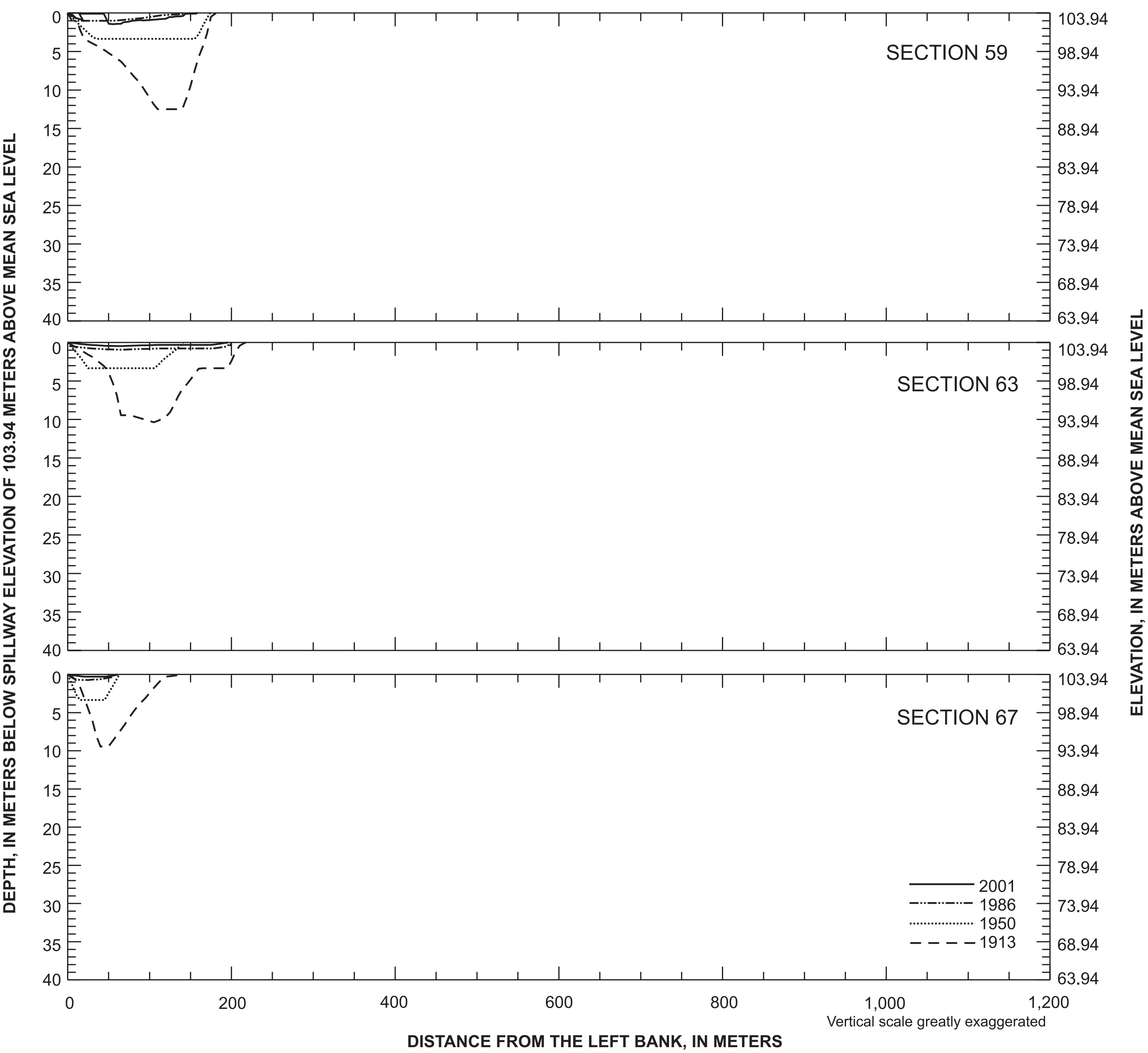

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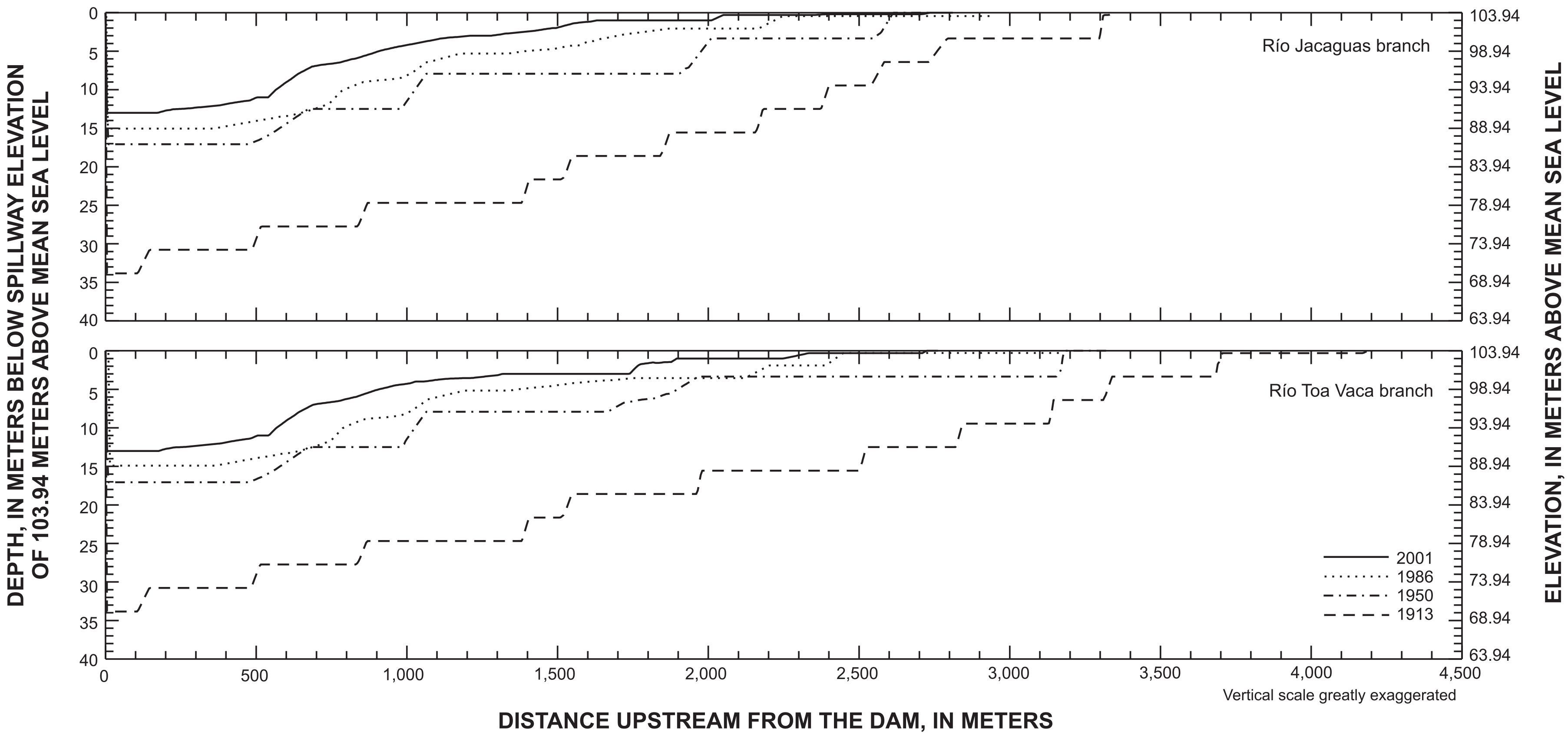

Figure 11. Longitudinal profiles generated from the TIN surface models along the thalweg of Lago Guayabal, Puerto Rico, for 1913, 1950, 1986, and December 2001.

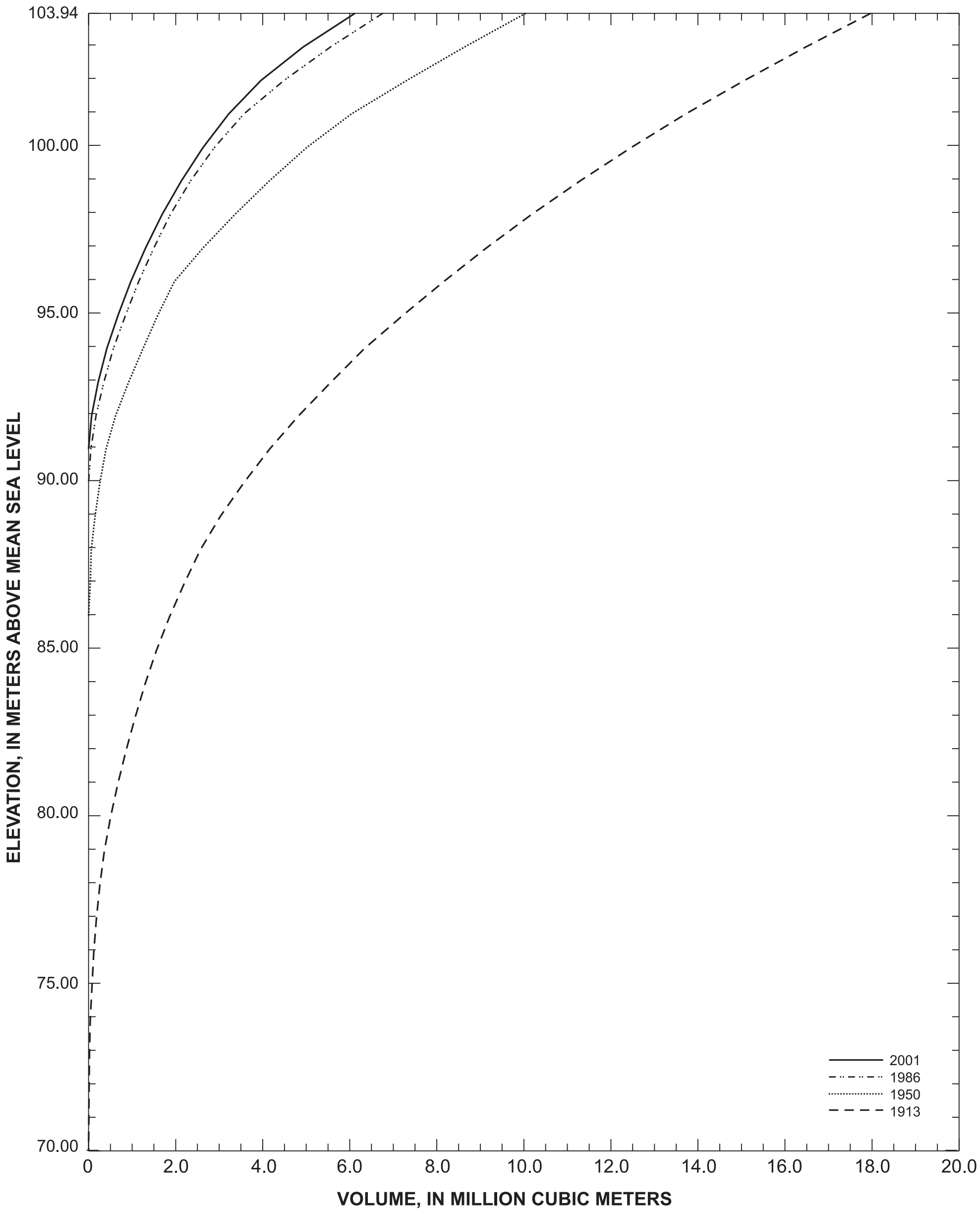

Figure 12. Relation between water storage capacity and pool elevation of Lago Guayabal, Puerto Rico, for 1913, 1950, 1986, and 2001.

Field Techniques

The bathymetric survey of Lago Guayabal was conducted on December 5, 2001. Data were collected using the bathymetric/land survey system (BLASS) developed by Specialty Devices, Inc. The system consists of two Novatel global positioning system (GPS) receivers interfaced with a depth sounder model SDI-IDS Intelligent. The GPS receivers monitor the horizontal position of the survey boat, while the depth sounder collects data on water depths. The GPS receivers were first used in static mode to establish a benchmark overlooking the reservoir. Satellite information was recorded simultaneously at the USGS District Office benchmark (referred as “USGS roof”) (latitude 18°25’N., longitude 66°06’W.) and at a site overlooking the reservoir. Then, the benchmark coordinates for “Guayabal dam” (latitude 18°05’N., longitude 66°30’W.), were calculated using the post-processing software CENTIPOINT. The new benchmark indicated a horizontal error of less than 10 centimeters. Once established, the “Guayabal dam” benchmark was established as the reference station. One GPS receiver was installed at the reference station and the other GPS unit was installed in the survey boat as the mobile station. The GPS on board the survey boat independently calculates a position every second while receiving a set of correction signals from the reference station and converting the system into a DGPS. This combination maintained the survey boat horizontal position accuracy within two meters. The bathymetric survey software HYPACK was used to navigate and collect data by integrating the depth and position data and storing the x, y, (geographic location) and z (depth) coordinates in a portable personal computer. A total of 71 survey sounding lines were planned in the office using the GIS (fig. 6); however, sediment accumulation and vegetation growth in riverine areas limited the data collection to only 45 cross sections (fig. 7).

Data Processing

Initial editing of the December 2001 data was performed using the HYPACK software. Positions were corrected to eliminate anomalies that occurred when the correction signal from the reference station was lost because of local topographic features or electromagnetic interference. Position errors were corrected by interpolating back to the mid-point between the correct antecedent and preceding position. The depth data were also corrected to eliminate incorrect depth readings. Incorrect depth readings can result from insufficient signal gain or because floating debris interferes with the transducer face. The incorrect depth readings were also interpolated between the correct antecedent or precedent depth readings. Once corrected, the edited data were transferred into the GIS database for further processing. The Arc/Info GIS software was customized to color-code the depth data according to different depth intervals. Data points of the same color code were connected by adding a line between them, and a contour map of the reservoir bottom depth was generated (plate 1). The bathymetric contour map (plate 1) was used to create the TIN surface model of the reservoir bottom for 2001 (fig. 8). In addition, the 1908 pre-impoundment topography of Lago Guayabal, the 1950, and 1986 bathymetric maps were converted into TINs to generate cross sections and longitudinal profiles.

Sampling the TIN every 5 meters along selected cross sections generated profiles representing the reservoir bottom from shore to shore for 1913, 1950, 1986, and 2001 (fig. 10). The same procedure used in generating the selected cross-section profiles was employed to generate the longitudinal profile along the thalweg of Lago Guayabal for the same years (fig. 11). The selected cross sections were located to represent flooded areas of reservoir, whereas the longitudinal profiles were located at the deepest part of the reservoir bottom from the dam to tributary river deltas.

The 1913, 1950, and 1986 bathymetric survey maps were scanned, geo-referenced (assign real-world coordinates and map projection), and converted into a TIN using the GIS. From these TINs, volumes were calculated; however, they yielded volumes that varied from 3 to 12 percent of the officially reported values. Since these differences could be attributed to different survey resolutions and methodologies, the reported storage capacities of each bathymetric survey were used for all calculations in this report. In addition, the 1951 and 1972 reservoir storage capacities were estimated using long-term sedimentation rates to standardize the analysis in order to account for the installation of flashboards during 1950-51, and the impoundment of the Río Toa Vaca branch to the east of Lago Guayabal drainage area in 1972 (refer to fig. 1).

PREVIOUS BATHYMETRIC SURVEYS, STORAGE CAPACITIES, AND SEDIMENT ACCUMULATION

The Lago Guayabal reservoir has been affected by a high sediment load and the consequent storage loss since its construction in 1913. A bathymetric survey conducted in 1914 indicated a storage capacity of 11.77 million cubic meters, which is essentially equivalent to the original storage capacity calculated from the topographic survey map prepared prior to reservoir impoundment in 1913. A second survey conducted in 1936 showed a reservoir storage of 7.02 million cubic meters, a decrease of 41 percent in the 23 years following impoundment. As a result of the rapid storage capacity loss due to sediment accumulation, corrective actions were taken to compensate for the storage loss. Between 1940 and 1948, dredging and sediment flushing through the sluice gates were conducted. However, these efforts were abandoned because they increased storage capacity by about 10 percent, making the effort unsuccessful because the reservoir was losing about 1.8 percent storage capacity per year as can be inferred by the previous 1936 survey. Another bathymetric survey conducted during 1950 showed a reservoir storage capacity of 5.27 million cubic meters, or a storage loss of about 55 percent. This storage loss and the resulting decrease of the reservoir yield for irrigation purposes prompted the decision to raise the pool elevation. After the installation of flashboards (identified in this report as 1951 for practical differentiation purposes), the reservoir storage capacity was increased from 5.27 million cubic meters to 12.09 million cubic meters, or about 2 percent increase above the original storage capacity of 11.82 million cubic meters. Although this corrective measure was effective in re-establishing storage capacity, the storage capacity loss problem continued. During 1964, a bathymetric survey indicated further sediment accumulation, reducing the storage capacity to 9.37 million cubic meters.

When the Toa Vaca dam was completed on the Río Toa Vaca tributary in 1972, this resulted in two benefits for Lago Guayabal: (1) the net effect of reducing the drainage area of Lago Guayabal, thus, reducing the sediment load; and (2) water that would have been impossible to store in Lago Guayabal and eventually lost to the river downstream was then stored in an upstream reservoir.

An estimate of the storage capacity of Lago Guayabal in 1972 was derived by using the 1964 long-term storage loss (sedimentation rate) and multiplying it by the number of years between 1964 and 1972, and subtracting the result from the 1964 reported volume. This yielded an estimated volume of about 7.89 million cubic meters.

In 1986, the USGS in cooperation with PREPA, conducted another bathymetric survey of the reservoir. This survey indicated a reservoir storage capacity of about 6.76 million cubic meters. Although the storage capacity loss continued, the annual rate of storage loss apparently decreased considerably, corroborating the effectiveness of the Toa Vaca dam construction project in terms of the useful life of Lago Guayabal. However, this analysis does not take into consideration that the sediment load from the Río Toa Vaca basin is being trapped in Lago Toa Vaca reservoir.

The current USGS survey during December 2001 used GIS and DGPS technology and showed a water storage volume of about 6.12 million cubic meters. The historical trend of reservoir storage capacity is presented in graphical form on figure 13 and in table 3.

Note in figure 13 that the rate of change in reservoir storage loss for the period 1913 to 1936 and 1951 to 1972 are essentially equal. If the storage loss rate is normalized by dividing the storage loss rate (cubic meters per square kilometer) by drainage area (square kilometers) to obtain an area-time storage loss rate in cubic meters per square kilometer per year, the 1913-1936 and 1951-1972 sedimentation rates were 1,863 and 1,787 cubic meters per square kilometer per year, respectively, and averaged 1,825 cubic meters per square kilometer per year. After the Río Toa Vaca was impounded by the Toa Vaca dam in 1972, the Lago Guayabal storage loss rate decreased to about 1,120 after adjusting the drainage area to 54.5 square kilometers. The sedimentation rate of the Río Toa Vaca portion of the original Lago Guayabal basin can be estimated by using the following relation:

(*Fraction of Río Jacaguas basin*) x (*Rate of Río Jacaguas basin) + (Fraction of Río Toa Vaca basin) x (Rate of Río Toa Vaca basin*) = 1,825 cubic meter per square kilometer per year

Thus, (*0.49*) x (*1,120) + (0.51) x (Rate of Río Toa Vaca basin*) = 1,825 cubic meter per square kilometer per year

Therefore, the sedimentation rate of the Río Toa Vaca basin portion of the original Lago Guayabal drainage area could have been in the order of 3,000 cubic meters per square kilometer per year. This estimated sedimentation rate from the Río Toa Vaca basin portion is in close agreement with the calculated area-normalized storage loss rate of Lago Toa Vaca of about 3,086 cubic meters per square kilometer per year (Soler-López, USGS, unpublished data, written commun., 2001). The Lago Guayabal 2001 storage capacity at 1-meter elevation intervals is presented on table 2 and the graphical relation between pool elevation and storage capacity is shown in figure 12.

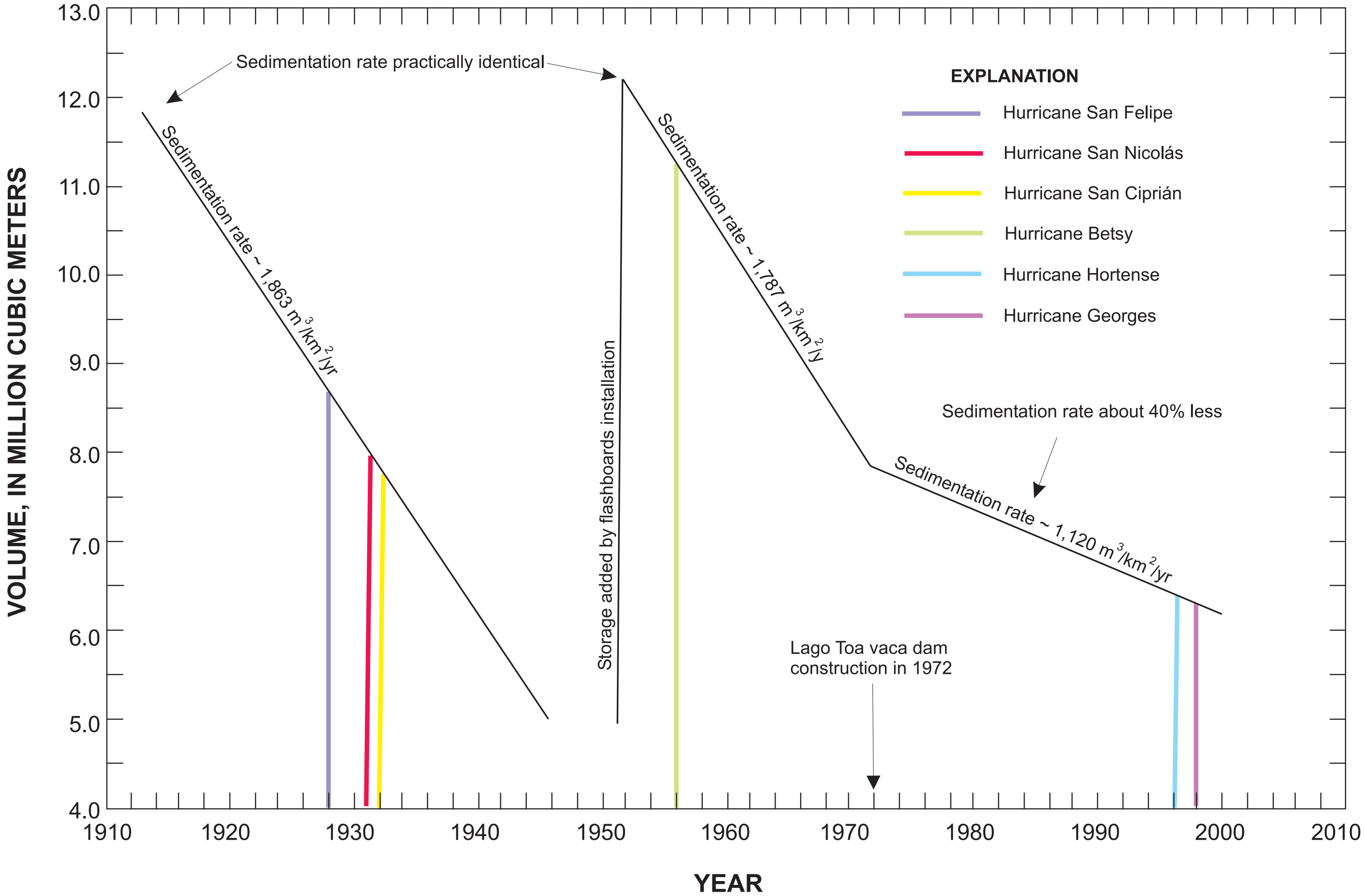

Figure 13. Lago Guayabal volume variations from 1913 to 2001.

The Lago Guayabal water-intake structure used for irrigation releases is located at the upstream face of the non-overflow section of the dam, between buttresses 20 and 21, at an invert elevation of 87.17 meters 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 (in the original design the dead storage is used to accommodate sediment without disabling reservoir structures). According to the 2001 bathymetric data, the reservoir bottom in the vicinity of the water intake tower had reached an approximate elevation of 90.94 meters above mean sea level. This suggests that the sediment accumulation around the structure is 3 meters thick, and that all the water contained in Lago Guayabal volume is within the live storage. Therefore, the water intake which feeds the Canal de Juana Díaz could be silted under 3 meters of sediment if not operated regularly.

The long-term sediment accumulation in the reservoir is not uniform. Along the Río Jacaguas branch, the profile presented on figure 11 indicates that a 21-meter thick layer of sediment has deposited near the dam. A uniform thickness of about 21 meters of sedimentation extends to a distance of about 1,250 meters upstream from the dam. A sediment layer about 12 meters thick, between a distance of 1,250 and 2,250 meters has been deposited, and a layer about 4 meters thick has been deposited in the riverine portion of the Río Jacaguas tributary. The long-term sediment deposition rates in these same segments are 24, 24, 14, and 4 centimeters per year, respectively, averaging about 17 centimeters per year. On the Río Toa Vaca branch, sediment deposition patterns are the same as in the Río Jacaguas branch up to about 1,150 meters upstream from the dam (fig. 9), where the total thickness of sediment deposition is about 13 meters. The total thickness of sediment deposition is about 11 meters at about 3,000 meters upstream from the dam. The deposition rates in the Toa Vaca branch averages about 14 centimeters per year.

The morphology of the reservoir bottom immediately after impoundment was wedge-shaped, very similar to the topographic relief of the surrounding hill slopes. Thus, it provided little submerged surface area for sediment deposition. After years of sediment accumulation, the topographic relief of the impounded area changed from a wedge to a trapezoidal-shaped surface. Therefore, sediment accumulation was dispersed over a larger area and the decrease in water depth due to sediment deposition is at a lesser rate. As an example of this process, the deposition rate near the dam from 1913 to 1950 was 34 centimeters per year; for the period of 1950 to 1986 it decreased considerably to about 6 centimeters per year; and, from 1986 to 2001 it increased slightly to about 13 centimeters per year. This apparent non-uniform long-term deposition rate process is more evident in reservoirs that have been surveyed on a more frequent basis (Webb and Soler-López, 1997).

TRAPPING EFFICIENCY

Heinemann (1981) considered trapping efficiency to be the most informative descriptor of a reservoir. Trapping efficiency is the proportion of the incoming sediment that is deposited or trapped in a pond, reservoir or lake and is dependent on several parameters, 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 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 the work of Brune (1953) is the most widely used and accepted. Brune developed a curve (fig. 14) 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 Guayabal was estimated using the relation established by Brune (1953) and was standardized by the drainage area reduction during 1972. For the period of 1913 to 1972, the drainage area was 112.0 square kilometers and since then (after the Toa Vaca dam construction), it is 54.5 square kilometers (table 1).

The Lago Guayabal drainage basin contains no streamgaging station to measure annual inflow to the reservoir. To estimate how much rainfall becomes runoff into the Lago Guayabal drainage area, the average ratio of runoff to rainfall (runoff/rainfall) of 0.25 was used (Giusti and López, 1967). The long-term average rainfall in the Lago Guayabal basin is 1,778 millimeters per year (Calvesbert, 1970). Thus, multiplying the mean-annual rainfall of 1,778 millimeters in the Lago Guayabal basin by the runoff/rainfall ratio of 0.25, the estimated runoff for the Lago Guayabal basin is 444 millimeters per year. This number multiplied by the current 54.5 square kilometers drainage area of Lago Guayabal, yields an estimated inflow to the reservoir of 24.22 million cubic meters per year. With a present storage capacity of 6.12 million cubic meters, the ratio of storage capacity to inflow is 0.25. The reservoir drainage area supplies enough runoff to renew the total storage an average of about four times per year, based on this estimate of mean-annual inflow.

Using the median curve of Brune's (1953) relation (fig. 14), and the corresponding annual inflow for each year, the ratio of storage capacity to inflow may have varied from 0.10 in 1950 to a maximum of 0.32 in 1972 (fig. 14). This gives an estimated change of the sediment trapping efficiency from 87 percent in 1950 to 93 percent in 1972; and, a long-term average trapping efficiency of Lago Guayabal of 92 percent for the period 1913 to 2001. However, the trapping efficiency of a reservoir decreases as sediment fills the reservoir and lowers the storage capacity, according to Brune's (1953) empirical relation.

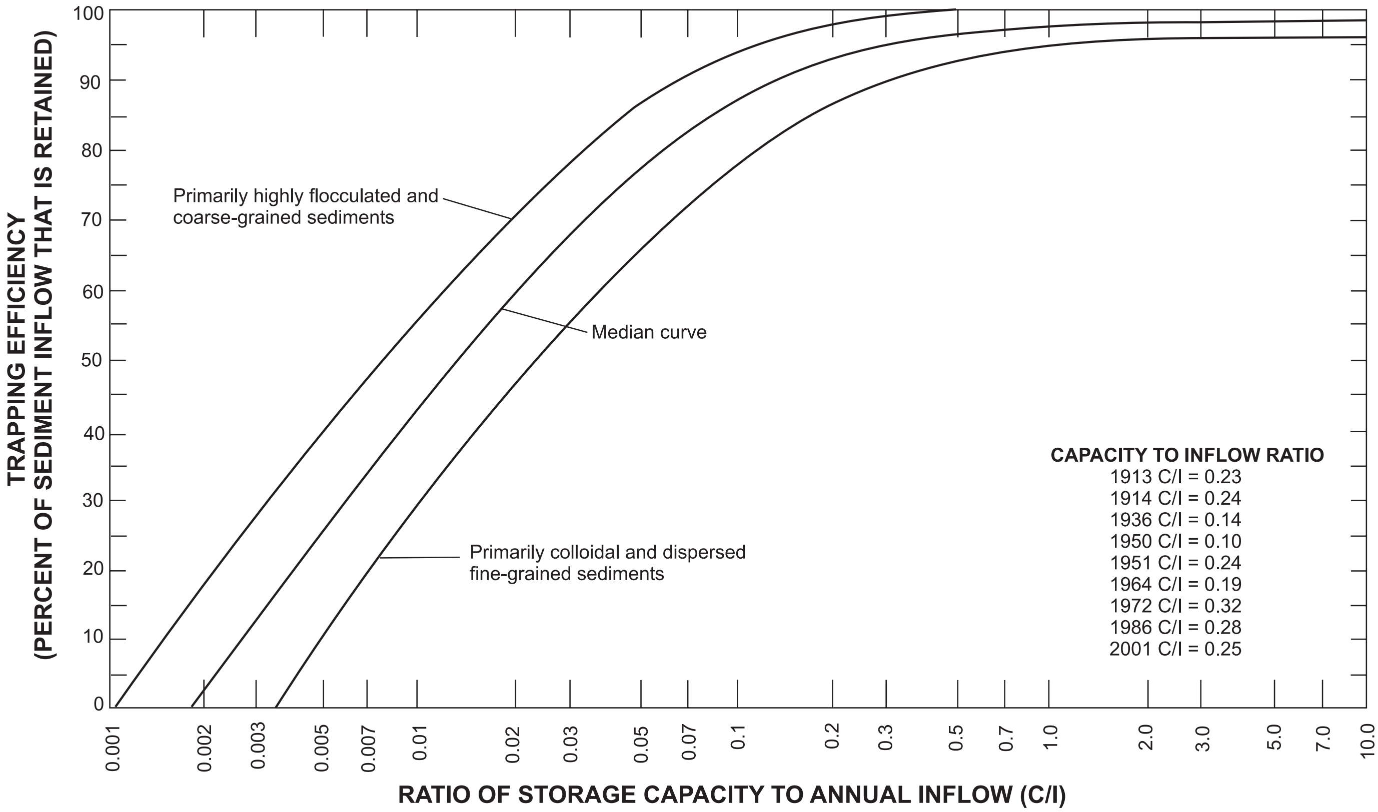

Figure 14. Reservoir trapping efficiency as a function of the ratio between storage capacity and annual water inflow volume.

SEDIMENT YIELD

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 (McManus and Duck, 1993). Based on this definition, several factors need to be normalized to take into consideration the drainage area upstream of the Toa Vaca dam and the change in trapping efficiency of Lago Guayabal. Therefore, for the bathymetric surveys previous to and including 1972, a net sediment contributing basin area of 110.81-square kilometers (the basin area minus the 1.19 square kilometer reservoir surface area) was used in the estimate, and for the surveys after 1972, the reduced drainage area of 54.5 square-kilometers was used. Although table 3 summarizes the historical sediment yields of the Lago Guayabal drainage area, only the 2001 sediment yield calculation is discussed herein.

For the period of 1972 to 2001 the total estimated volume of sediment contributed to Lago Guayabal from a reduced drainage area of 54.5 square kilometers was estimated by dividing 1.77 million cubic meters of sediment accumulation (the volume loss between 1972 and 2001) by the estimated 2001 trapping efficiency of 0.93, which is 1.90 million cubic meters. This estimated rate of sediment influx (1.90 million cubic meters) divided by the years between 1972 and 2001 (29 years), results in an average of 65,517 cubic meters per year. The estimated rate of sediment influx of the Lago Guayabal basin (65,517 cubic meters per year) divided by the net sediment contributing area of 53.06 square kilometers, (the total drainage area of 54.5 square kilometers minus the 1.44

square kilometer surface area of the reservoir) results in an average basin sediment yield and reservoir storage loss 1,235 cubic meters per square kilometer per year. An estimate of the sediment yield from the drainage area of Lago Guayabal on a mass basis can be obtained by using the sediment dry-bulk density of one gram per cubic centimeter reported for Lago Yahuecas, a reservoir located about 25 kilometers northwest of Lago Guayabal (Soler-López and others, 1998). Therefore, the Lago Guayabal sediment yield on a mass basis is 1,235 megagrams per square kilometer per year.

The life expectancy of Lago Guayabal, or any other reservoir, can be estimated by dividing the remaining storage capacity by the annual storage capacity loss. However, in this case, the average storage capacity loss of Lago Guayabal since 1972 was used because it is a reliable indicator of the true volume loss after the construction of the Lago Toa Vaca dam. Based on the average reservoir storage loss between 1972 and 2001, the reservoir would be completely silted in about 100 years, or by about 2100.

SUMMARY

The December 2001 bathymetric survey of Lago Guayabal was conducted by the USGS, in cooperation with PREPA, using state-of-the-art GIS and DGPS technology. A series of anthropogenic and climatological events, including agricultural land-use practices and six major hurricanes, that could have adversely affected the storage capacity of Lago Guayabal were analyzed. The reservoir was losing storage capacity at a faster rate than at present (2001); however, when Lago Toa Vaca was constructed in 1972 in the Río Toa Vaca tributary to Lago Guayabal, the rate decreased about 40 percent. The December 2001 bathymetric survey of Lago Guayabal indicates that the reservoir had lost about 12.70 million cubic meters of water storage capacity. This represents a long-term storage loss of about 1.22 percent per year. With a current reservoir trapping efficiency of about 95 percent, any increase in rural development and land disruption within the Lago Guayabal drainage area could result in an increased sediment yield, which is currently about 1,235 cubic meters per square kilometer per year. At the current long-term sedimentation rate and estimated sediment trapping efficiency, Lago Guayabal would be completely silted by the year 2100. Although the life expectancy of Lago Guayabal was a pressing concern in the early years after impoundment, the life expectancy of the reservoir has increased, according to recent data. However, sediment accumulation in the reservoir can impair the use of essential reservoir structures such as the outlet to the Canal de Juana Díaz.

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