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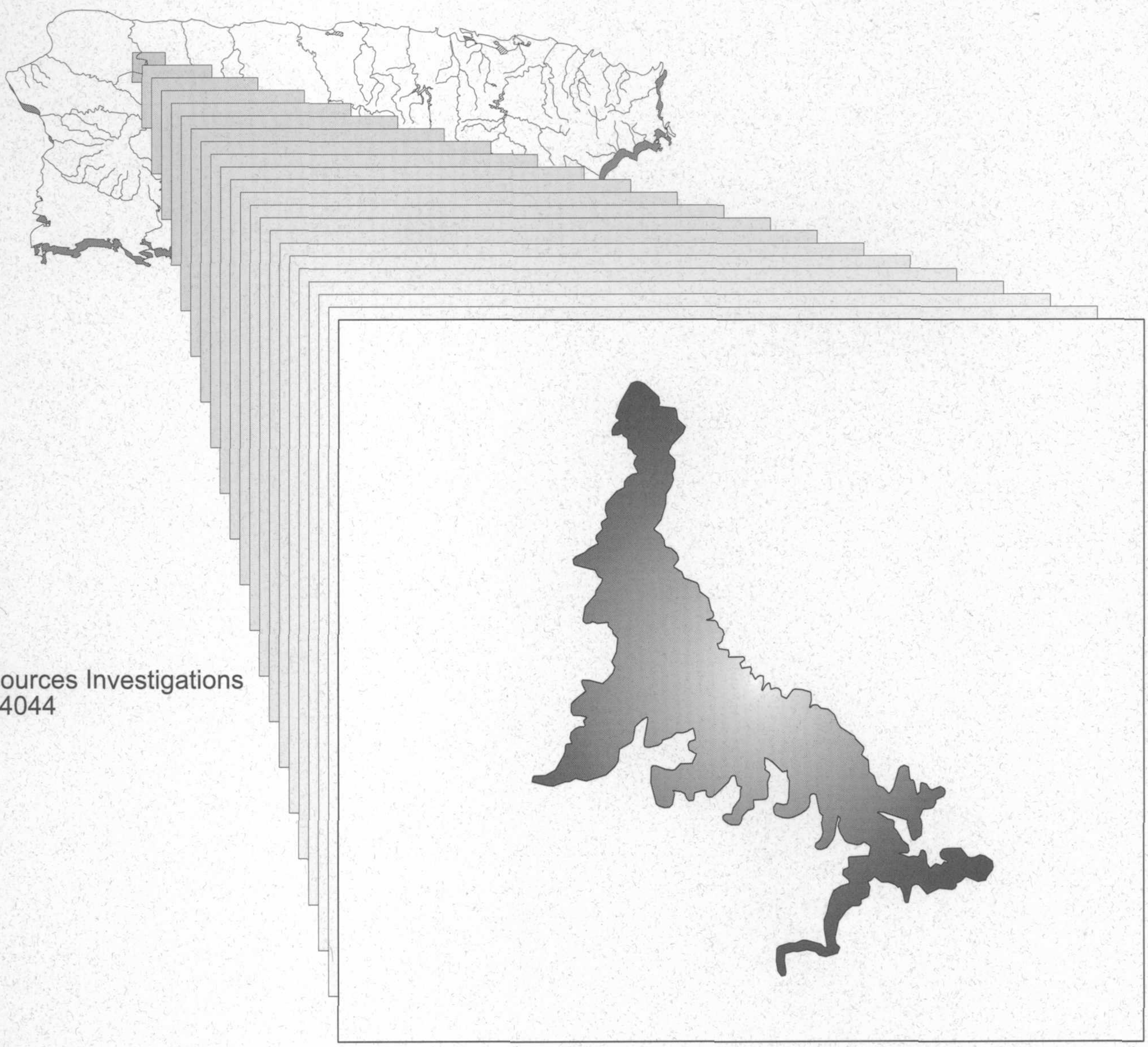
Sedimentation Survey of Lago Guajataca, Puerto Rico, January 1999



Water-Resources Investigations
Report 00-4044

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

Sedimentation Survey of Lago Guajataca, Puerto Rico, January 1999

By Luis R. Soler-López, Richard M.T. Webb, and Ramón A. Carrasquillo-Nieves

Water-Resources Investigations Report 00-4044

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San Juan, Puerto Rico: 2000

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information write to:

District Chief
U.S. Geological Survey
GSA Center, Suite 400-15
651 Federal Drive
Guaynabo, Puerto Rico 00965-5703

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U.S. Geological Survey
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[Plate is in pocket]

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CONVERSION FACTORS, DATUMS, ACRONYMS, and TRANSLATIONS

Multiply	By	To obtain
	Length	
centimeter	0.03281	foot
meter	3.281	foot
millimeter	0.03937	inch
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
million cubic meters	810.7	acre-foot
cubic meter	0.0008107	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
	Mass per area (includes sediment yield)	
gram per cubic centimeter	62.43	pound per cubic foot
megagram per square kilometer	2.855	ton per square mile

Datums

Horizontal Datum - Puerto Rico Datum, 1940 Adjustment

Vertical Datum - National Geodetic Vertical Datum 1929 (NGVD 1929)

Acronyms used in this report

DGPS	Differential Global Positioning System
GIS	Geographic Information System
PREPA	Puerto Rico Electric Power Authority
TIN	Triangulated Irregular Network
USGS	U.S. Geological Survey

Translations

Spanish	English
Lago	Lake
Río	River

Sedimentation Survey of Lago Guajataca, Puerto Rico, January 1999

By Luis R. Soler-López, Richard M.T. Webb, *and* Ramón A. Carrasquillo-Nieves

Abstract

Compared to other reservoirs in Puerto Rico, sediment accumulation in Lago Guajataca has been moderate since its construction in 1928. The storage capacity has been reduced from 48.46 million cubic meters in 1928 to 42.28 million cubic meters in 1999. This represents a storage loss of 6.18 million cubic meters or about 13 percent of the original capacity. The average long-term sedimentation rate was calculated to be about 87,000 cubic meters per year or 0.2 percent of capacity loss per year. Using the capacity/inflow relation established by Brune in 1953, the trapping efficiency of the reservoir was estimated to be 97 and 96 percent for 1928 and 1999, respectively. Based on the average long-term trapping efficiency of the reservoir, the mean annual runoff, and the sediment contributing drainage area of the reservoir, the sediment yield of the Lago Guajataca basin was estimated to be about 1,188 megagrams per square kilometer per year. At the average long-term sedimentation rate, the remaining useful life of the reservoir, in terms of flood control and recreation, is about 486 years, which means the reservoir is expected to completely fill with sediments by the year 2485.

INTRODUCTION

The U.S. Geological Survey (USGS) in cooperation with the Puerto Rico Electric Power Authority (PREPA) has conducted sedimentation surveys in several reservoirs around the island of Puerto Rico. PREPA owns these reservoirs and uses them for hydroelectric power generation, irrigation of croplands, and as water supply for domestic and industrial use. Lago Guajataca is the principal water supply for the northwestern part of the island, and during the summer of 1997, it experienced one of the largest drawdowns recorded in the reservoir's history. This drawdown resulted in rationing water from the water-supply system in the northwestern part of the island. During January 20-22, 1999, the USGS conducted a bathymetric survey of Lago Guajataca to determine the current storage capacity, the average long-term sedimentation rate, the amount of sediment accumulated, the current trapping efficiency, and the sediment yield of the basin. This information will help PREPA in managing effectively the available resources in the reservoir. Data on geographic position and water depths were simultaneously collected using a differential global positioning system (DGPS) and a depth sounder. These data were stored in a personal computer in digital form. A hard copy of the data also was generated for later editing. The digital data were loaded into a geographic information system (GIS) for processing and analysis. GIS was used to construct a contour map of the reservoir bottom and to calculate the January 1999 storage capacity of the reservoir.

Dam and Reservoir Characteristics

Lago Guajataca is located in the northwestern part of Puerto Rico about 8 kilometers south of the town of Quebradillas, and about 10 kilometers northeast of the town of San Sebastián (fig. 1). The reservoir is the principal water supply for the northwestern part of Puerto Rico. The reservoir was built in 1928, and originally had the capacity to store 48.46 million cubic meters of water for domestic, agricultural, and industrial use. This original capacity was determined by using a mathematical back calculation, which is explained on page 7 of this report. The Guajataca dam is a hydraulic-fill structure. The crest of the dam is 9.50 meters wide, 316 meters long, and has an elevation of 202.5 meters above mean sea level. The spillway is located on the left abutment, and consists of an approach channel, an uncontrolled semicircular ogee crest at an elevation of 196.9 meters above mean sea level, and a tapering trapezoidal concrete chute that terminates at the old river channel. The outlet works intake, located through the right abutment, consists of a diversion inlet, an intake tower, an intake shaft, a horseshoe tunnel, and a gate chamber with two side-by-side 1.22 by 1.22-meter-high pressure gates. Extending from one of the gates is the canal outlet works, which consists of a 54-inch reinforced concrete cylinder pipe that tapers to a 42-inch reinforced concrete cylinder pipe, a flow meter, a 1.37-meter-diameter sleeve valve for regulation, and an outlet canal. Extending from the other gate is the river outlet works, which consists of a horseshoe section tunnel, a transition structure, a 0.91-meter-diameter reinforced pipe, and a terminal structure. The river structure works discharges into the Río Guajataca, while the canal outlet structure supplies water for municipal needs (Puerto Rico Electric Power Authority, 1984). The principal characteristics of Lago Guajataca and structures are listed in table 1.

Table 1. Principal characteristics of Lago Guajataca and Guajataca dam, Puerto Rico (Modified from the Puerto Rico Electric Power Authority, 1984)

[All elevations in meters above mean sea level]

Length of dam	316 meters
Elevation of crest of dam	202.5 meters
Maximum flood elevation	200.4 meters
Spillway crest elevation	196.9 meters
Drainage area at dam site	79.77 square kilometers
Elevation of the tower intake structure	180.5 meters
Surcharge storage for flood control	11.62 million cubic meters
Lago Guajataca surface area in 1999[1]	3.42 square kilometers
Maximum depth during the 1999 survey[2]	27.0 meters

[1] At spillway elevation of 196.9 meters.

[2] Below spillway elevation of 196.9 meters.

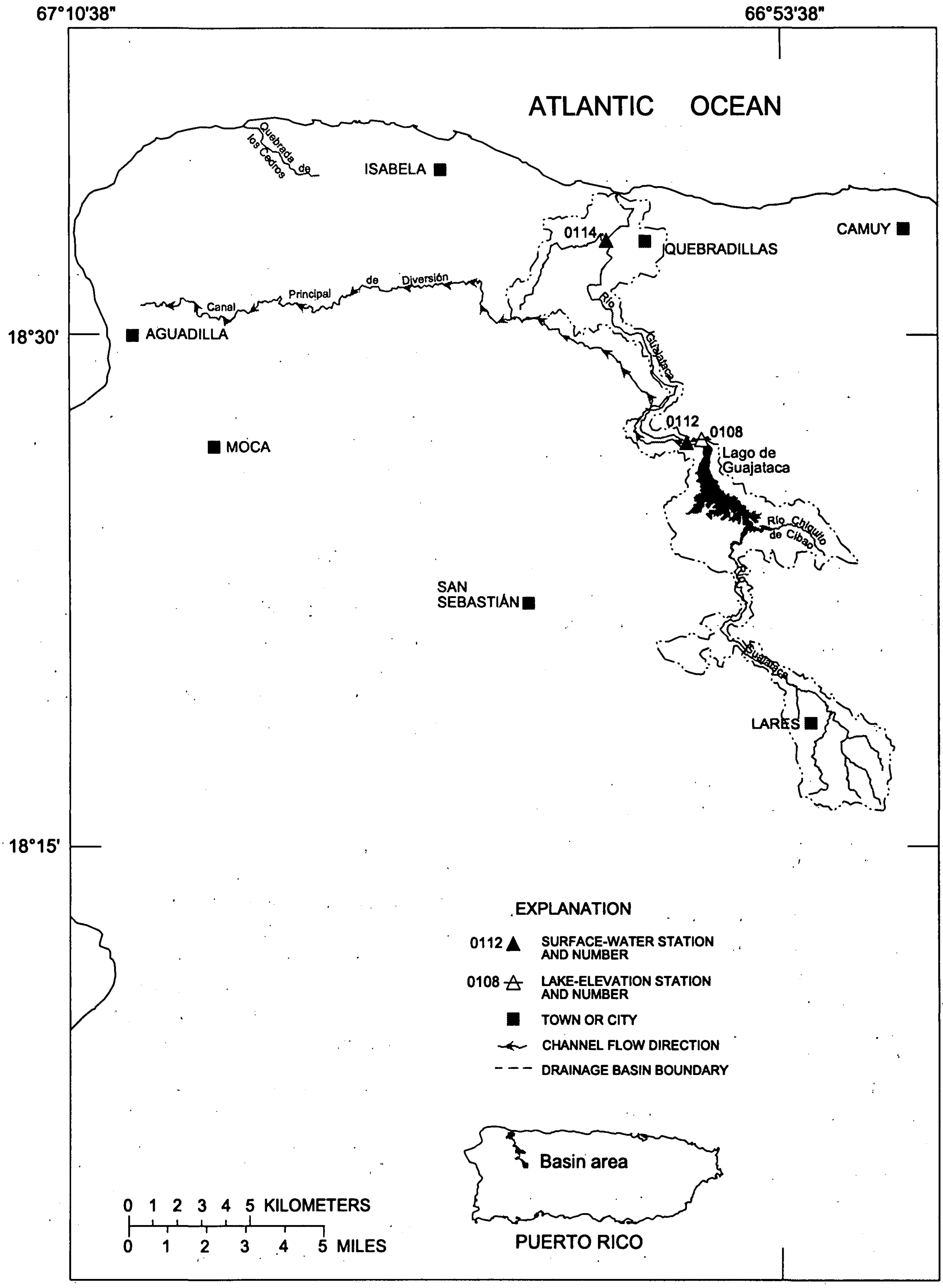

Figure 1. Location of Lago Guajataca in northwestern Puerto Rico.

Method of Survey

The sedimentation survey of Lago Guajataca involved planning, data collection, data processing, and analysis of the results. A geographic information system, Arc/Info (by Environmental System Research Institute, Inc.), was used to plan the survey lines and to analyze the bathymetric data. Planned cross-section locations were spaced 50 meters apart, starting at the dam and continuing upstream along the different branches of the reservoir (fig. 2). Geographic position and water depths were acquired simultaneously by using a DGPS interfaced to a depth sounder. The soundings were subsequently adjusted to represent water depths below the spillway elevation. The pool elevation of the reservoir was continuously monitored at the USGS lake-level station 50010800 (shown as station 0108 on fig. 1). The water level changed slightly during the data-collection process. To account for this change, a time-elevation correction factor was applied to adjust the measured depths to represent depths below the spillway elevation. A bathymetric map representing the reservoir bottom in January 1999 was then generated (plate 1).

Field Techniques

The data-collection process took place during January 20-22, 1999. Data were collected by using the bathymetric/land survey system developed by Specialty Devices Inc. The system uses two Motorola SixGun DGPS receivers. The DGPS units were first used in a static mode to establish reference marks at several sites overlooking the reservoir. These sites were later used as master stations for geographic positioning control. Satellite information was simultaneously recorded for one hour at a control station QUEBRAS 2 (lat 18°28'01.989"N., long 66°55'43.316"W.), which was established by the local government agency "Centro de Recaudación de Ingresos Municipales", and at the following four reference stations overlooking the reservoir: GJ1 (lat 18°23'51.535"N., long 66°55'31.913"W.) near the left abutment of the dam; GJ2 (lat 18°24'00.288"N., long 66°55'26.056"W.) at the middle of the earthfill dam; GJ3 (lat 18°24'02.762"N., long 66°55'25.180"W.) at the right abutment of the dam; and GJ4 (lat 18°22'56.636"N., long 66°54'36.789"W.) at a hill on the upper reach of the reservoir. Once established, one DGPS unit was installed at the station with the best view of the area to be surveyed, and the other DGPS unit was installed in the survey boat. The DGPS on board the survey boat independently calculated a position every second while receiving a set of pseudo-range correction factors from the master station to maintain a positional accuracy within 2 meters. Water depths were measured by using a RAYTHEON DE-719 depth sounder coupled to an ODOM DIGITRACE to record data both in analog and digital form. The depth recorder shows depth to the nearest 0.1 meter, and was calibrated at water depths of 3 and 15 meters. The bathymetric survey software HYPACK (Coastal Oceanographics Inc.) was used to receive and record the geographic position and depth once every second while in survey mode. A total of 41,047 data points were collected over the entire reservoir. HYPACK, which runs on a portable personal computer, can be used to record data and to navigate. The helmsman of the survey boat is provided with a graphical display showing the lakeshore, the location of the planned cross sections, the actual position of the survey boat while underway, and indicators of speed and the amount of deviation from the planned survey lines.

A total of 187 cross sections spaced approximately 50 meters apart were planned in the office; however, low water depths in the riverine sections and vegetation in some areas of the reservoir limited data collection to only 155 cross sections (fig. 3). Additional data were collected in a random pattern along the reservoir deltas. At the beginning and end of each survey day, the survey boat was secured to an assigned point on the shore and positional data were recorded for at least 30 seconds to verify the precision of the DGPS-calculated positions.

Random errors can be generated in positional data because of DGPS calculation errors or topographic interference by elevated land surfaces. When this occurred, either a new master station was occupied or a signal repeater was deployed to regain positional corrections. Also, errors in depth data can occur because of insufficient signal gain or because of debris or bubbles obstructing the transducer face. Physical or electronic problems encountered in the field were corrected as soon as they were detected.

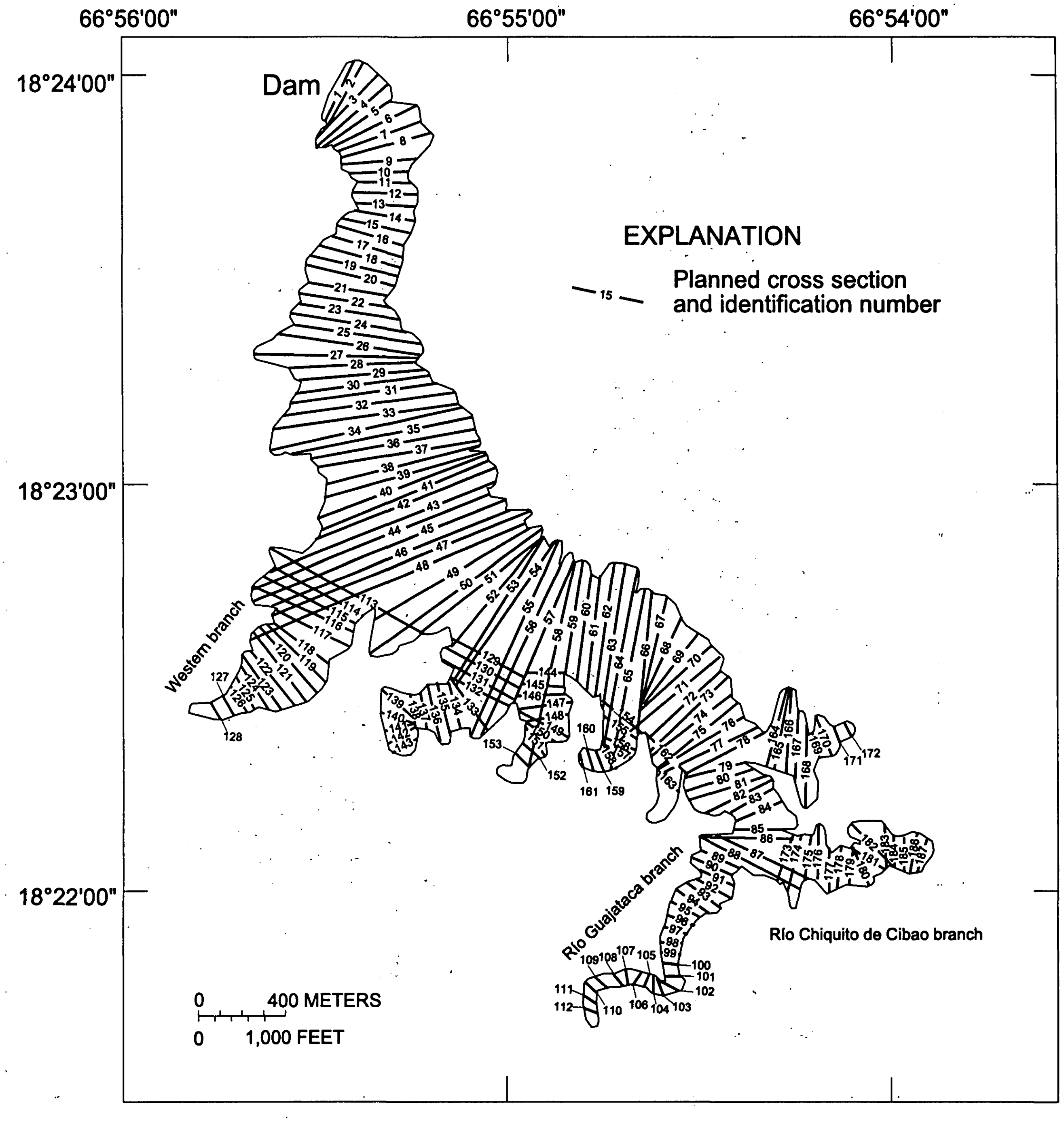

Figure 2. Planned cross-section locations for the January 1999 bathymetric survey of Lago Guajataca, Puerto Rico.

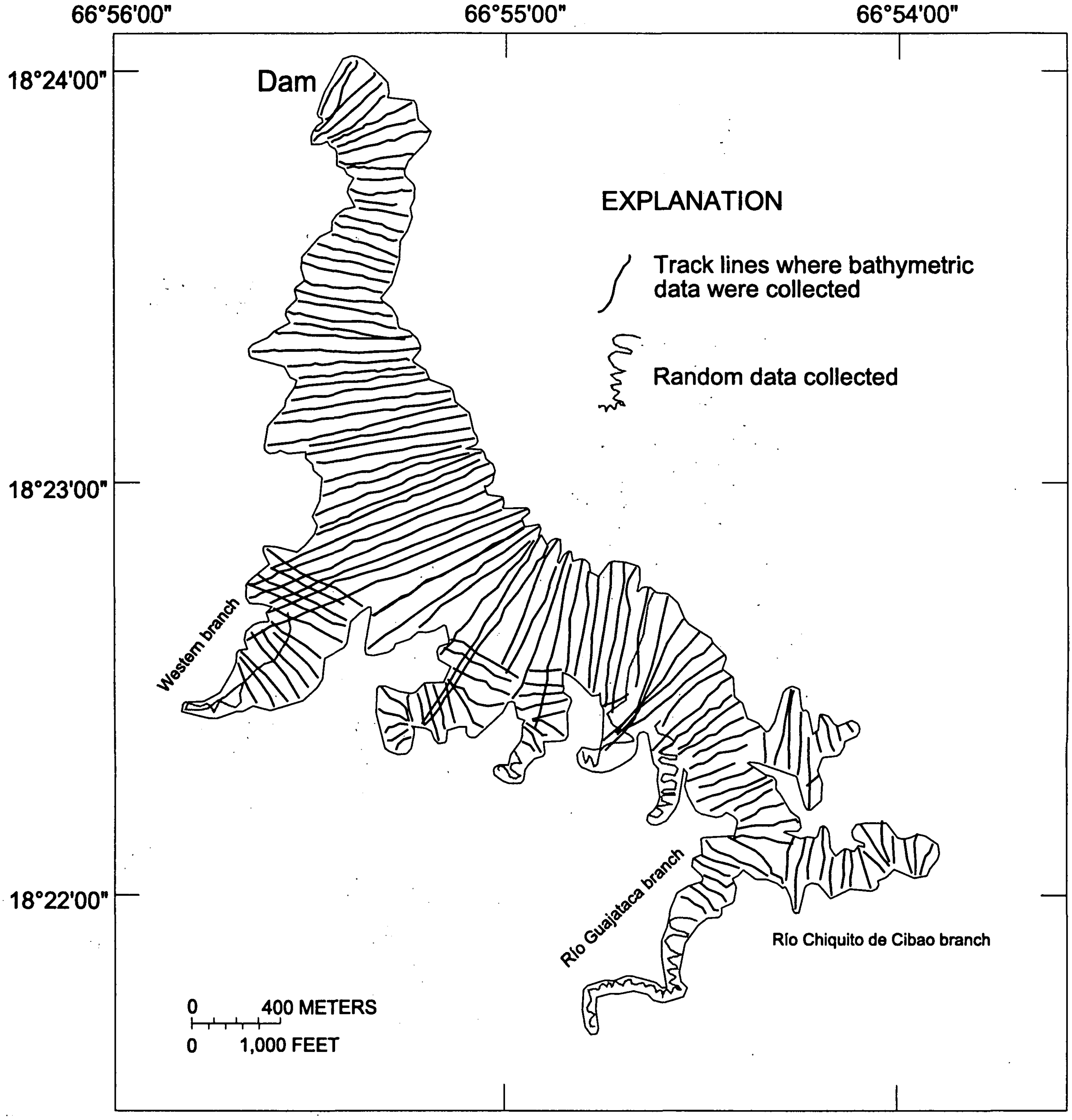

Figure 3. Actual track lines of the January 1999 bathymetric survey of Lago Guajataca, Puerto Rico.

Data Processing

Initial editing and verification of the position and depth data were performed by using the HYPACK program. Position data were corrected to eliminate anomalous positions that occurred when satellite information was obstructed by local topographic features by interpolating between the nearest correct anterior and posterior positions. The edited data were then transferred into the GIS for processing and analysis. Contour lines were drawn by using the collected data. These data points were color coded according to depth so that the drawn contour lines matched the corresponding color and depth ranges. The bathymetric contour lines were then converted into a surface model by creating a triangulated irregular network (TIN). The TIN surface model of the reservoir bottom consists of thousands of adjoining triangles with x, y, and z coordinates assigned to all vertices (Environmental Systems Research Institute, Inc., 1992).The volume of the reservoir was then calculated at incremental pool elevations of 1 meter to develop a stage-storage curve.

ACTUAL CAPACITY AND SEDIMENT ACCUMULATION

The original total storage capacity (live plus dead storage) of the Lago Guajataca reservoir is not reported in any existing literature. Only the useful (live storage) volume of 40.21 million cubic meters is reported (Puerto Rico Electric Power Authority, 1998). Dead storage (that volume below the elevation of the intake structure—180.5 meters above mean sea level) was not determined. The original total capacity of the reservoir is paramount in adequately estimating the sedimentation rate of the reservoir, the trapping efficiency of the reservoir, and the sediment yield of the drainage area. To account for this important information, a dead-storage loss rate was calculated and used to carry out a mathematical back calculation to estimate the original dead storage.

In 1978, the USGS conducted an unpublished bathymetric survey of Lago Guajataca (F. Gómez-Gómez, U.S. Geological Survey, written commun., 1999). The 1978 dead storage was determined to be 5.82 million cubic meters. The 1999 dead storage was calculated to be 4.80 million cubic meters. The resulting average annual loss of dead storage was calculated to be 48,571 cubic meters per year. This value then was used to estimate the total dead storage loss for the 50-year period from 1928 to 1978; the estimated loss was 2.43 million cubic meters. When this 50-year loss is combined with the 1978 dead-storage loss of 5.82 million cubic meters, the estimated original dead-storage capacity of the reservoir is 8.25 million cubic meters. Combining the reported original live storage volume of 40.21 million cubic meters with the estimated original dead storage volume of 8.25 million cubic meters produces a value of 48.46 million cubic meters, which could be considered as the original total capacity of the reservoir. The estimated total capacity of 48.46 million cubic meters was used to calculate the sedimentation rate, the trapping efficiency, and the sediment yield of the reservoir basin.

The storage capacity in 1999 was computed to be 42.28 million cubic meters. This represents a reduction of 6.18 million cubic meters in 71 years or about 13 percent of the original capacity. The average long-term sedimentation rate of the reservoir was calculated to be about 87,000 cubic meters per year, or 0.2 percent of storage loss per year. At this sedimentation rate, the remaining useful life expectancy of the reservoir is about 486 years. As a result, the reservoir is expected to fill completely by the year 2485. However, at the average dead-storage loss rate of 48,571 cubic meters per year, the reservoir bottom is expected to reach the elevation of the intake structure in about 99 years or by the year 2098. Data for prior and current sedimentation surveys of Lago Guajataca are summarized in table 2.

Table 2. Summary data for prior and current sedimentation surveys of Lago Guajataca, Puerto Rico

[Elevation datum, National Geodetic Vertical Datum 1929, ---, not applicable]

	1928	1999
Total capacity at spillway elevation of 196.9 meters above mean sea level (million cubic meters)	48.46[1]	42.28
Live storage (million cubic meters)	40.21[2]	37.48
Dead storage (million cubic meters)	8.25[3]	4.80
Sediment accumulation (million cubic meters)	0	6.18
Storage loss (percent)	0	13
Annual loss of capacity (cubic meters)	0	87,000
Annual loss of capacity (percent)	0	0.2
Approximate year that reservoir is expected to completely fill with sediment	---	2485[4]

[1] Original total capacity estimated from mathematical back-calculation procedure.
[2] Reported live storage (Puerto Rico Electric Power Authority, 1998).
[3] Original dead storage estimated from mathematical back-calculation procedure.
[4] Assuming that the reservoir would continue to fill at the average long-term sedimentation rate.

In this report, cross sections representing the reservoir bottom are referred to as selected cross sections. Selected cross-section locations for the January 1999 bathymetric survey of Lago Guajataca are shown in figure 4. Longitudinal distances along the different branches of the reservoir are presented in figure 5. Selected cross sections representing the reservoir bottom in January 1999 were generated from the TIN surface model of Lago Guajataca, and are shown in figure 6. Longitudinal profiles of the reservoir bottom along the different branches of Lago Guajataca are shown in figure 7. A stage-storage curve, which is shown in figure 8, was generated by calculating the reservoir volume at 1-meter incremental pool elevations. The stage-storage relation of figure 8 is shown in tabulated form in table 3.

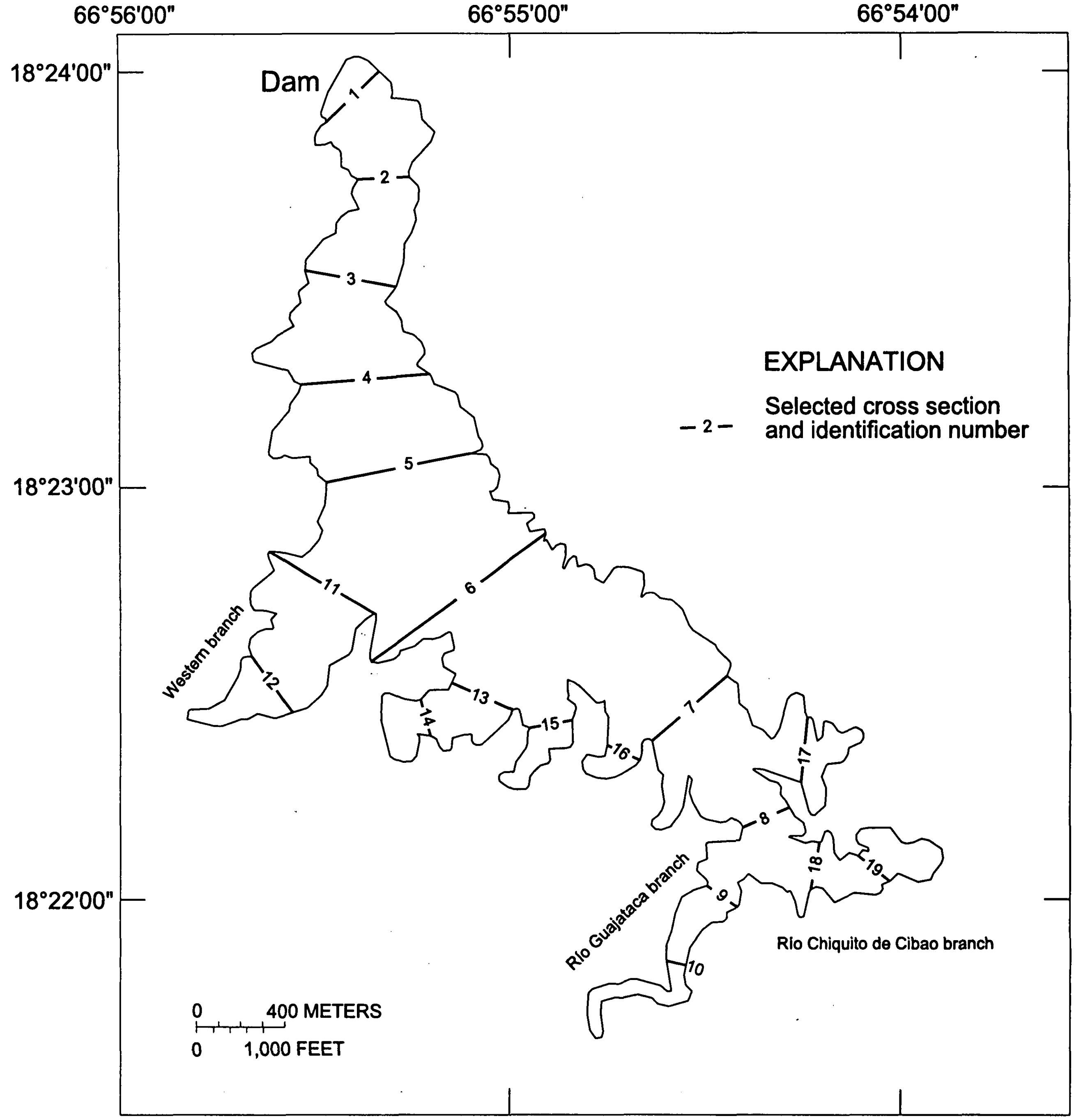

Figure 4. Selected cross-section locations for the January 1999 bathymetric survey of Lago Guajataca, Puerto Rico.

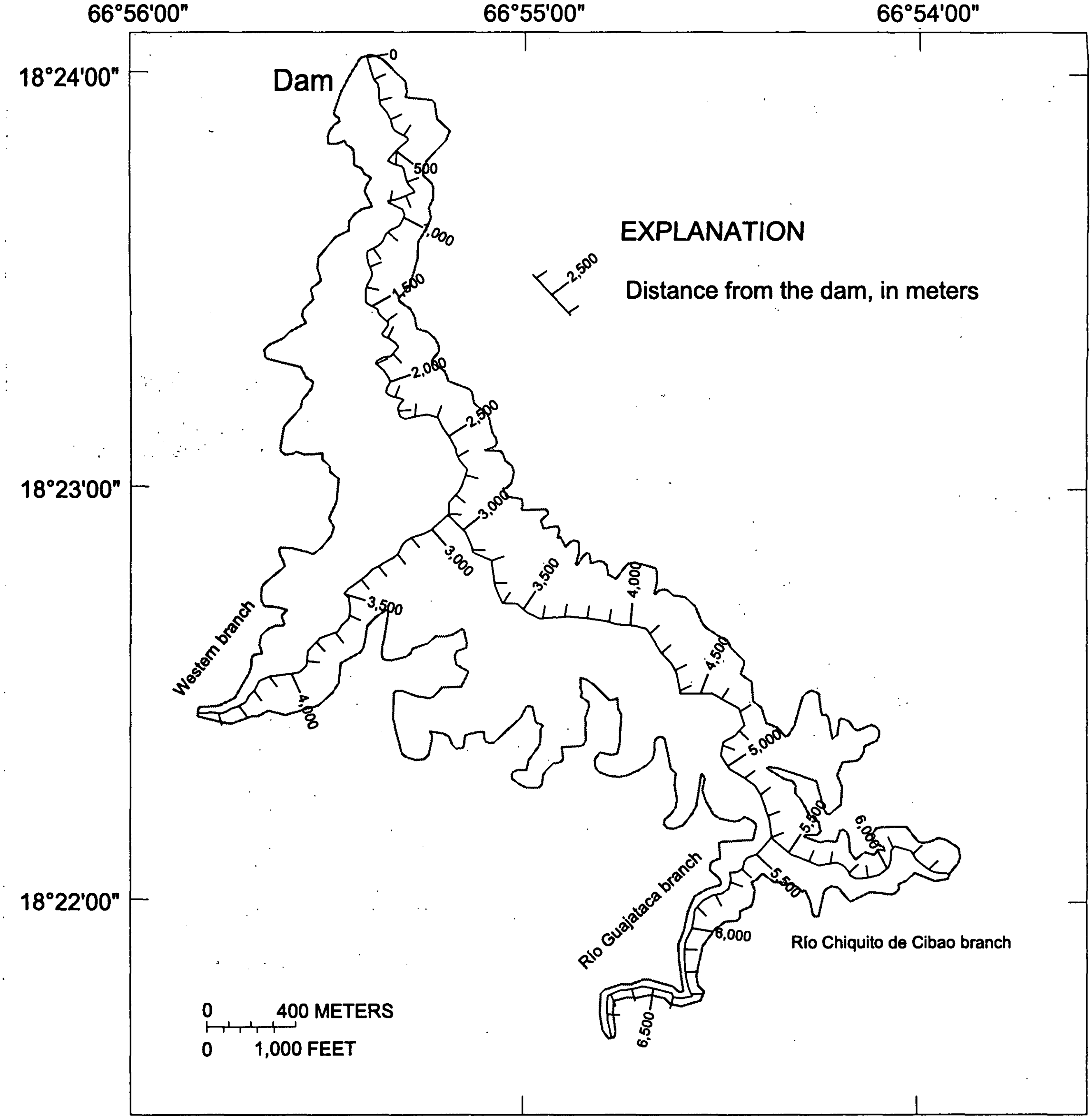

Figure 5. Reference distances for longitudinal profiles of Lago Guajataca, Puerto Rico, for the January 1999 bathymetric survey.

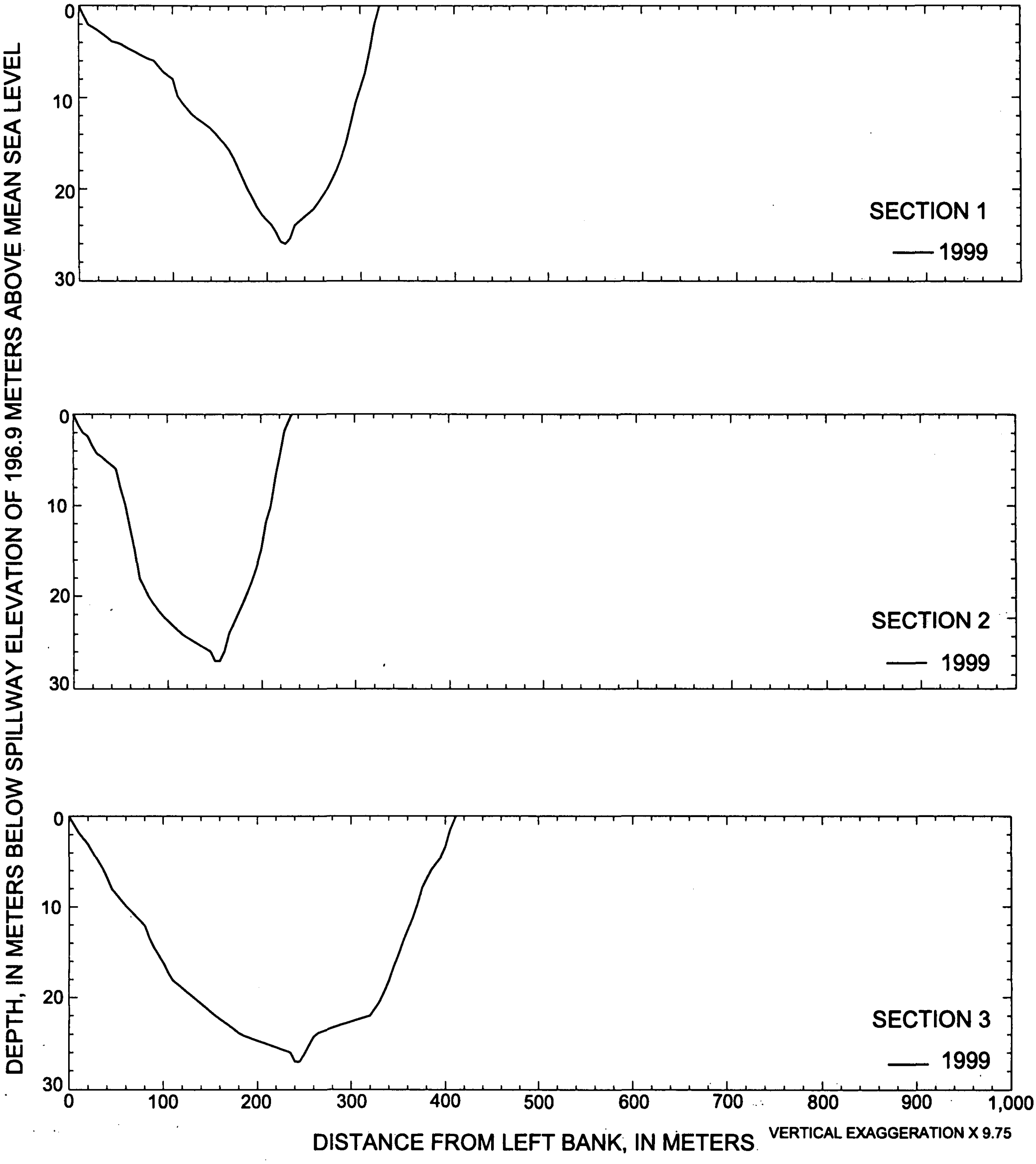

Figure 6. Selected cross sections generated from the TIN surface model of Lago Guajataca, Puerto Rico, for January 1999.

[Cross sections are oriented with the observer looking in the downstream direction (refer to figure 4 for cross-section locations).]

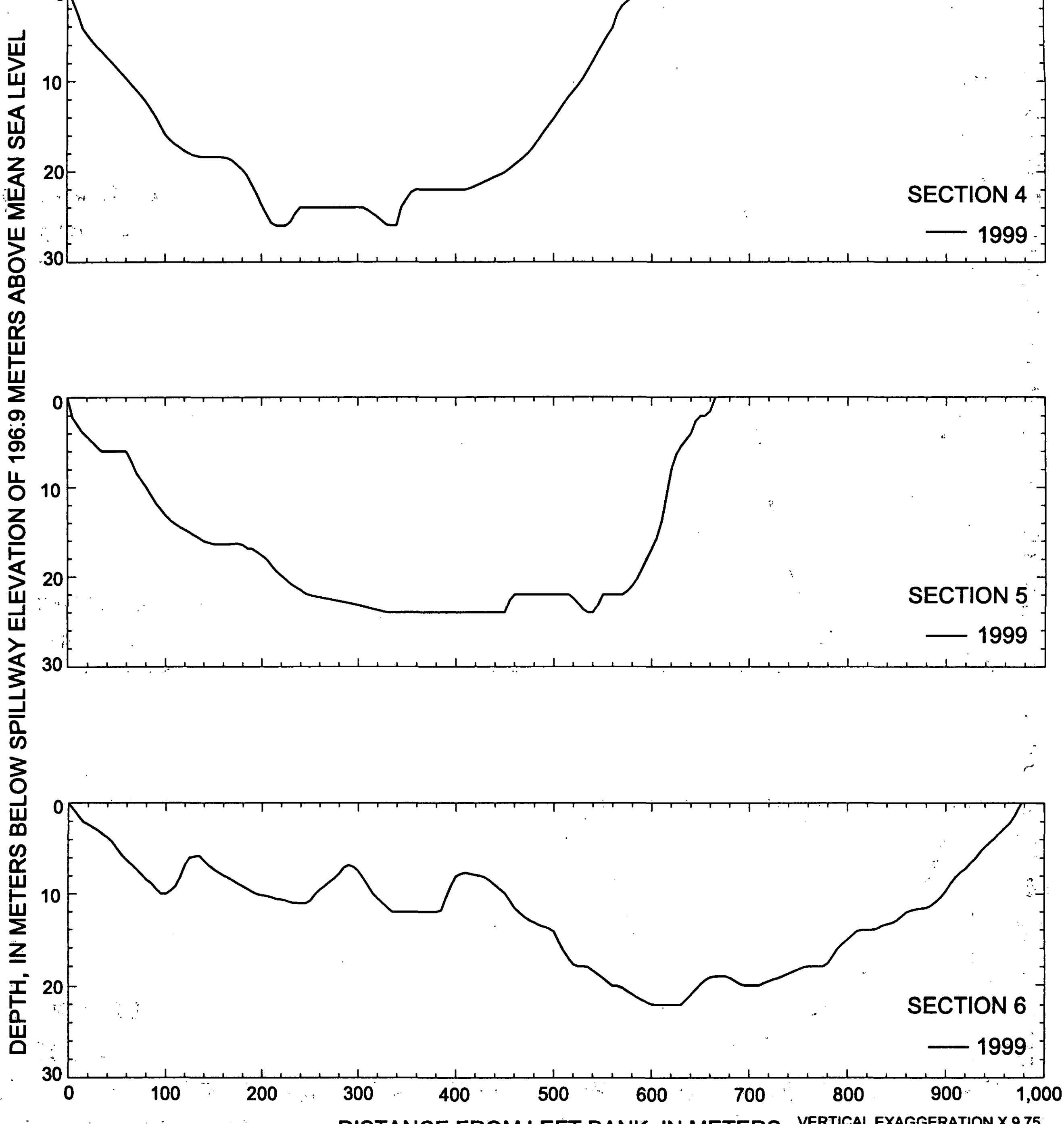

Figure 6. Selected cross sections generated from the TIN surface model of Lago Guajataca, Puerto Rico, for January 1999—Continued.

[Cross sections are oriented with the observer looking in the downstream direction (refer to figure 4 for cross-section locations).]

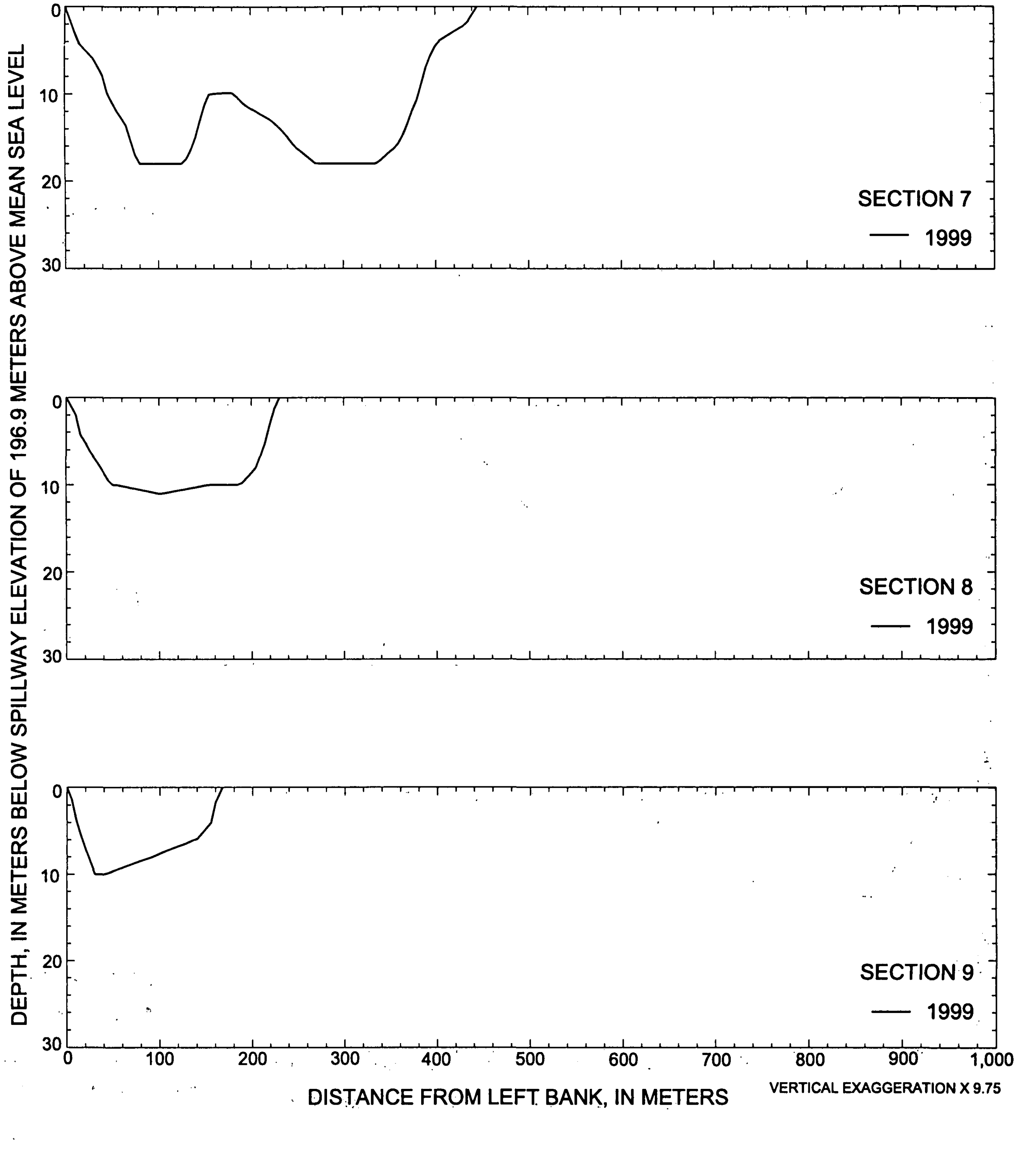

Figure 6. Selected cross sections generated from the TIN surface model of Lago Guajataca, Puerto Rico, for January 1999—Continued.

[Cross sections are oriented with the observer looking in the downstream direction (refer to figure 4 for cross-section locations).]

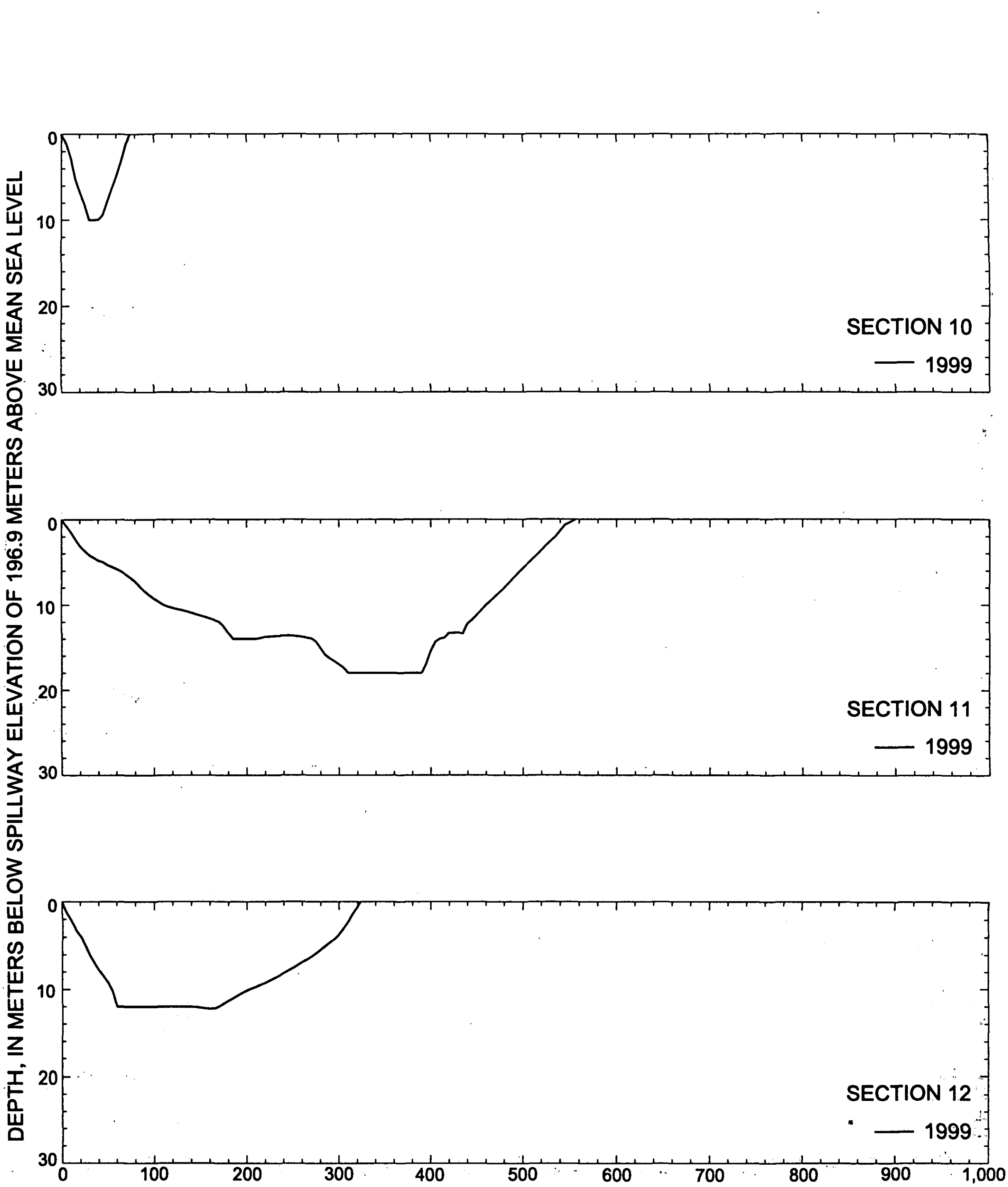

Figure 6. Selected cross sections generated from the TIN surface model of Lago Guajataca, Puerto Rico, for January 1999—Continued.

[Cross sections are oriented with the observer looking in the downstream direction (refer to figure 4 for cross-section locations).]

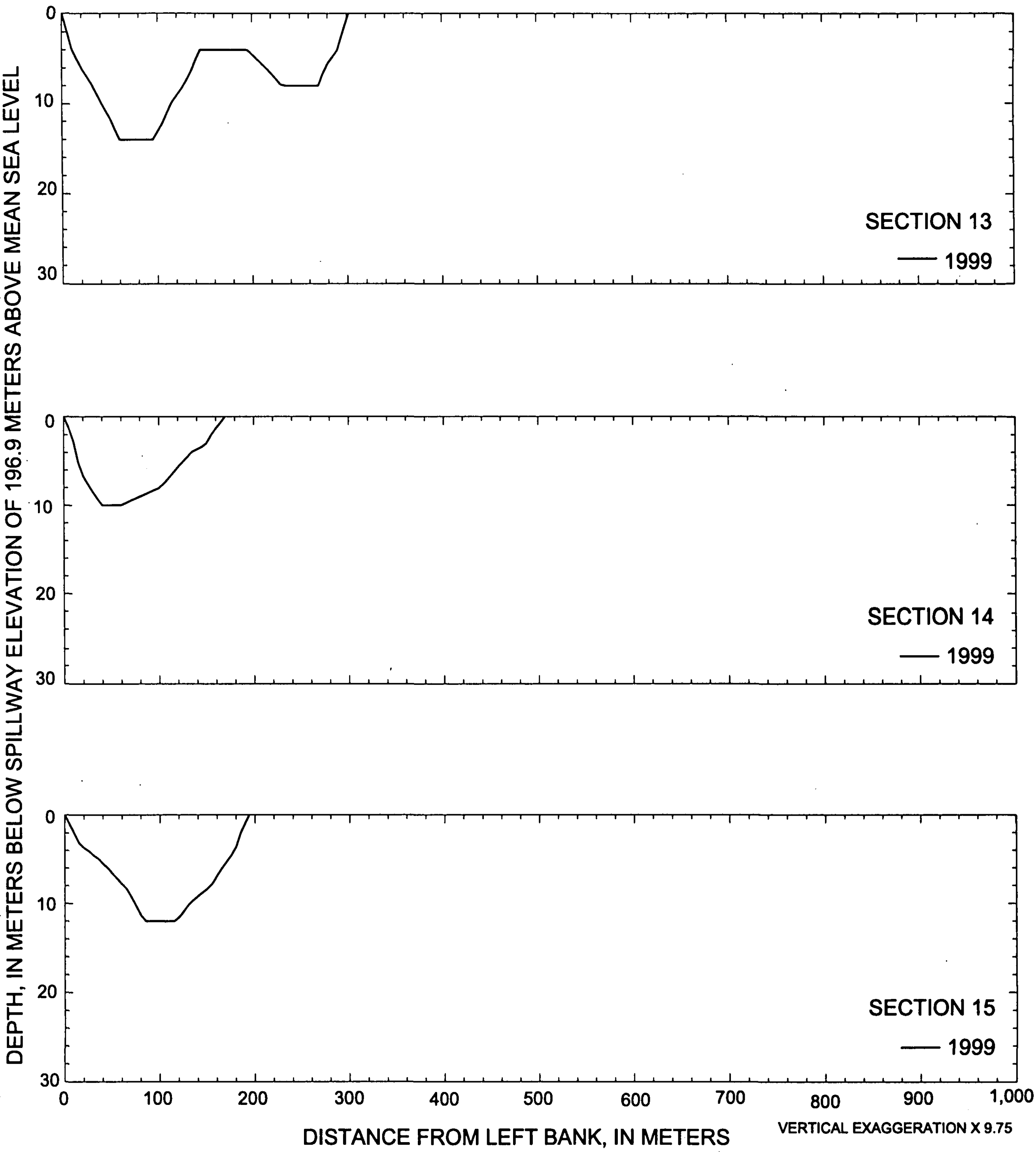

Figure 6. Selected cross sections generated from the TIN surface model of Lago Guajataca, Puerto Rico, for January 1999—Continued.

[Cross sections are oriented with the observer looking in the downstream direction (refer to figure 4 for cross-section locations).]

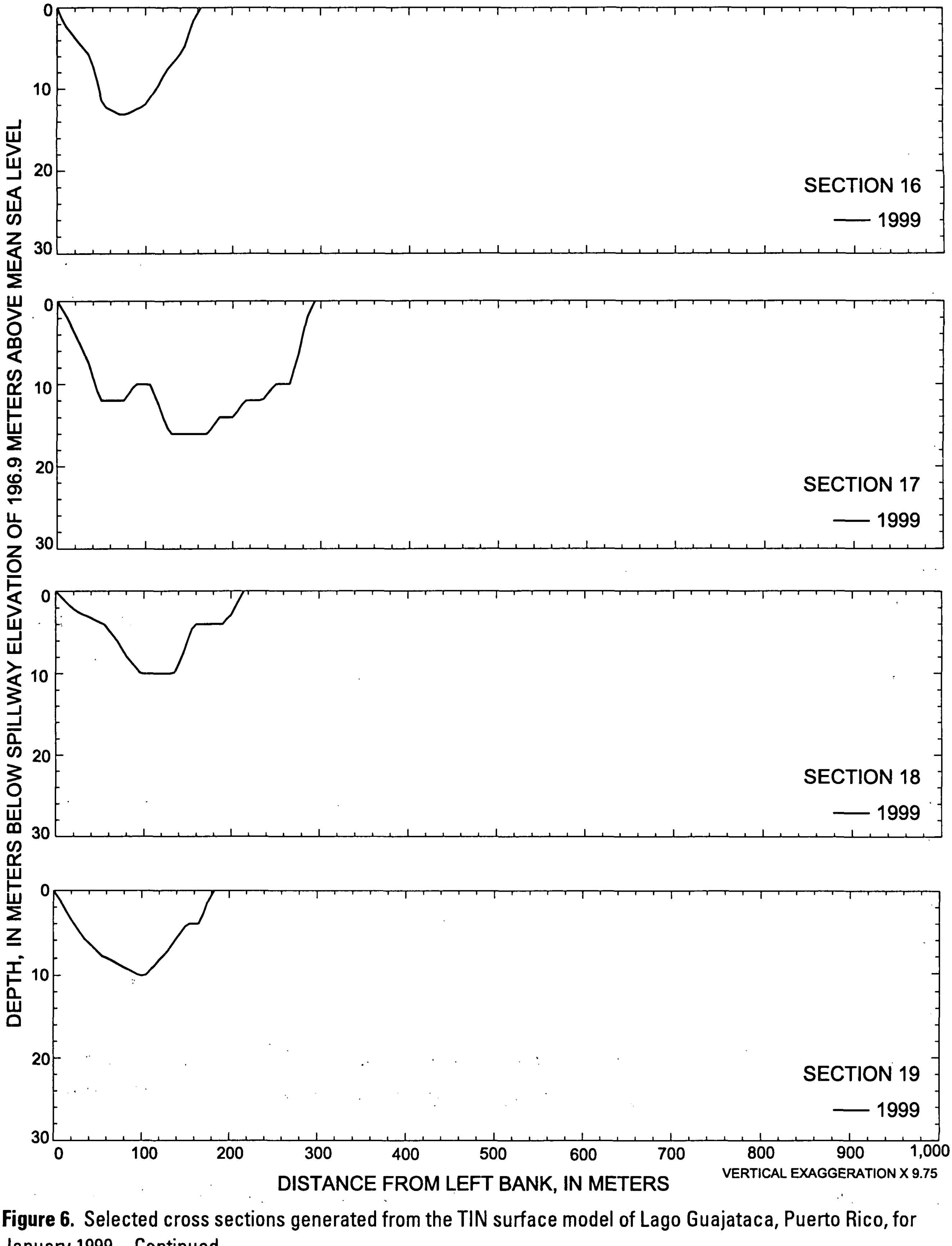

Figure 6. Selected cross sections generated from the TIN surface model of Lago Guajataca, Puerto Rico, for January 1999—Continued.

[Cross sections are oriented with the observer looking in the downstream direction (refer to figure 4 for cross-section locations).]

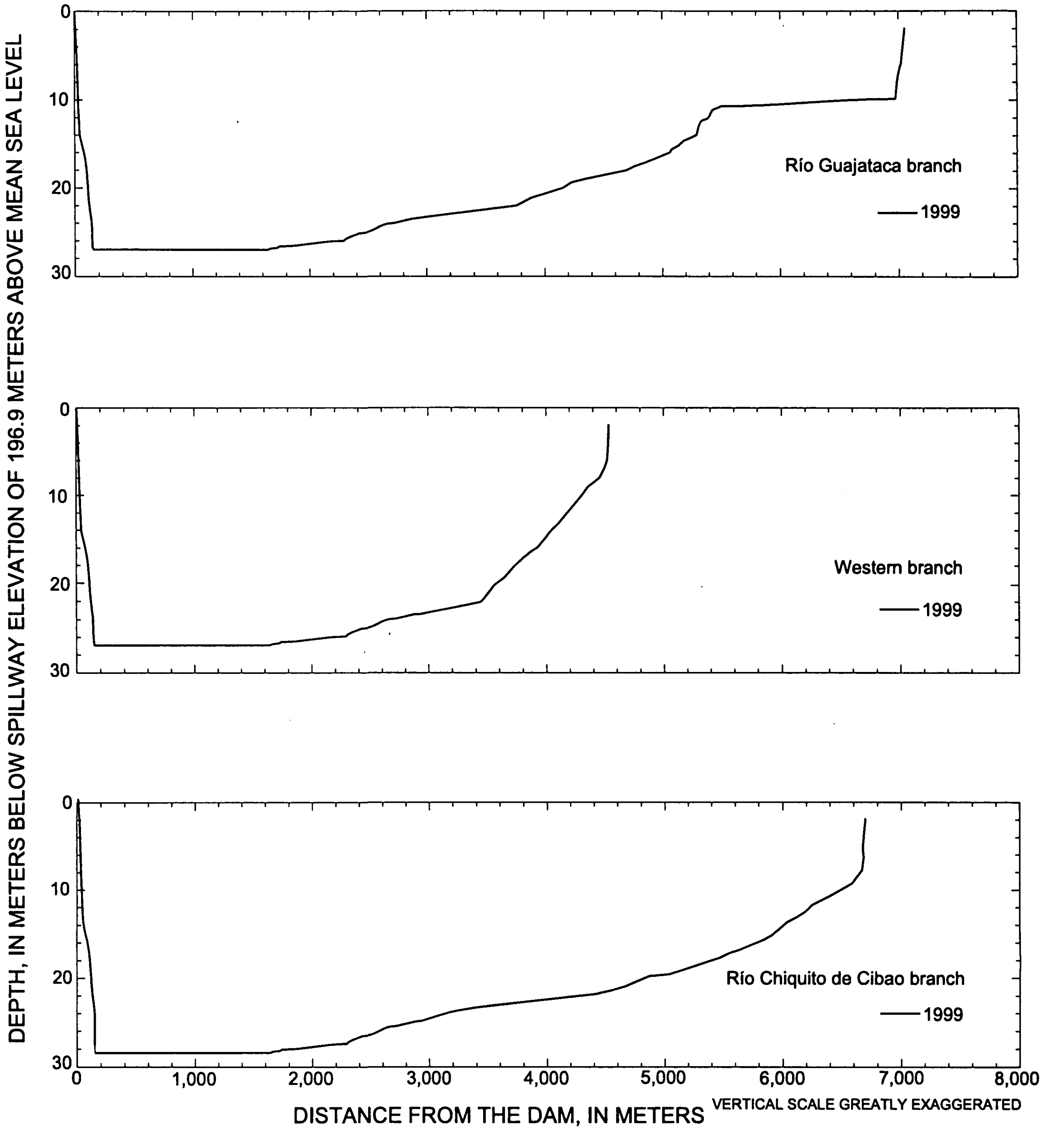

Figure 7. Longitudinal profiles generated from the TIN surface model of Lago Guajataca, Puerto Rico, for the January 1999 bathymetric survey.

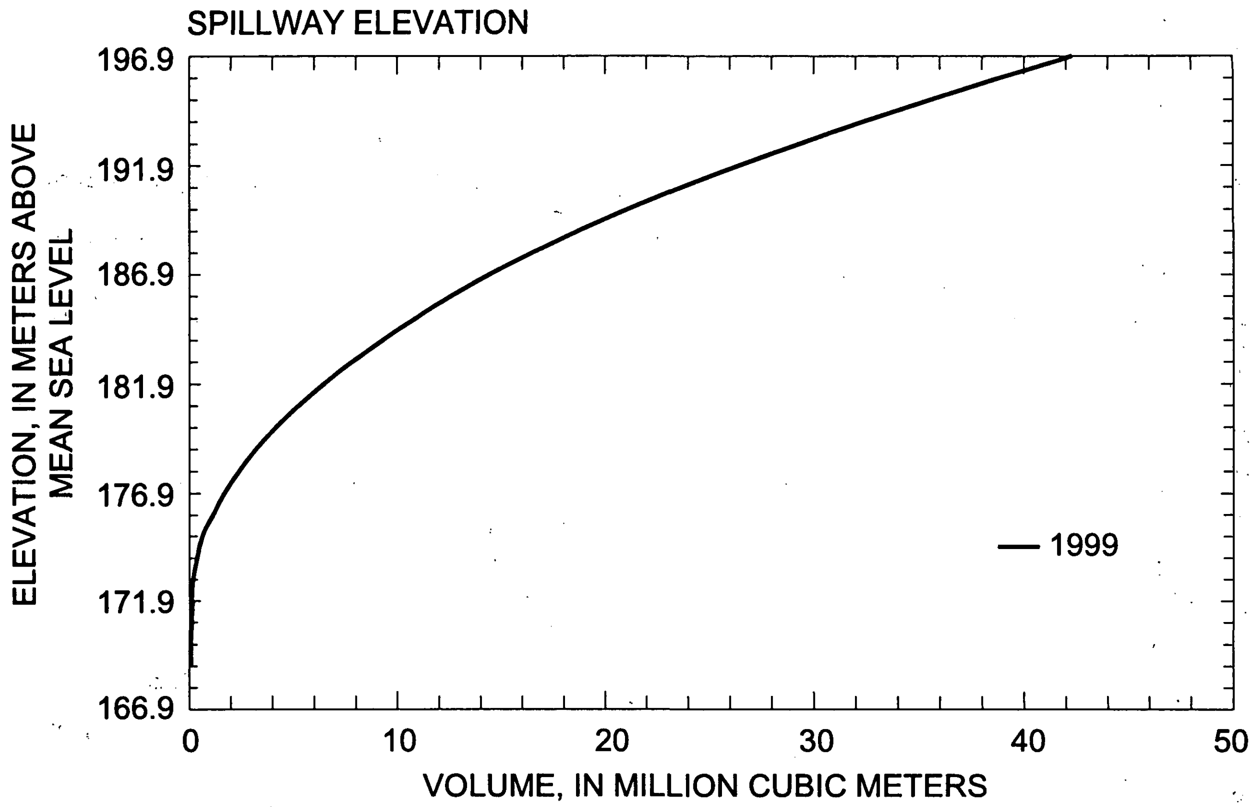

Figure 8. Capacity curve for Lago Guajataca, Puerto Rico, for January 1999.

Table 3. Storage capacity for Lago Guajataca, Puerto Rico, for January 1999

[amsl, above mean sea level]

Elevation, in meters amsl	Capacity, in million cubic meters
196.9	42.28
195.9	38.91
194.9	35.64
193.9	32.48
192.9	29.40
191.9	26.48
190.0	23.72
189.9	21.15
188.9	18.74
187.9	16.52
186.9	14.45
185.9	12.61
184.9	10.88
183.9	9.30
182.9	7.82
181.9	6.48
180.9	5.24
179.9	4.16
178.9	3.19
177.9	2.40
176.9	1.69
175.9	1.13
174.9	0.63
173.9	0.36
172.9	0.16
171.9	0.07
170.9	0.02
169.9	0

TRAPPING EFFICIENCY AND SEDIMENT YIELD

The rapid rates of sediment accumulation in many upland reservoirs make it important to estimate the trapping efficiency if a true erosion rate is to be calculated. Heinemann (1981) considered trap efficiency as the most informative single descriptor of a reservoir. A number of empirical studies have been conducted on trapping efficiency; the best known and most commonly used is that of Brune (1953). The Lago Guajataca trapping efficiency was estimated by using the capacity/inflow ratio described by Brune (1953). The capacity/inflow ratio is the reservoir capacity divided by the mean annual flow. In the Lago Guajataca drainage area, the average long-term rainfall is 2.18 meters per year and the rainfall/runoff ratio is 0.6 (Giusti and López, 1967). Thus, the mean annual runoff reaching Lago Guajataca is calculated to be 1.31 meters per square kilometer. Based on the 79.77-square-kilometer drainage area, the inflow to the reservoir is about 104.5 million cubic meters per year. The capacity/inflow ratio was calculated to be 0.5 for 1928 and 0.4 for 1999. These values then were plotted on the curve generated by Brune (1953) with the estimated trapping efficiency interpolated from the curve. The trapping efficiency of Lago Guajataca was estimated to be 97 percent in 1928 and 96 percent in 1999. The average long-term trapping efficiency of Lago Guajataca is about 96 percent.

Sediment yield has been defined by the American Society of Civil Engineers as the total sediment outflow from a catchment or drainage basin measurable at a point of reference over a specified period of time (McManus and Duck, 1993).

Based on this definition, the sediment yield for the Lago Guajataca basin was calculated by first dividing the amount of deposited material in Lago Guajataca (6.18 million cubic meters) by the average long-term trapping efficiency (0.96), which yielded the total amount of sediment eroded from the Lago Guajataca catchment area (6.44 million cubic meters). This number then was divided by the sediment-contributing area of the reservoir, which was calculated to be 76.35 square kilometers (for example, the total drainage area, 79.77 square kilometers minus the reservoir flooded area, 3.42 square kilometers), and the number of years since construction (71 years). Based on an estimated dry-bulk density of 1 gram per cubic centimeter, the sediment yield for the Lago Guajataca basin was calculated to be 1,188 megagrams per square kilometer per year.

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District Chief
Caribbean District
U.S. Geological Survey
Water Resources Division
GSA Center, Suite 400-15
651 Federal Drive
Guaynabo, Puerto Rico 00965-5703