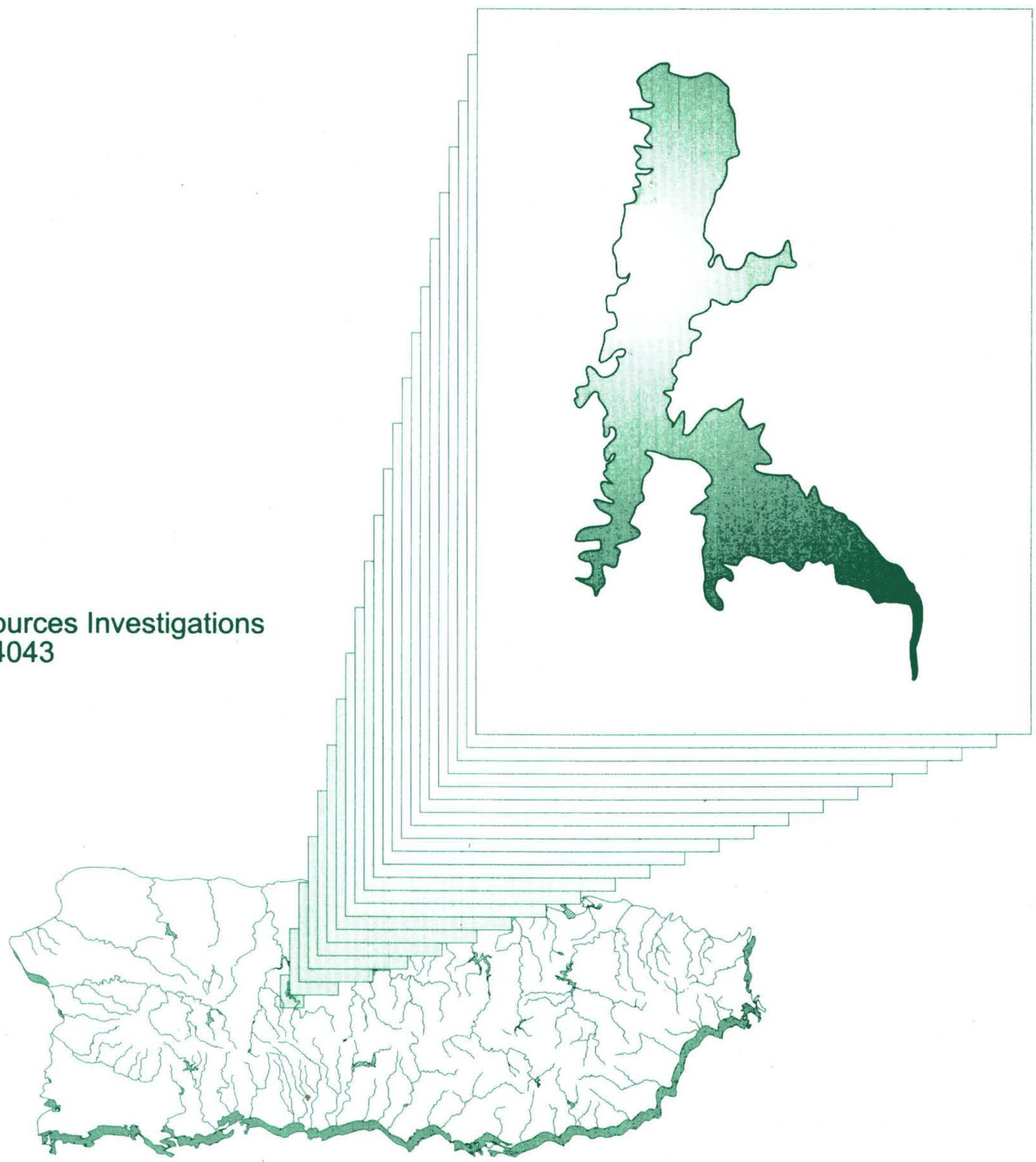
U.S. Geological Survey
U.S. Department of the Interior

Prepared in cooperation with the
PUERTO RICO AQUEDUCT AND SEWER AUTHORITY

Sedimentation Survey of Lago Caonillas, Puerto Rico, February 2000



Water-Resources Investigations
Report 01-4043

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

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By Luis R. Soler-López

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San Juan, Puerto Rico: 2001

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CONVERSION FACTORS, DATUMS, and ACRONYMS

Multiply	By	To obtain
	Length	
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 centimeter	0.06102	cubic inch
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)	
gram per cubic centimeter	62.43	pound per cubic foot
kilogram per square kilometer	0.002855	ton per square mile
megagram per square kilometer	2.855	ton per square mile
megagram per year	1.102	ton per year

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
GIS	Geographic Information System
PRASA	Puerto Rico Aqueduct and Sewer Authority
TIN	Triangulated Irregular Network
USGS	U.S. Geological Survey

Sedimentation Survey of Lago Caonillas, Puerto Rico, February 2000

By Luis R. Soler-López

Abstract

Lago Caonillas, a reservoir owned by the Puerto Rico Electric Power Authority and located in the central part of Puerto Rico, is one of the two reservoirs (the other being Lago Dos Bocas) proposed to supply water for the Puerto Rico Aqueduct and Sewer Authority project called the Superaqueduct. The reservoir was impounded in 1948 and originally provided about 55.66 million cubic meters of water for hydroelectric power generation. Sediment derived from the reservoir basin has been transported and deposited in the reservoir bottom, substantially decreasing the water storage capacity over time. Successive bathymetric surveys indicated that in 1990 the storage capacity was 49.25 million cubic meters, decreasing to 48.80 million cubic meters in 1995 and to 42.27 million cubic meters in 2000. This represents an overall storage loss of about 11.5 percent by 1990, 12.3 percent by 1995 and 24.1 percent by 2000. The long-term sedimentation rate of the reservoir was about 153,000 cubic meters per year in 1990, remaining almost constant at about 146,000 cubic meters per year in 1995, but nearly doubling to 258,000 cubic meters per year in 2000. The two-fold increase in sedimentation rate, and consequently, the reservoir storage capacity loss, can be attributed to Hurricane Hortense in September 1996 and Hurricane Georges in September 1998. Twenty-four percent of the original storage capacity of Lago Caonillas has been lost to sediment accumulation. About 49 percent of the reservoir sediment was deposited in the last five years, demonstrating the impact of these major storms on the reservoir.

Based on the ratio of storage capacity to inflow rate, the estimated trapping efficiency of Lago Caonillas is about 93 percent for 2000. The sediment yield of the Lago Caonillas net sediment-contributing drainage area (total drainage area minus the reservoir surface area) of 218.74 square kilometers, is about 1,266 megagrams per square kilometer per year. This represents an increase of about 69 percent in the material transport and deposition process of the Lago Caonillas basin between 1990 and 2000. The life expectancy of Lago Caonillas was more than 300 years in 1995; however, at the storm-accelerated sedimentation rate, the life expectancy has decreased to about 164 years. This implies that the reservoir could be filled with sediments by the year 2164 if major hurricanes continue to pass through Puerto Rico regularly (every 2 to 4 years).

Sumario

Lago Caonillas, un embalse perteneciente a la Autoridad de Energía Eléctrica de Puerto Rico y localizado en la región central de Puerto Rico, es uno de los dos embalses que se han propuesto para suplir agua al proyecto del Superacueducto de la Autoridad de Acueductos y Alcantarillados de Puerto Rico (el otro embalse propuesto es Lago Dos Bocas). El embalse comenzó a operar en 1948 y originalmente proveía unos 55.66 millones de metros cúbicos de agua para generar energía hidroeléctrica. Con el paso de los años, el fondo del embalse se ha ido llenando de sedimento proveniente de la cuenca del embalse, lo cual ha disminuido sustancialmente su capacidad de almacenaje de agua. Estudios de batimetría sucesivos indicaron que en 1990 la capacidad de almacenaje del

embalse era de 49.25 millones de metros cúbicos, la cual disminuyó a 48.80 millones de metros cúbicos en 1995, y a 42.27 millones de metros cúbicos en el 2000. Esto representa una pérdida total de alrededor de 11.5 por ciento para 1990, 12.3 por ciento para 1995 y 24.1 por ciento para el 2000. La tasa de sedimentación del embalse a largo plazo era de alrededor de 153,000 metros cúbicos al año en 1990, la cual permaneció casi constante a alrededor de 146,000 metros cúbicos al año en 1995, pero casi duplicada a 258,000 metros cúbicos para el 2000. El aumento simultáneo de sedimentación y, por consiguiente, la pérdida de capacidad de almacenaje del embalse pueden atribuirse al paso del huracán Hortense en septiembre de 1996 y al paso del huracán Georges en septiembre de 1998. Veinticuatro por ciento de la capacidad de almacenaje original del Lago Caonillas se ha perdido debido a la acumulación de sedimento. Alrededor del 49 por ciento del sedimento del embalse se ha depositado en los últimos cinco años, lo cual demuestra el impacto de estas dos grandes tormentas en el embalse.

Basados en la relación entre capacidad de almacenaje y afluente, la eficiencia estimada del Lago Caonillas para atrapar sedimento es de un 93 por ciento para el 2000. El rendimiento de sedimento del área neta de aportación de sedimento de 218.74 kilómetros cuadrados del Lago Caonillas (área total de drenaje menos el área de superficie del embalse) es de alrededor de 1,266 megagramos por kilómetro cuadrado al año. Esto representa un aumento de un 69 por ciento en el proceso de transporte y acumulación de sedimento en la cuenca del Lago Caonillas entre 1990 y 2000. La expectativa de vida del Lago Caonillas era de más de 300 años en 1995; sin embargo, al incrementar la tasa de sedimentación por el paso de las tormentas, la expectativa de vida se ha reducido a alrededor de 164 años. Esto implica que el sedimento pudiera llenar la totalidad del embalse para el año 2164 si huracanes como éstos continuaran afectando a Puerto Rico con regularidad (cada 2 a 4 años).

INTRODUCTION

As originally designed, Lago Caonillas generates hydroelectric power at a facility downstream of the Caonillas dam. The water used to generate power is released into the Río Caonillas delta of Lago Dos Bocas, and is then available for additional power generation at the Lago Dos Bocas dam. Lago Caonillas is proposed to be a supplemental part of the Puerto Rico Aqueduct and Sewer Authority (PRASA) project called the Superaqueduct. Plans are to capture water released during hydroelectric power generation at the Lago Dos Bocas dam in a retention pond constructed adjacent to the Río Grande de Arecibo below the dam. The captured water will then be used to supply potable water for north coast residents of the island of Puerto Rico. The project's success, however, depends on the combined available storage capacity of the Caonillas and Dos Bocas reservoirs.

Bathymetric surveys of Lago Caonillas in 1990 and 1995 had been used to estimate the storage capacity and rates of storage loss (Webb and Soler-López, 1996). Recent decreases in storage capacity of both reservoirs, however, have constrained the original project plans. The passage of Hurricane Hortense during September 1996 brought torrential rains and extensive land erosion. Two years later, during September 1998, Hurricane Georges made landfall on the island of Puerto Rico, and the rainfall and sediment erosion and transport were even greater than that associated with Hurricane Hortense. During October 1999, a sedimentation survey of Lago Dos Bocas was performed in cooperation with PRASA to determine the impact of these storms on Lago Dos Bocas. Because Lago Caonillas is the larger reservoir in terms of storage capacity for the Superaqueduct project, it was necessary to conduct a sedimentation survey to assess the impact of Hurricanes Hortense and Georges on Lago Caonillas as well.

During February 8 to 11, 2000, the U.S. Geological Survey (USGS), in cooperation with PRASA, conducted a bathymetric survey of Lago Caonillas to determine the storage capacity, the sedimentation rate of the reservoir, the amount and location of deposited material, and to estimate the trapping efficiency of Lago Caonillas and the sediment yield of the reservoir drainage area. A differential global positioning system (DGPS) coupled to a depth sounder was used to collect geographic positions and water depths. The data were stored in digital form and then transferred into a Geographic Information System (GIS) for processing and analysis. The GIS was then used to calculate the existing storage capacity, the volume and distribution of accumulated sediment, and to determine the sedimentation rate of the reservoir as of February 2000.

DAM, RESERVOIR, AND DRAINAGE BASIN CHARACTERISTICS

Lago Caonillas is located approximately 7 kilometers east of the town of Utuado and about 10 kilometers northwest of the town of Jayuya (fig. 1). The reservoir dam was completed in 1948 and is the principal unit of the Caonillas Hydroelectric project. The dam is a concrete gravity structure with a total length of 248.41 meters, a maximum height of 71.63 meters, and a maximum base width of 59.44 meters. Nonoverflow sections on each abutment have a total length of 183.79 meters. (Sheda and Legas, 1968). The principal characteristics of Lago Caonillas and Caonillas dam are listed in table 1.

Table 1. Principal characteristics of Lago Caonillas and Caonillas dam as of 2000 (modified from Noll, 1953 and Sheda and Legas, 1968)

[Elevations in meters above mean sea level]

Total length of dam at top (spillway and nonoverflow sections)	248.41 meters
Length of spillway section	61.0 meters
Elevation of crest of spillway	251.76 meters
Maximum width at base	59.44 meters
Crown elevation of penstocks	213.06 meters
Installed power-generating capacity	22,000 kilowatts
Maximum flood-level storage	71.4 million cubic meters
Design discharge over the spillway at a head of 7.93 meters (elevation 259.69 meters)	3,030 cubic meters per second
Surcharge storage (flood control) [1]	22.6 million cubic meters
Drainage area at damsite [2]	221.44 square kilometers
Maximum height of dam	71.63 meters
Maximum depth during the February 2000 survey [3]	40 meters
February 2000 reservoir surface area	2.70 square kilometers

[1] Assumes that the capacity between elevations of 251.76 and 259.69 meters has not changed since dam construction.

[2] Includes 126.65 square kilometers of the natural Caonillas drainage basin and 94.79 square kilometers that is diverted from the Río Grande de Arecibo drainage basin (Noll, 1953, p. 10).

[3] Below spillway elevation of 251.76 meters above mean sea level.

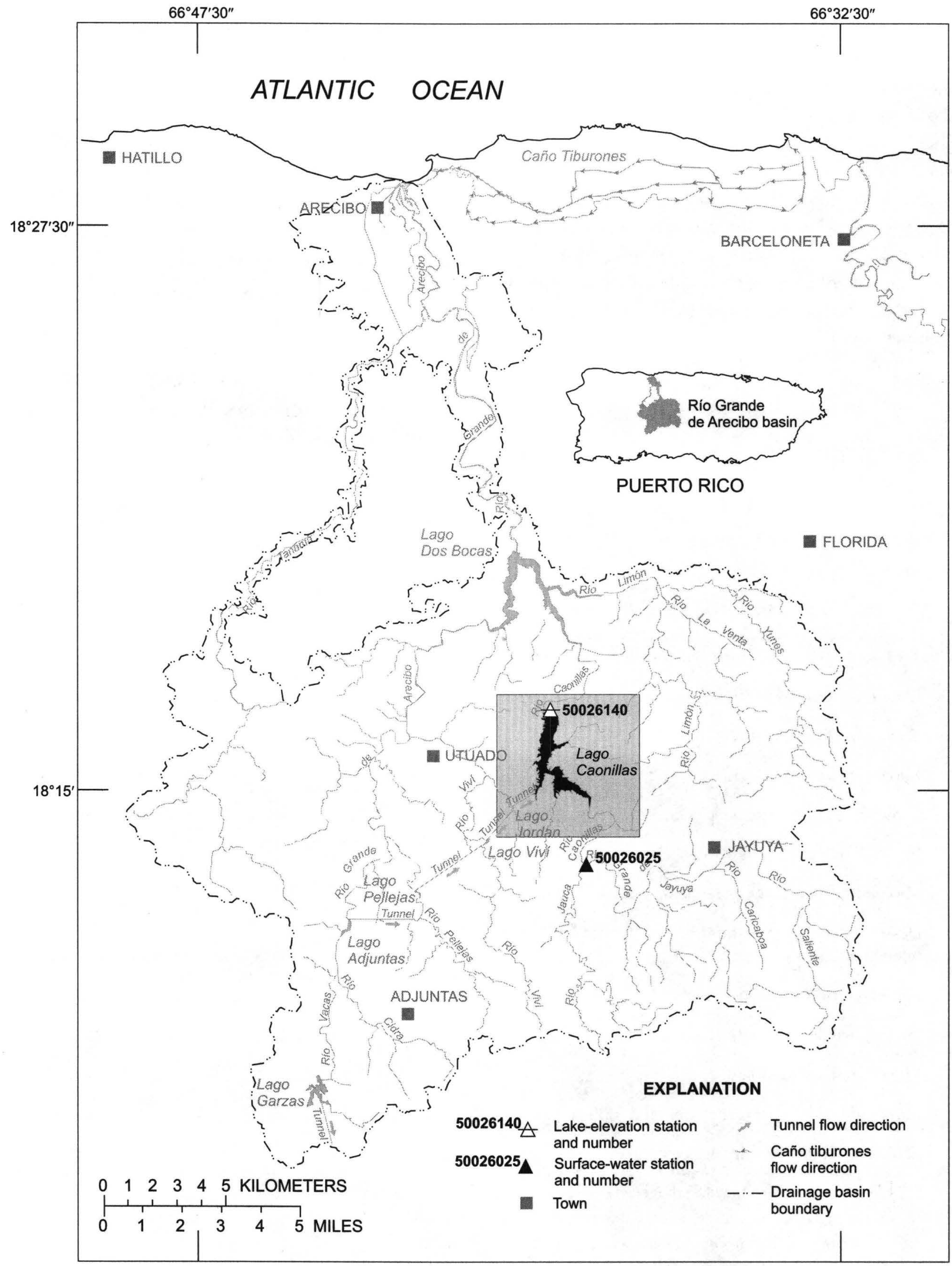

Figure 1. Location of Lago Caonillas in the Río Grande de Arecibo basin, Puerto Rico.

Although flash boards were originally installed at the dam to increase the storage capacity of the reservoir, they were removed after a short period of time. The original storage capacity of the reservoir was reported to be 61.86 million cubic meters at the maximum pool elevation of 252.98 meters above mean sea level with flash boards (Noll, 1953). In 1995, however, the original storage capacity was recomputed using GIS technology and yielded a capacity of 55.66 million cubic meters at the spillway elevation of 251.76 meters above mean sea level (Webb and Soler-López, 1996). The recomputed original storage capacity of 55.66 million cubic meters is used as the starting point for calculations of storage loss in this report.

The predominant soil types in the Lago Caonillas drainage basin are those within the Pellejas-Lirios-Ingenio association of the Arecibo area. The Pellejas soil type constitutes about 85 to 90 percent of the total soil coverage. These soils are generally deep, steep, and excessively drained with slopes ranging from 40 to 60 percent. Typically, the surface layer is a clay loam about 15 centimeters thick. The subsoil is a sandy clay loam about 25 centimeters thick. The substratum is sandy loam to a depth of about 18 meters or more. Infiltration is moderate in the upper layers and high in the lower layer. The available water capacity is moderate and the runoff is very rapid, thus making this soil association somewhat unstable and suited for erosion by runoff (Acevedo, 1982). Vegetation is abundant with pasture, fallow fields, forest, and rangeland. Agricultural practices within the basin have declined over time, and only small private lands are currently being farmed.

METHOD OF SURVEY

The sedimentation survey of Lago Caonillas involved planning, data collection, processing, and analysis. A GIS (Arc/Info) was used to plan the cross-section locations for the survey and for analysis of the bathymetric data. Cross-section locations were established at a spacing of 50 meters starting at the dam and continuing upstream along the different branches of the reservoir (fig. 2). Position and depth data were acquired using a DGPS coupled to a depth sounder. A total of 21,545 data points with x, y (geographic location) and z (depth) coordinates were collected over the entire reservoir. Using the positional and depth data, a contour map representing the reservoir bottom surface was constructed. The contour map was converted into a triangulated irregular network (TIN) surface model of the reservoir using the GIS. For this study, GIS algorithms (Environmental Systems Research Institute, 1992) were used to calculate the volume of the tridimensional surface model represented by the 2000 contour map. From the TIN, the storage capacity and sedimentation rate were calculated. The same methodology was used previously to calculate reservoir volumes for 1990 and 1995. The algorithms used for all volume calculations are mathematical equations intrinsic to the Arc/Info program.

Field Techniques

The bathymetric data were collected during February 8 to 11, 2000. The reservoir pool elevation was continuously monitored at the USGS lake-level station Lago Caonillas at damsite near Utuado, Puerto Rico (number 50026140, fig. 1). Water was continuously flowing over the spillway structure (just a film) during the survey, therefore, depth data did not have to be corrected to represent depths below spillway elevation. The Bathymetric/Land Survey System (BLASS) developed by Specialty Devices, Inc., was used for the bathymetric survey. The system consists of two Novatel DGPS receivers for horizontal positioning of the survey boat. One unit was located at a master or reference station with known coordinates and the other was installed on the survey boat and used as the mobile unit.

The benchmark "LOOKCAON2" (18°17'17.771"N., 66°39'29.206"W.) established by the USGS in 1998, was used to locate the reference station on the north side of the Lago Caonillas dam, on a hill with an unobstructed view of the entire reservoir.

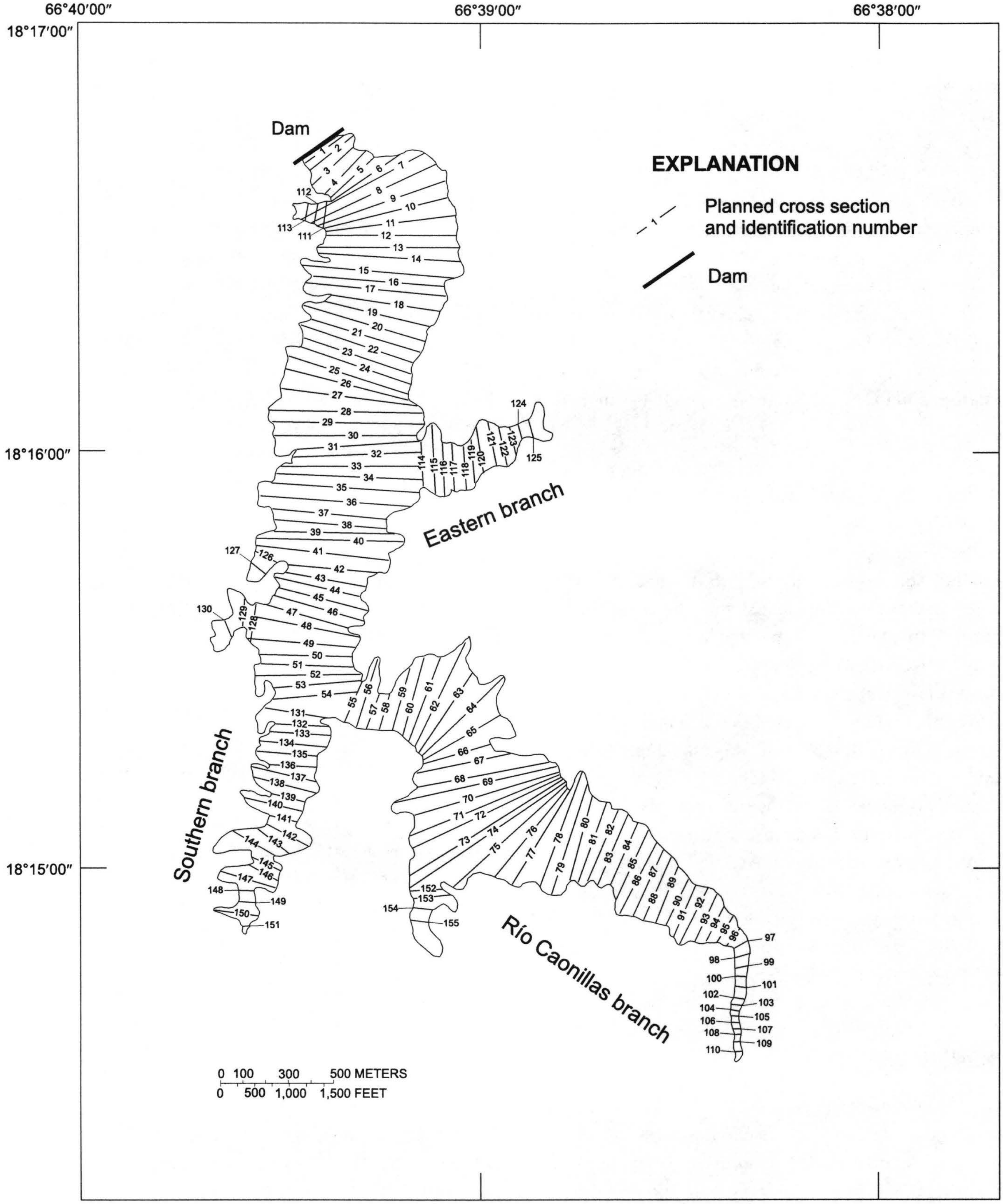

Figure 2. Planned cross-section locations for the February 2000 bathymetric survey of Lago Caonillas, Puerto Rico.

The DGPS unit at the reference station sent correction signals to the DGPS unit on the survey boat every 5 seconds, to maintain the horizontal position precision of the survey boat to within 2 meters of the true geographic position while navigating along the planned survey lines. When the correction signal of the reference station was lost because elevated land surfaces obstructed the view, a signal repeater was installed at a convenient location to regain correction signals. Reservoir depths were measured using a BLASS-MSU-IDS Intelligent Depth Sounder that collects depth data with an accuracy of 2 centimeters. The depth sounder was calibrated at water depths of 2, 6, 10, and 16 meters. The bathymetric survey software HYPACK was used to collect data and to navigate. HYPACK received and recorded water depth and geographic position every second while in survey mode. The data were stored in a computer hard disk and were later transferred into the GIS. Plans were to collect data at 155 pre-established cross sections to match most of the 1995 survey lines. Sediment accumulation in the riverine sections of the reservoir, however, limited data collection to 139 cross sections. Figure 3 shows the actual track lines where bathymetric data were collected for the February 2000 bathymetric survey of Lago Caonillas. The longitudinal distances from the dam upstream to the different branches of the reservoir are shown in figure 4.

Data Processing

Initial editing and verification of the positional and depth data were performed within the HYPACK program. Positions were corrected to eliminate anomalous spikes or jumps, which can occur if the signal transmission from the satellites or reference station are obstructed by local topographic features or disrupted by electromagnetic interference. In these cases, the erroneous positions were interpolated between the correct anterior and posterior positions. Depth data were also corrected to eliminate erroneous depth readings. Errors in depth readings can be generated by floating debris or insufficient signal gain of the fathometer. In these cases, the incorrect depth was interpolated between the correct anterior and posterior depth readings. The edited data were then transferred into the GIS, where data points were color coded according to different depth values. Then, data points having the same color were connected manually by drawing a line between the points, and a reservoir bathymetric contour map was generated (plate 1). The contour map of the reservoir was used to generate a TIN surface model of the reservoir. From the TIN surface model, selected cross sections (locations shown on figure 5) representing the reservoir bottom from shore to shore (fig. 6) and longitudinal profiles along the different branches of the reservoir (fig. 7) were generated. These cross sections and longitudinal profiles were compared with the 1995 data to show the extent and location of sediment accumulation.

The Arc/Info program was customized by creating an Arc-Macro Language (a series of sub-commands within a master command) to calculate the reservoir water volume at 1-meter datum increments, and capacity curves for 1995 and 2000 were generated (fig. 8). The reservoir surface model was divided into three distinct segments, and the volumes of those individual segments for 1995 and 2000 were calculated. The volumes comparison is discussed later in this report.

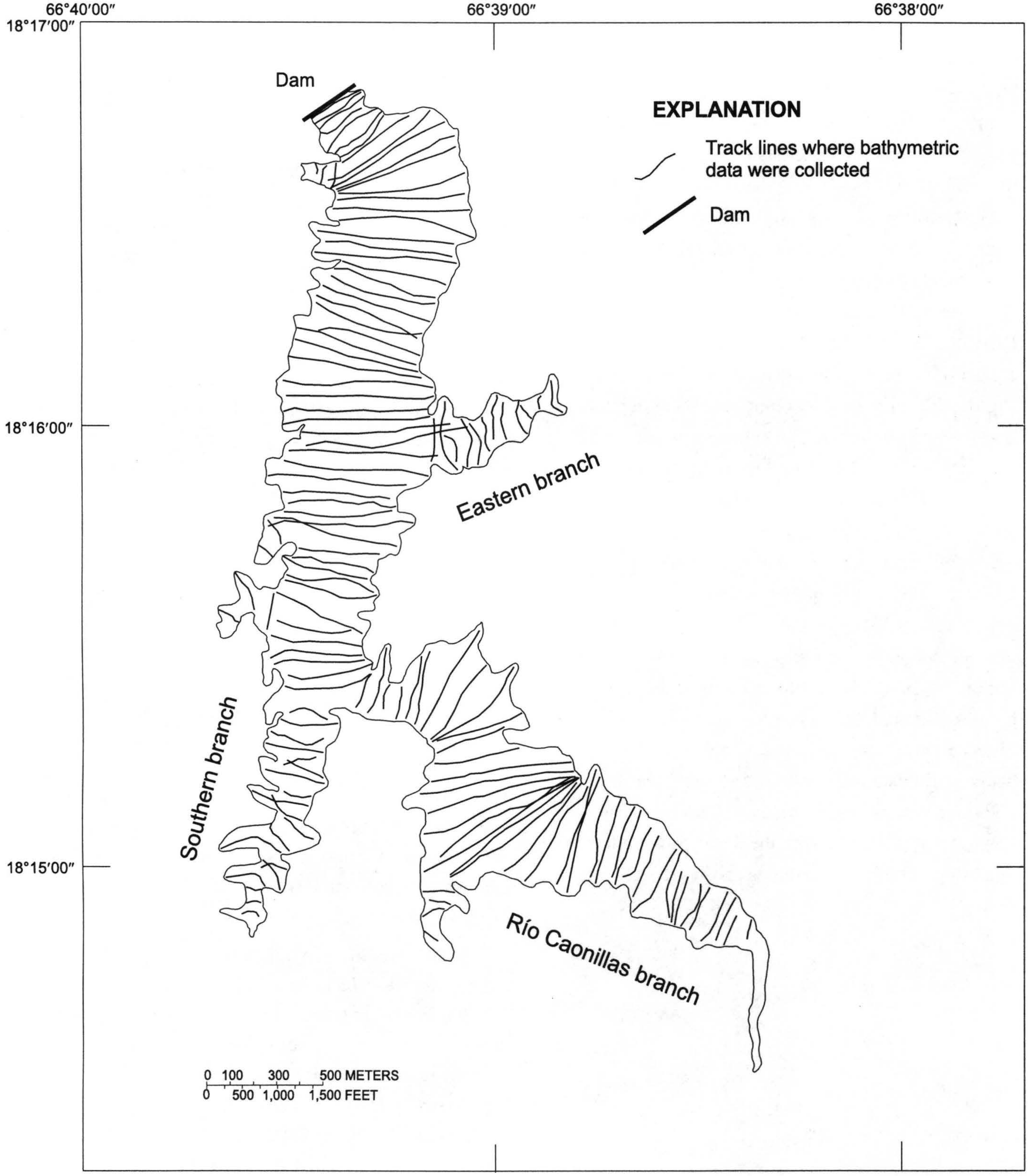

Figure 3. Actual track lines of the February 2000 bathymetric survey of Lago Caonillas, Puerto Rico.

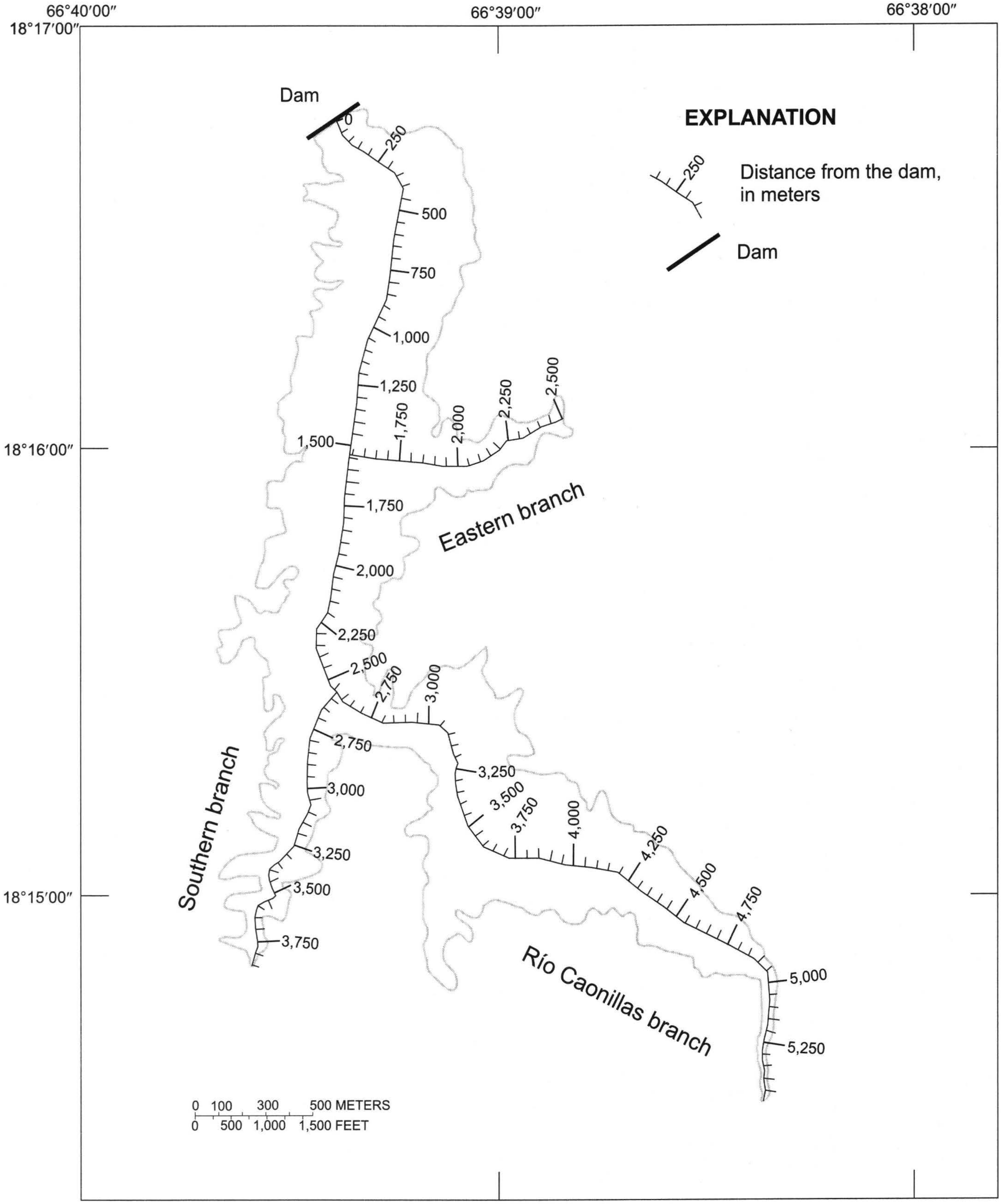

Figure 4. Reference longitudinal distances along the different branches of Lago Caonillas, Puerto Rico.

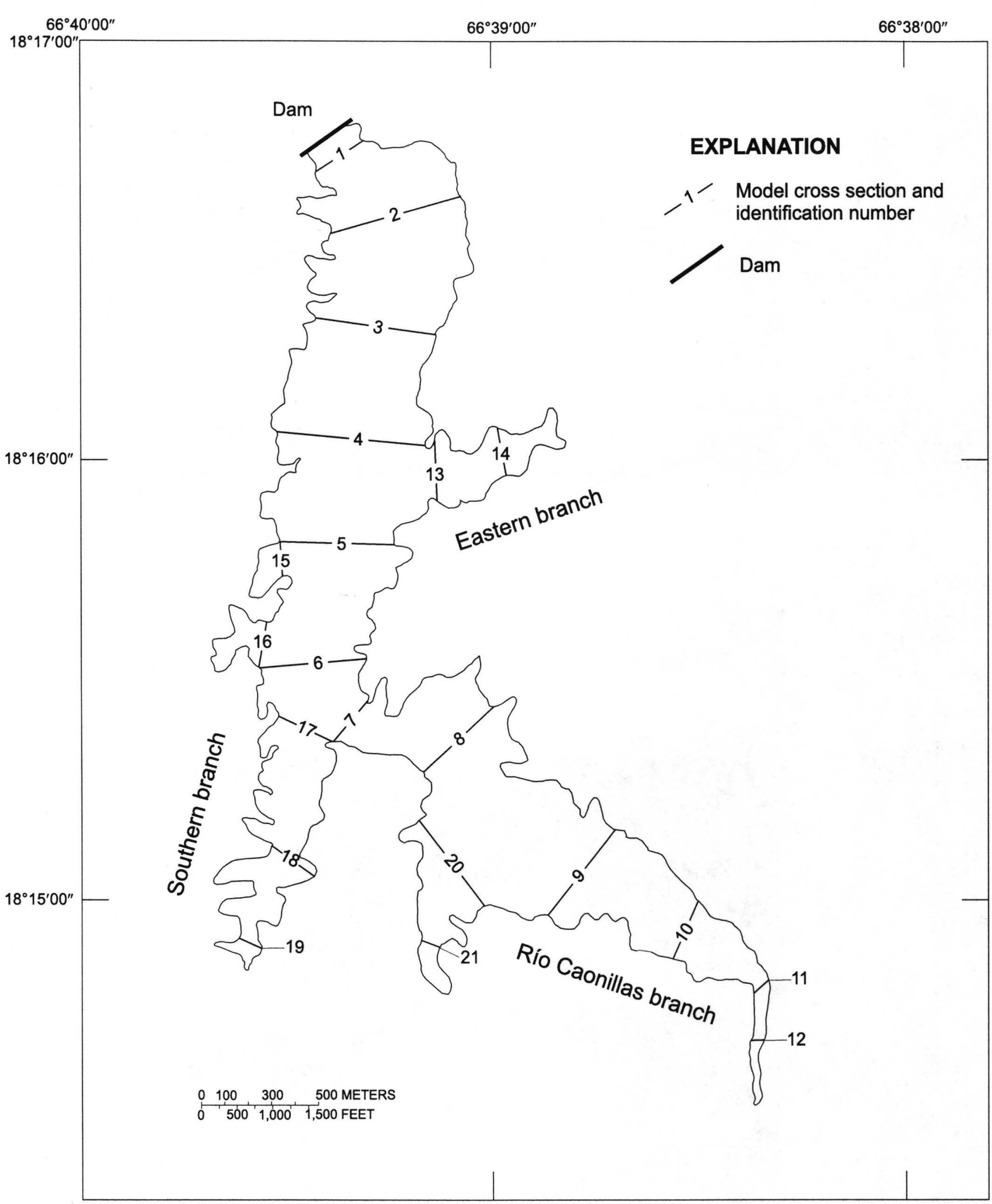

Figure 5. Selected cross-section locations for the February 2000 bathymetric survey of Lago Caonillas, Puerto Rico.

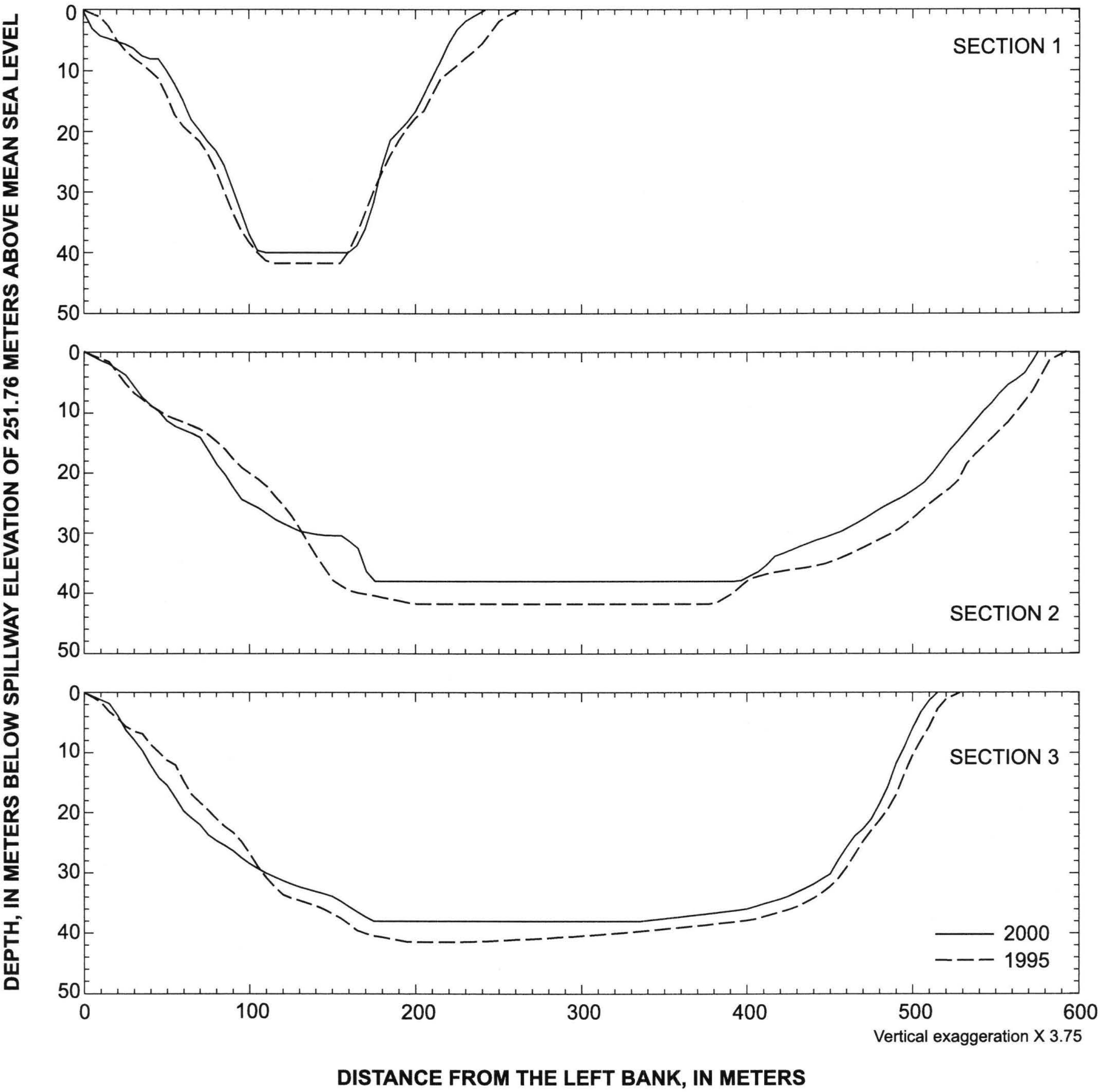

Figure 6. Selected cross sections generated from the TIN surface model of Lago Caonillas, Puerto Rico, for 1995 and 2000. Refer to figure 5 for cross-section locations.

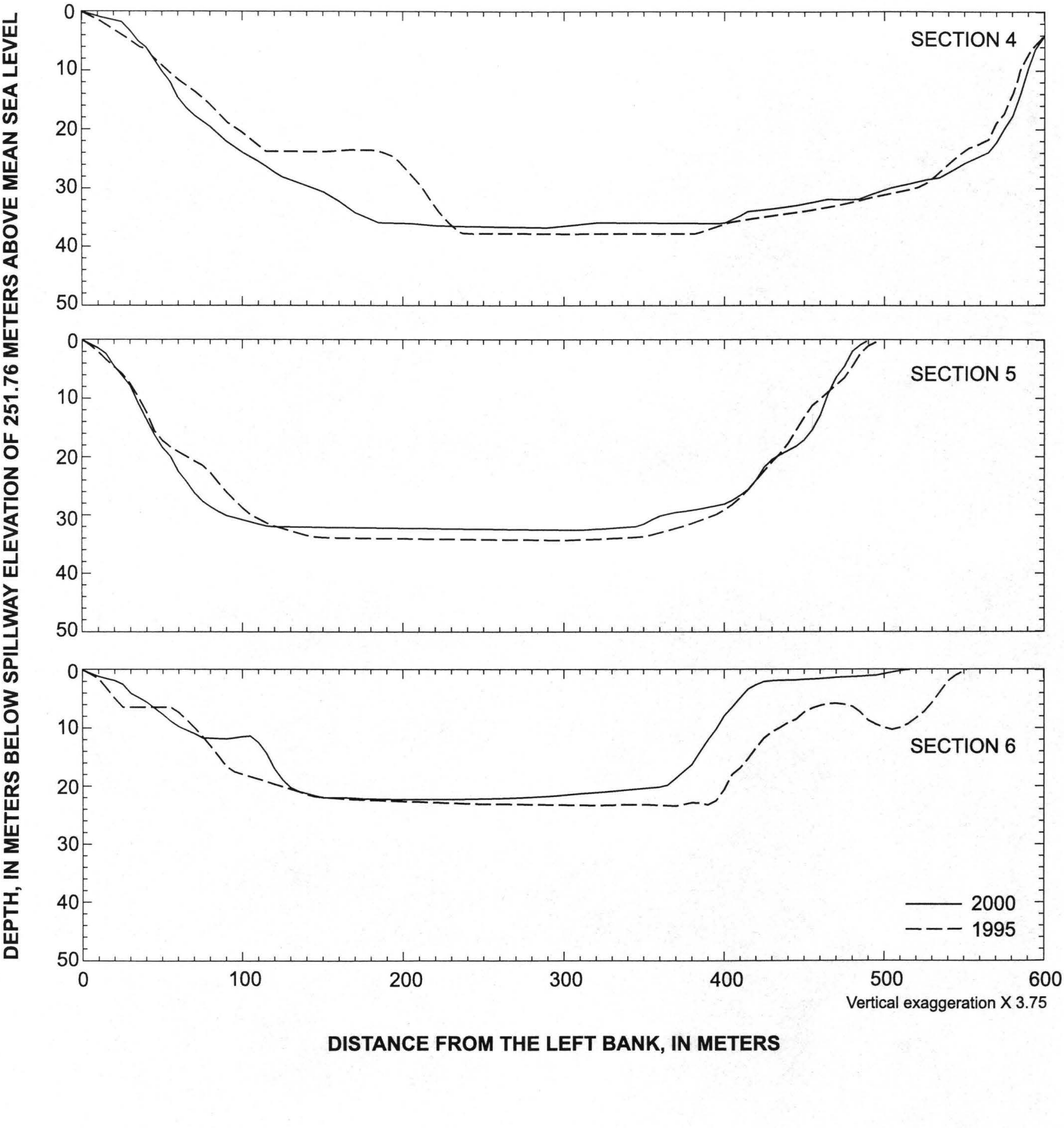

Figure 6. Selected cross sections generated from the TIN surface model of Lago Caonillas, Puerto Rico, for 1995 and 2000—Continued. Refer to figure 5 for cross-section locations.

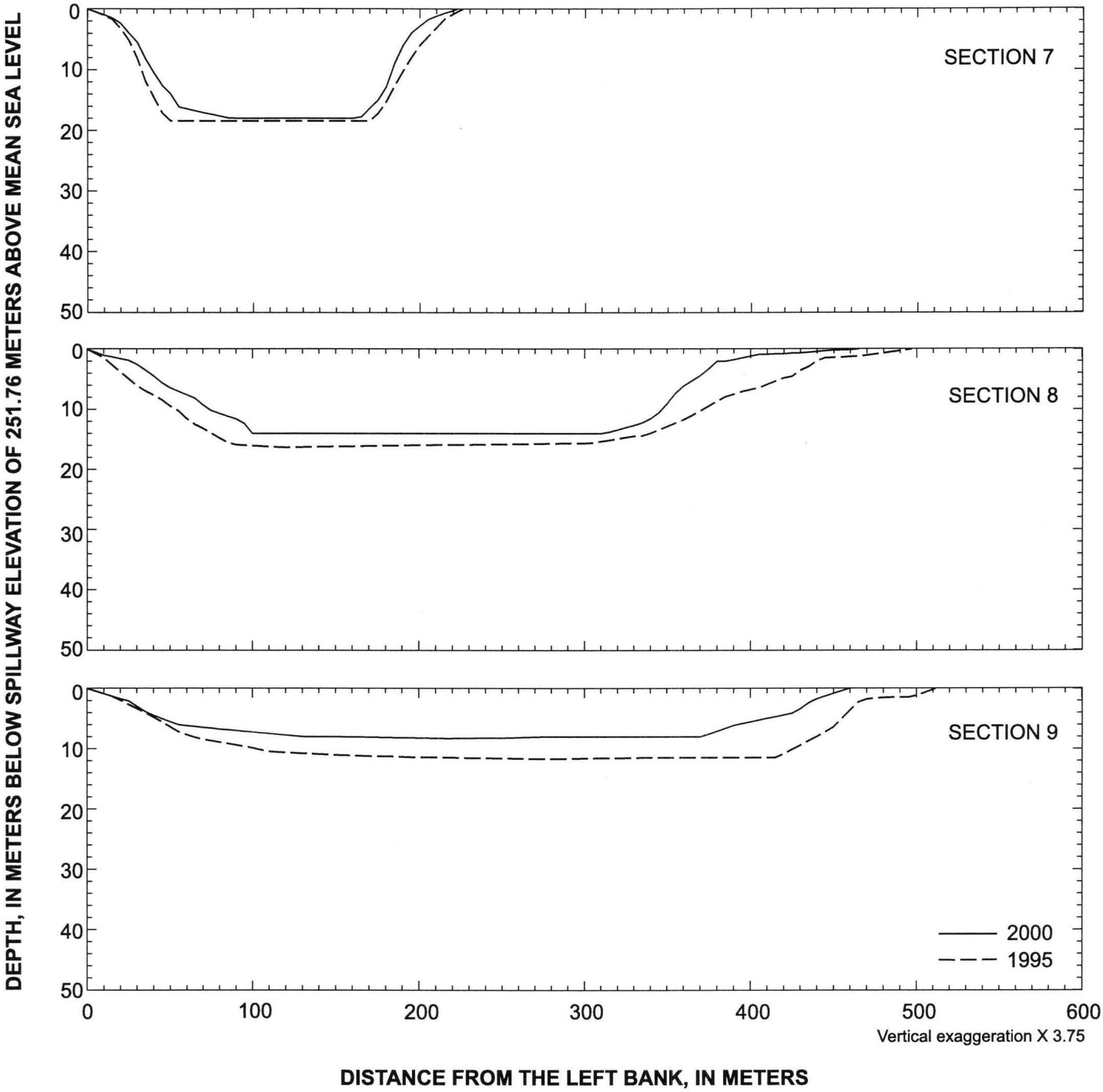

Figure 6. Selected cross sections generated from the TIN surface model of Lago Caonillas, Puerto Rico, for 1995 and 2000—Continued. Refer to figure 5 for cross-section locations.

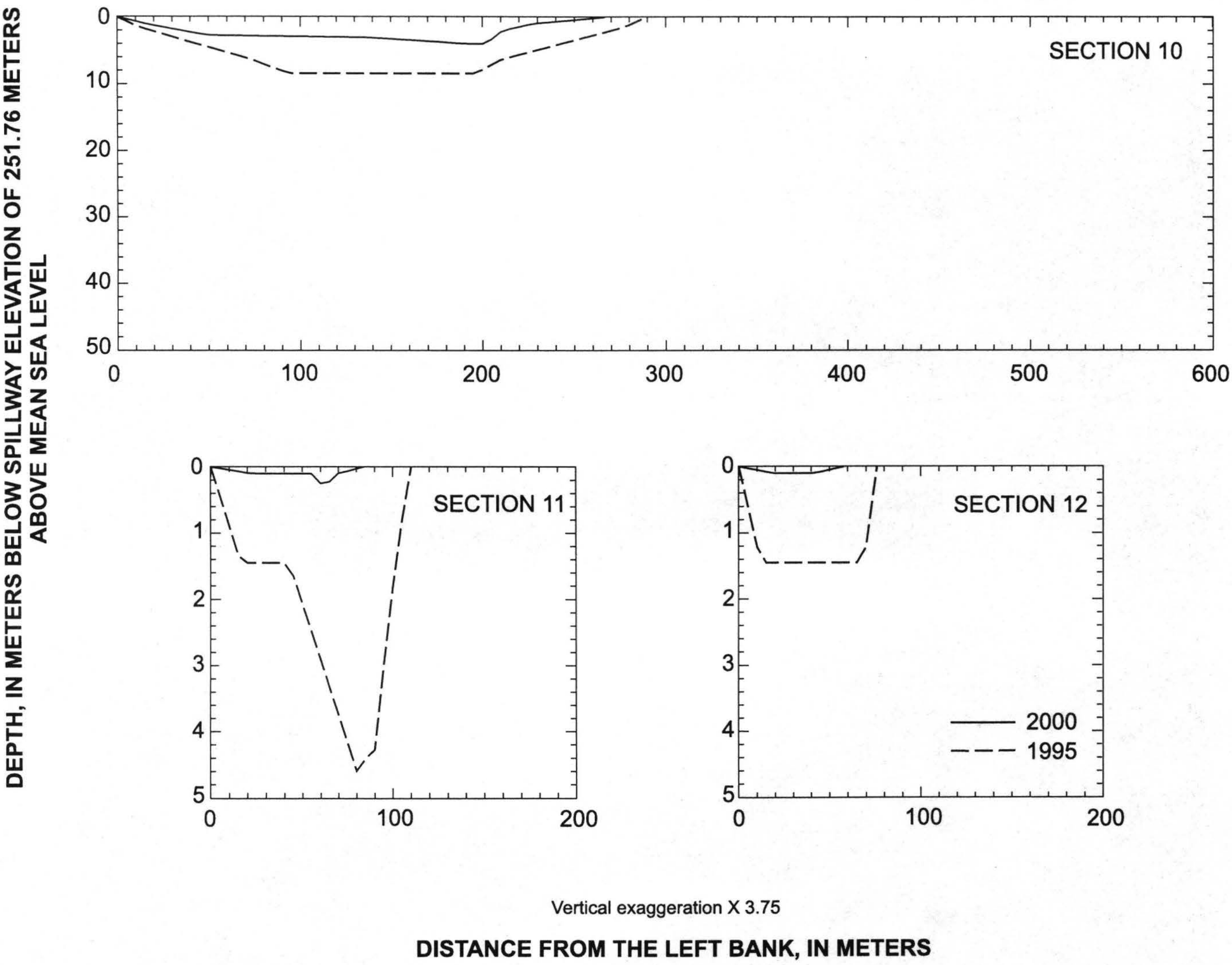

Figure 6. Selected cross sections generated from the TIN surface model of Lago Caonillas, Puerto Rico, for 1995 and 2000—Continued. Refer to figure 5 for cross-section locations.

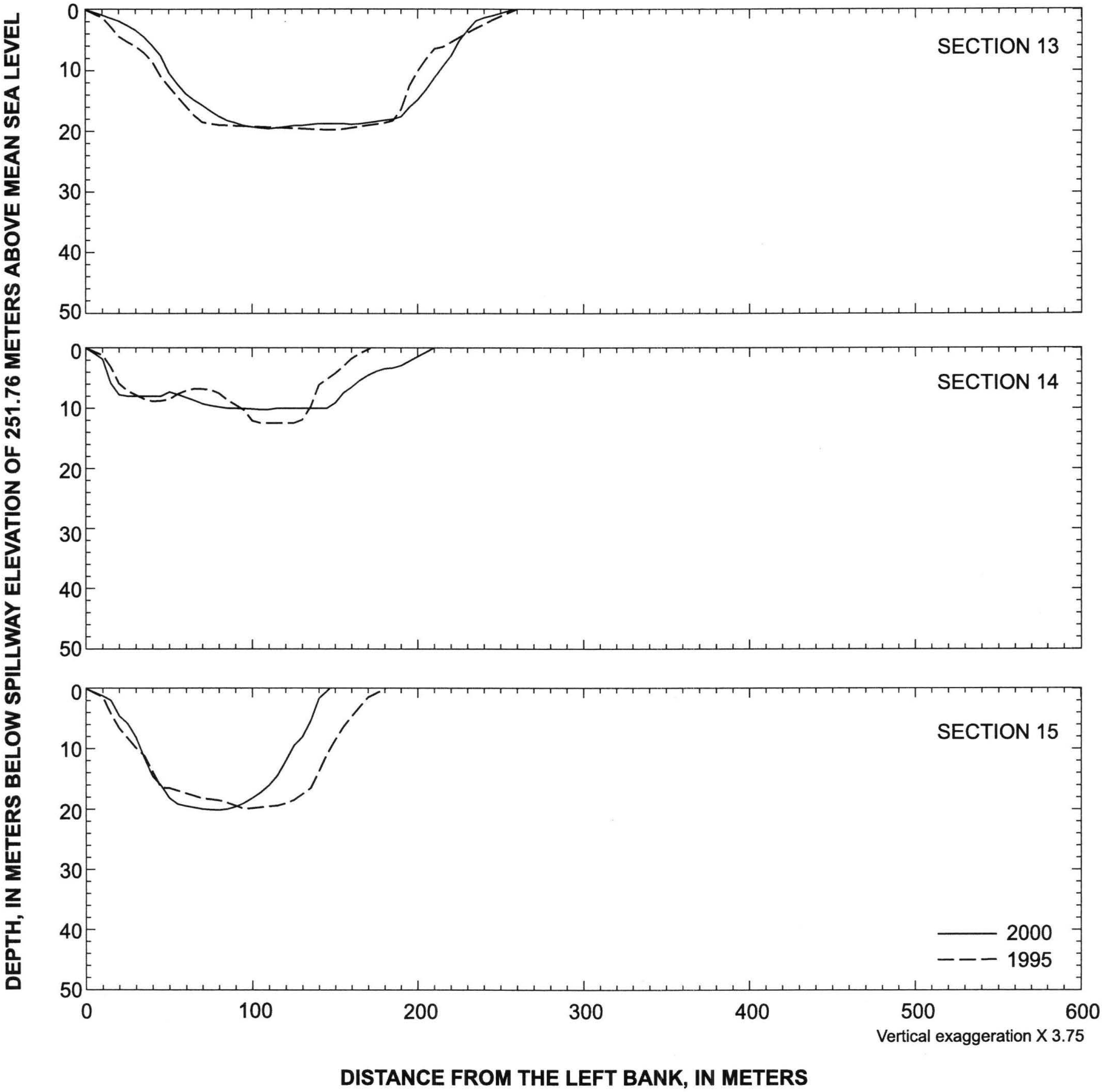

Figure 6. Selected cross sections generated from the TIN surface model of Lago Caonillas, Puerto Rico, for 1995 and 2000—Continued. Refer to figure 5 for cross-section locations.

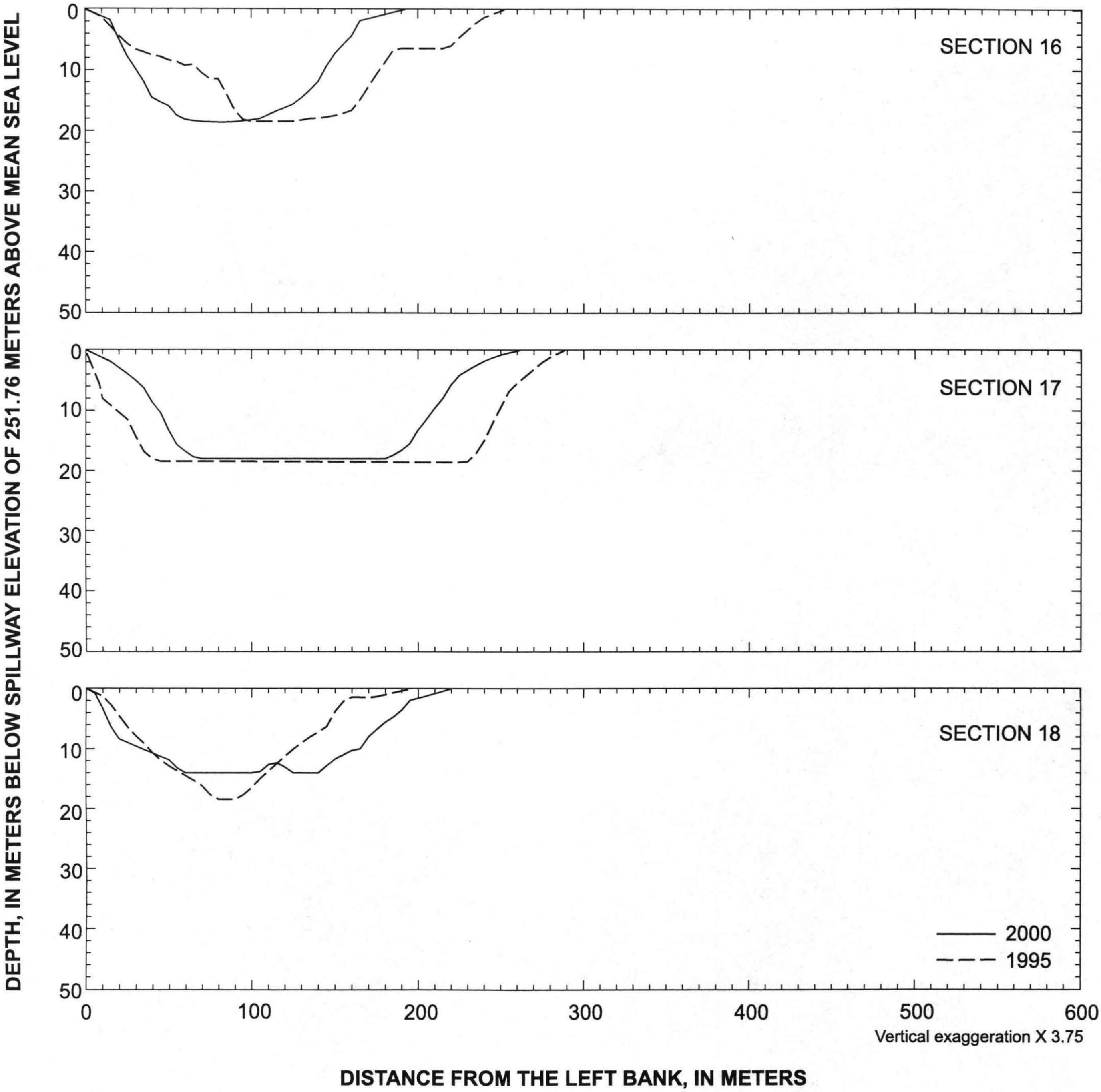

Figure 6. Selected cross sections generated from the TIN surface model of Lago Caonillas, Puerto Rico, for 1995 and 2000—Continued. Refer to figure 5 for cross-section locations.

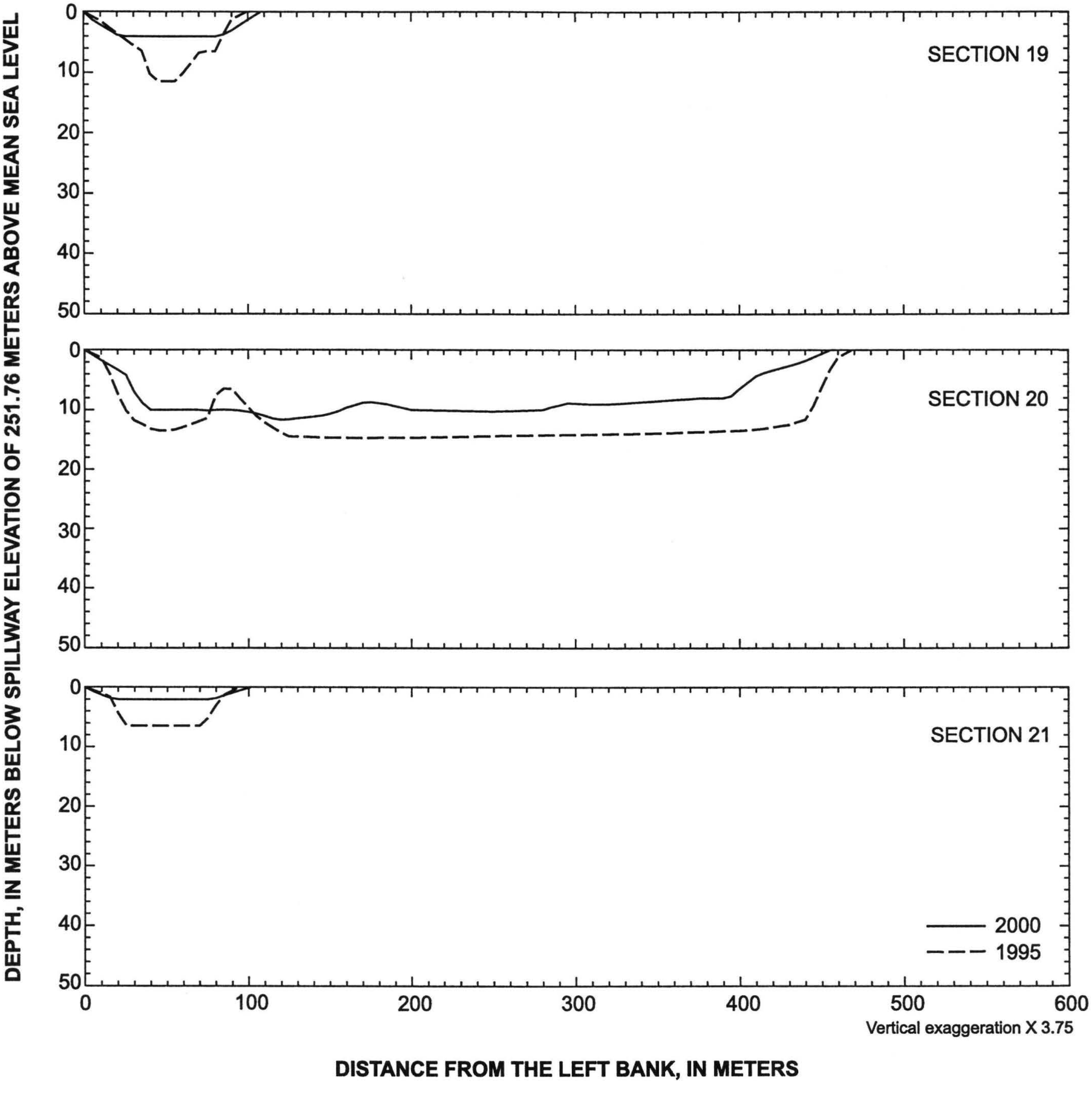

Figure 6. Selected cross sections generated from the TIN surface model of Lago Caonillas, Puerto Rico, for 1995 and 2000—Continued. Refer to figure 5 for cross-section locations.

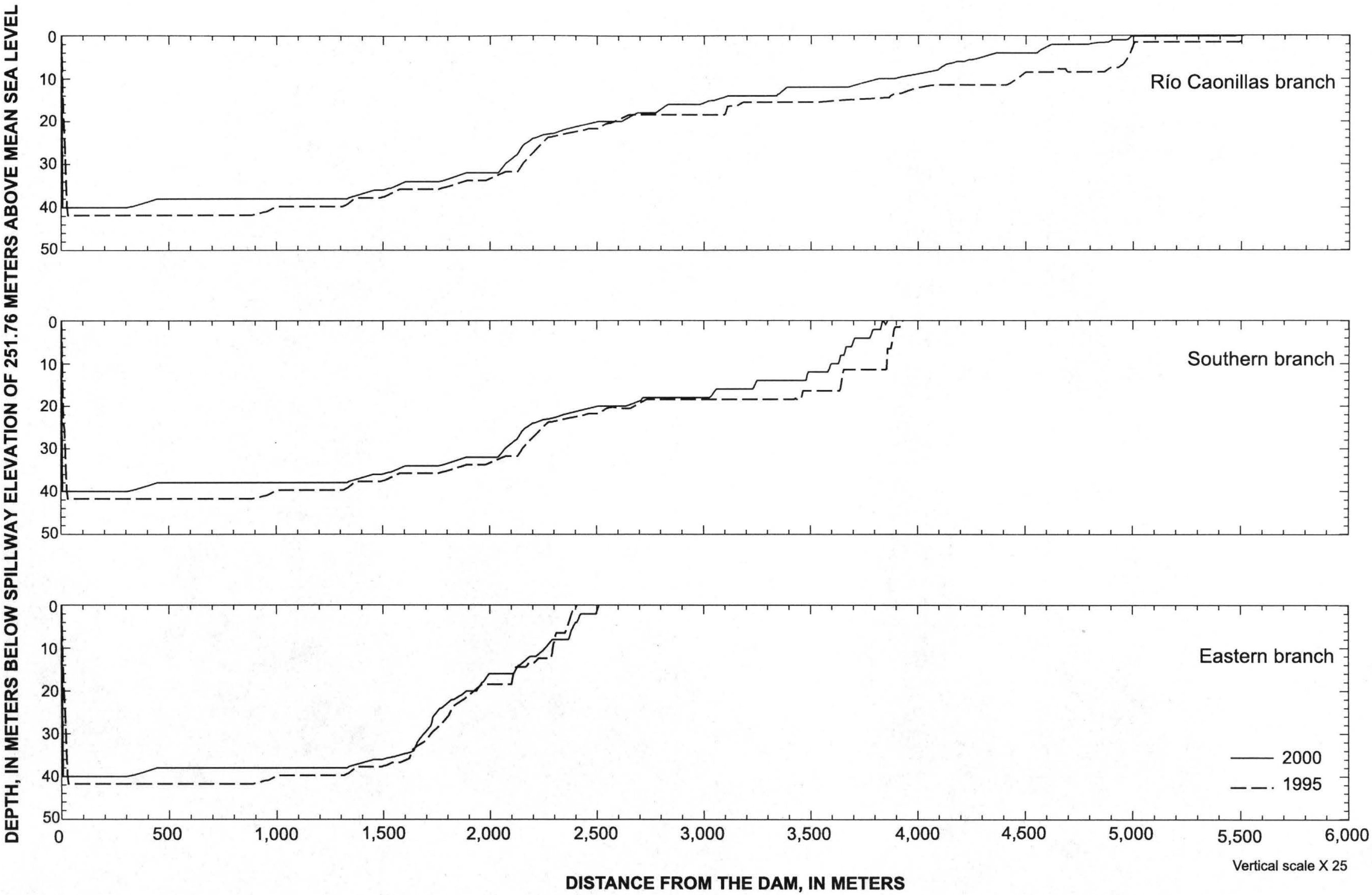

Figure 7. Longitudinal profiles along the thalweg of the different branches of Lago Caonillas, Puerto Rico, for 1995 and 2000.

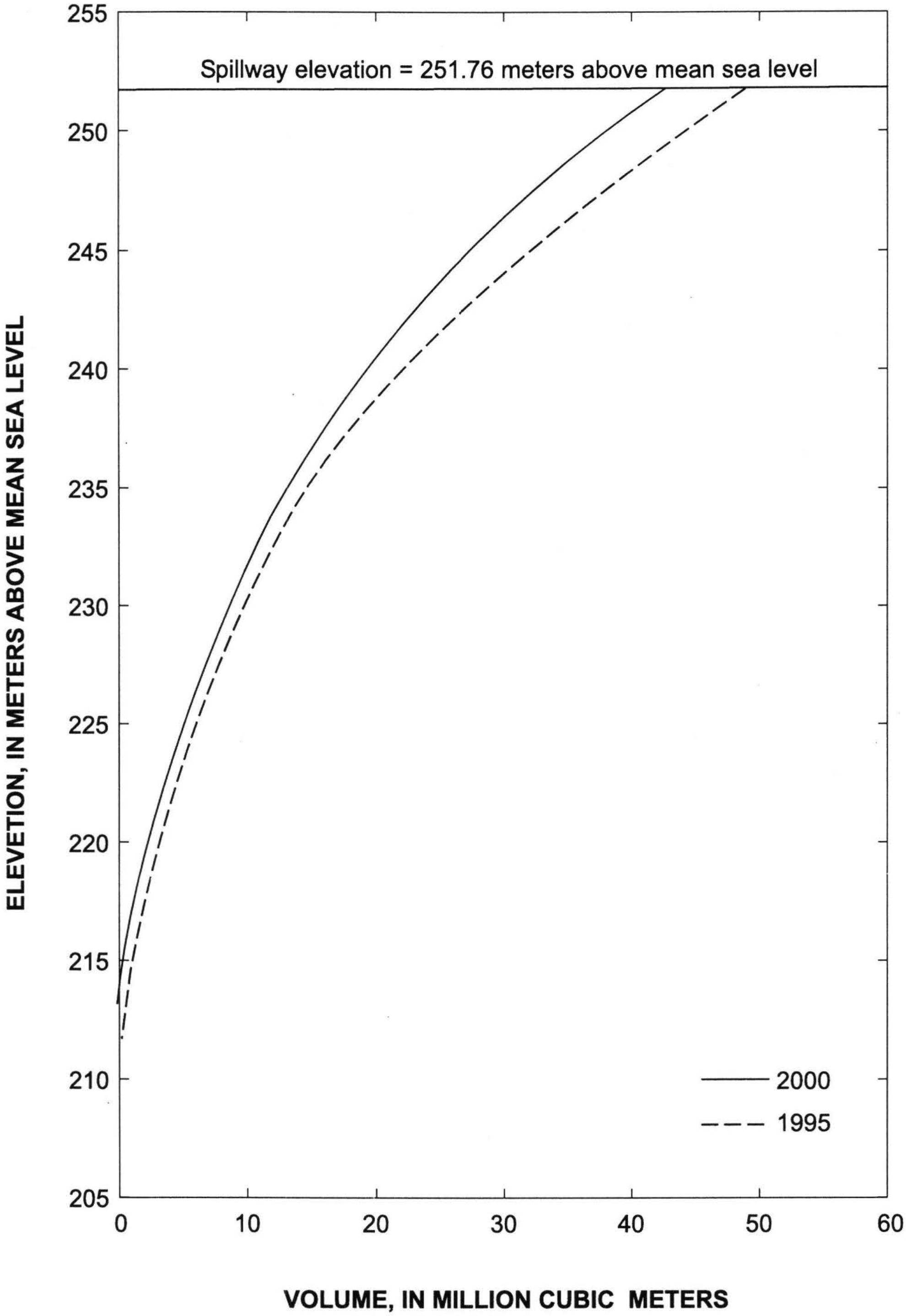

Figure 8. Storage capacity curves for Lago Caonillas, Puerto Rico, for 1995 and 2000.

STORAGE CAPACITY AND SEDIMENT ACCUMULATION

The bathymetric surveys and GIS analysis indicate that the storage capacity of Lago Caonillas has decreased considerably, about 12.6 percent over the last 10 years and 24.1 percent since construction. In 1990, the storage capacity was 49.25 million cubic meters, decreasing to 48.80 million cubic meters in 1995 and to 42.27 million cubic meters in 2000. The capacity loss of 0.45 million cubic meters from 1990 to 1995 was minimal. On the other hand, of the 13.39 million cubic meters of sediment that has accumulated since dam construction, 6.53 million cubic meters or 49 percent of the total accumulation occurred between 1995 and 2000. Probably most of this recent sediment accumulation between 1995 and 2000 actually occurred between 1996 and 1998. Table 2 shows the February 2000, storage capacity of Lago Caonillas at 1-meter stage intervals.

The accelerated loss of storage capacity in the last 5 years can be attributed primarily to two major storms: Hurricane Hortense in September 1996 and Hurricane Georges in September 1998. These storms brought intense rainfall, so that water and sediment discharge into Lago Caonillas was high. Peak discharges measured at the Río Caonillas at Paso Palmas, Puerto Rico, gaging station (number 50026025, fig. 1) were 626 and 1,020 cubic meters per second for Hurricanes Hortense and Georges, respectively. Both peak discharges are historical highs for the period of record at the station (from October 1995 to present day). Runoff entering the reservoir from the other tributaries was not measured. Historical peak suspended-sediment loads entering the reservoir, measured at station Río Caonillas at Paso Palmas were 449,000 tonnes on September 10, 1996, and 864,000 tonnes on September 22, 1998 (associated with Hurricanes Hortense and Georges, respectively; Díaz and others, 1998).

Table 2. Storage capacity of Lago Caonillas, Puerto Rico, for February 2000, at 1-meter elevation intervals

Elevation, in meters above mean sea level	Volume, in million cubic meters
251.76	42.27
250.76	39.67
249.76	37.25
248.76	35.02
247.76	32.87
246.76	30.83
245.76	28.87
244.76	27.00
243.76	25.19
242.76	23.48
241.76	21.84
240.76	20.32
239.76	18.88
238.76	17.55
237.76	16.28
236.76	15.10
235.76	13.97
234.76	12.90
233.76	11.87
232.76	10.91
231.76	9.98
230.76	9.12
229.76	8.30
228.76	7.52
227.76	6.78
226.76	6.08
225.76	5.41
224.76	4.77
223.76	4.15
222.76	3.55
221.76	2.98
220.76	2.45
219.76	1.94
218.76	1.51
217.76	1.12
216.76	0.80
215.76	0.51
214.76	0.27
213.76	0.07
212.76	0.02
211.76	0.00

Although several sedimentation surveys of the reservoir have been conducted in the past, for the purpose of this report (the impact of two major storms on the reservoir) only the results of the latest three bathymetric surveys are presented. Table 3 summarizes the results of the 1990, 1995, and 2000 sedimentation surveys of Lago Caonillas.

Sediment accumulation in the reservoir is not uniform. More than half of the sediment accumulation between 1995 and 2000 occurred along the Río Caonillas and southern branches of the reservoir. On the Río Caonillas branch, a total of about 3.23 million cubic meters accumulated since 1995, according to GIS calculations. The volume for the Río Caonillas branch was calculated for the portion of the reservoir upstream of selected cross section number 7. On the southern branch of Lago Caonillas, a total of about 0.44 million cubic meters have accumulated in the same period of time. The volume was calculated for the portion of the reservoir upstream of selected cross section number 17. The third segment consisted of the remaining portion of the reservoir downstream of selected cross sections 7 and 17.

The combined sediment accumulation in both upstream branches is 3.67 million cubic meters. This represents about 56 percent of the total sediment accumulation of 6.53 million cubic meters in the reservoir since 1995. The storage loss of the reservoir downstream of selected cross sections 7 and 17 is about 2.86 million cubic meters or 44 percent of the total loss.

Table 3. Comparison of the 1990, 1995 (Webb and Soler-López, 1996), and 2000 sedimentation surveys of Lago Caonillas, Puerto Rico

[---, no data available or undetermined]

	1990	1995	2000
Total capacity, in millions of cubic meters	[1]49.25	48.80	42.27
Live storage, in millions of cubic meters [2]	---	48.35	42.24
Dead storage, in millions of cubic meters [3]	---	0.45	0.03
Years since construction	42	47	52
Sediment accumulated, in millions of cubic meters	6.41	6.86	13.39
Storage loss, in percent	11.5	12.3	24.1
Annual loss of capacity, in percent	0.27	0.26	0.46
Intersurvey sedimentation rate, in cubic meters per year	---	90,000	1,306,000
Long-term sedimentation rate, in cubic meters per year	152,619	145,957	257,500
Year the reservoir is projected to fill	2313	2329	2164
Sediment yield, in megagrams per square kilometer per year [4]	750[5]	717[6]	1,266[7]

[1] From Webb and Soler-López (1996). Original capacity in 1948 was 55.66 millions of cubic meters.

[2] Above penstock crown elevation of 213.06 meters above mean sea level

[3] Below penstock crown elevation of 213.06 meters above mean sea level

[4] Assuming a dry bulk density of 1 gram per cubic centimeter and excluding the reservoir surface area of 2.70 square kilometers.

[5] Adjusted by the trapping efficiency of the reservoir for 1990.

[6] Adjusted by the trapping efficiency of the reservoir for 1995.

[7] Adjusted by the trapping efficiency of the reservoir for 2000.

On the Río Caonillas branch, a layer averaging about 3.5 meters in thickness has accumulated since 1995 (fig. 6, sections 8 to 12 and 20 to 21). On the southern branch an average of about 4 meters in thickness accumulated in the same period of time (fig. 6, sections 17 to 19). Some of the cross sections presented in figure 6 show what could be bank slumping and material depositional patterns near the reservoir shore or may be artifact differences in surveys resolution. The soils comprising the Lago Caonillas shoreline were subjected to extraordinary hydraulic and aerodynamic forces during the storms which could have eroded shoreline material. Lago Caonillas also is subjected to seasonal changes in pool elevation that exposes the banks to weathering. Scour and depositional features are apparent in some areas near the shoreline. During major flood events such as the ones generated by hurricanes, the reservoir may behave like a natural river channel with areas of very high water velocities and erosion along the outside of meanders and areas of low water velocities and deposition inside of meanders. Another explanation for this apparent scour and depositional pattern is that the 1995 survey was conducted at low pool elevation, and the data near the reservoir shoreline (from depths between 22 meters and 0 meter) were generated from aerial photographs taken by Caribbean Aerial Surveys Inc. in 1990. Depth data generated from aerial photography are not as reliable as bathymetric surveys, and some discrepancies are expected, but are considered to be relatively small compared to the volume of sediment influx between 1995 and 2000.

Sediment accumulation in the vicinity of the penstock structure at the dam has reached an elevation of 211.76 meters above mean sea level, according to the 2000 data. The crown elevation (the elevation of the upper part of the structure) is at 213.06 meters above mean sea level. This means that the reservoir bottom is about 1.3 meters from reaching the elevation of the penstock. In terms of dead storage (the volume below the elevation of the penstock structure, used to accommodate sediments without disabling the structure), the capacity was reduced from 0.45 million cubic meter in 1995 to 0.03 million cubic meter in 2000. In a future flood event, the penstock could become inoperable by the influx of sediment if the structure is not operated on a regular basis. The sluiceway structure (at an elevation of 202.69 meters above mean sea level) is currently buried under about 9 meters of sediment.

Lago Caonillas is currently an effective sediment trap, such that insignificant quantities of sediments pass from Lago Caonillas reservoir to Lago Dos Bocas reservoir (Soler-López and Webb, 1998). Additional moderate to severe flood events, however, will disable the penstock structure if it is not operated regularly. Most importantly, because dead storage has been reduced to almost zero, considerable amounts of sediments will begin to pass to Lago Dos Bocas through the power-generating structure, which could exacerbate the rapidly declining storage capacity of Lago Dos Bocas (Soler-López, 2000).

TRAPPING EFFICIENCY

Heinemann (1981) suggested that the single most informative descriptor of a reservoir is its trapping efficiency. This value is the proportion of the incoming sediment that is deposited, or trapped, in a pond, reservoir, or lake. Trapping efficiency is dependent on several parameters. They include the particle size distribution, which controls the trapping efficiency in relation to retention time (for example, the average time that the incoming runoff remains in the reservoir). Coarser material will have a higher settling velocity, and will require less time for deposition. Very fine material, on the other hand, requires more time to be deposited. The trapping efficiency is also determined by the characteristics of the inflow hydrograph in terms of high- and base-flow runoffs and frequencies. Small runoffs tend to have low rates of sediment influx, while large runoffs tend to have high rates of sediment influx. Also, the shape of the reservoir and outlet structures influence the retention time, and hence, the trapping efficiency (Verstraeten and Poesen, 2000).

Many empirical studies showing the relation between reservoir storage capacity, water inflow, and trapping efficiency have been conducted, of which Brune's (1953) is the most widely used and accepted. Brune developed a curve that estimates the trapping efficiency of a reservoir based on the relation of storage capacity to annual inflow (fig. 9). The trapping efficiency of Lago Caonillas was estimated using the relation established by Brune.

Although a stream gaging station measures the inflow to Lago Caonillas from the Río Caonillas (USGS station number 50026025), this station was installed in October 1995 and does not have sufficient period of record to estimate the long-term flow characteristics of the basin. Thus, the neighboring basin of Río Saliente was used to estimate the average annual runoff for the Lago Caonillas drainage area. The Río Saliente basin has somewhat similar topography, land use, and slopes, and the runoff/rainfall ratio is considered to be similar to the Lago Caonillas basin. The USGS surface-water station Río Saliente at Coabey near Jayuya, Puerto Rico (number 50025155) has an average annual runoff of 1.12 meters for a period from 1989 to 1998. (Díaz and others, 1998). The average annual rainfall for the Río Saliente basin is 2.29 meters (Calvesbert, 1970), thus the runoff/rainfall ratio equals 0.49. The Lago Caonillas drainage area has the same average annual rainfall of 2.29 meters (Calvesbert, 1970). Multiplying the average annual rainfall of 2.29 by the runoff/rainfall ratio of 0.49 gives the estimated runoff of 1.12 meters per year for the Lago Caonillas basin. Multiplying this value by the Lago Caonillas drainage area gives an estimated annual inflow value of 248.01 million cubic meters. Using the median curve of Brune (fig. 9) the estimated trapping efficiency of Lago Caonillas was about 94, 93, 93, and 93 percent during 1948, 1990, 1995, and 2000, respectively, giving an average long-term trapping efficiency of 93 percent for Lago Caonillas.

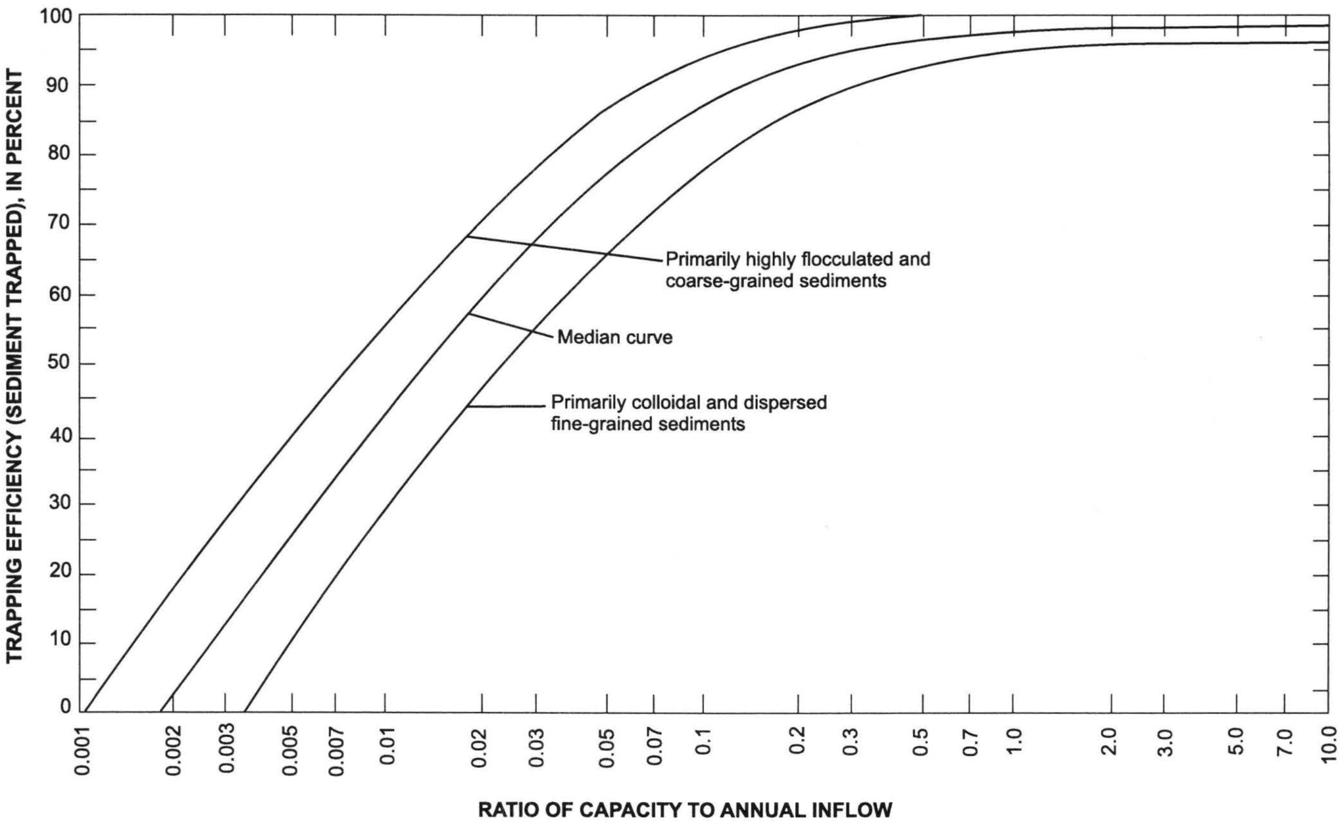

Figure 9. Storage capacity to inflow relation established by Brune (1953).

SEDIMENT YIELD

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 and for a specified period of time per unit of surface area (McManus and Duck, 1993). For Lago Caonillas, the total amount of sediment that has entered the reservoir (14.40 million cubic meters) was estimated by dividing the accumulated sediment (13.39 million cubic meters) by the long-term trapping efficiency (0.93). To determine the average annual rate of sediment influx, 14.40 million cubic meters was divided by the age of the reservoir (52 years), to give 276,923 cubic meters per year. The sediment yield of the Lago Caonillas drainage basin was calculated by dividing 276,923 cubic meters per year by 218.74 square kilometers (the drainage area minus the reservoir surface area) resulting in a yield of 1,266 cubic meters per square kilometer per year. Assuming a sediment dry-bulk density of one gram per cubic centimeter, the estimated sediment yield of the Lago Caonillas drainage area is about 1,266 megagrams per square kilometer per year for 2000.

Using the same calculations, the average annual sediment yield of Lago Caonillas was 750 megagrams per square kilometer per year in 1990, decreasing to 717 megagrams per square kilometer per year in 1995 and almost doubling to 1,266 megagrams per square kilometer per year in 2000. This represents a 69 percent increase in erosion rate within the Lago Caonillas basin since 1990. The true sediment yield of the basin, however, is likely higher than estimated because the calculations do not account for eroded material resulting from Hurricanes Hortense and Georges, as well as other rainfall events which is temporarily stored in river channels upstream from the reservoir. High flows such as those tend to flush downstream previously eroded material, but also deposit additional material in the river beds upstream of the reservoir. This temporarily stored material has the potential to reduce the storage capacity of the reservoir further when transported and deposited into the reservoir during future floods.

The life expectancy of Lago Caonillas did not seem to be a pressing concern according to the previous surveys of 1990 and 1995 (table 3); however, the 2000 survey indicates that large storm events such as Hurricanes Hortense and Georges can substantially reduce the life expectancy of the reservoir. These storm events induced erosion and transport of large volumes of material that is naturally weathered or made available by human activity. Although these flood events do not regularly occur, such events will likely affect Puerto Rico in the future. If the storm-accelerated sedimentation rate recorded between 1995 and 2000 continues, Lago Caonillas has a useful life of about 164 more years. However, the actual life expectancy of Lago Caonillas could be somewhat shorter or longer depending on the future rainfall frequencies and magnitudes.

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