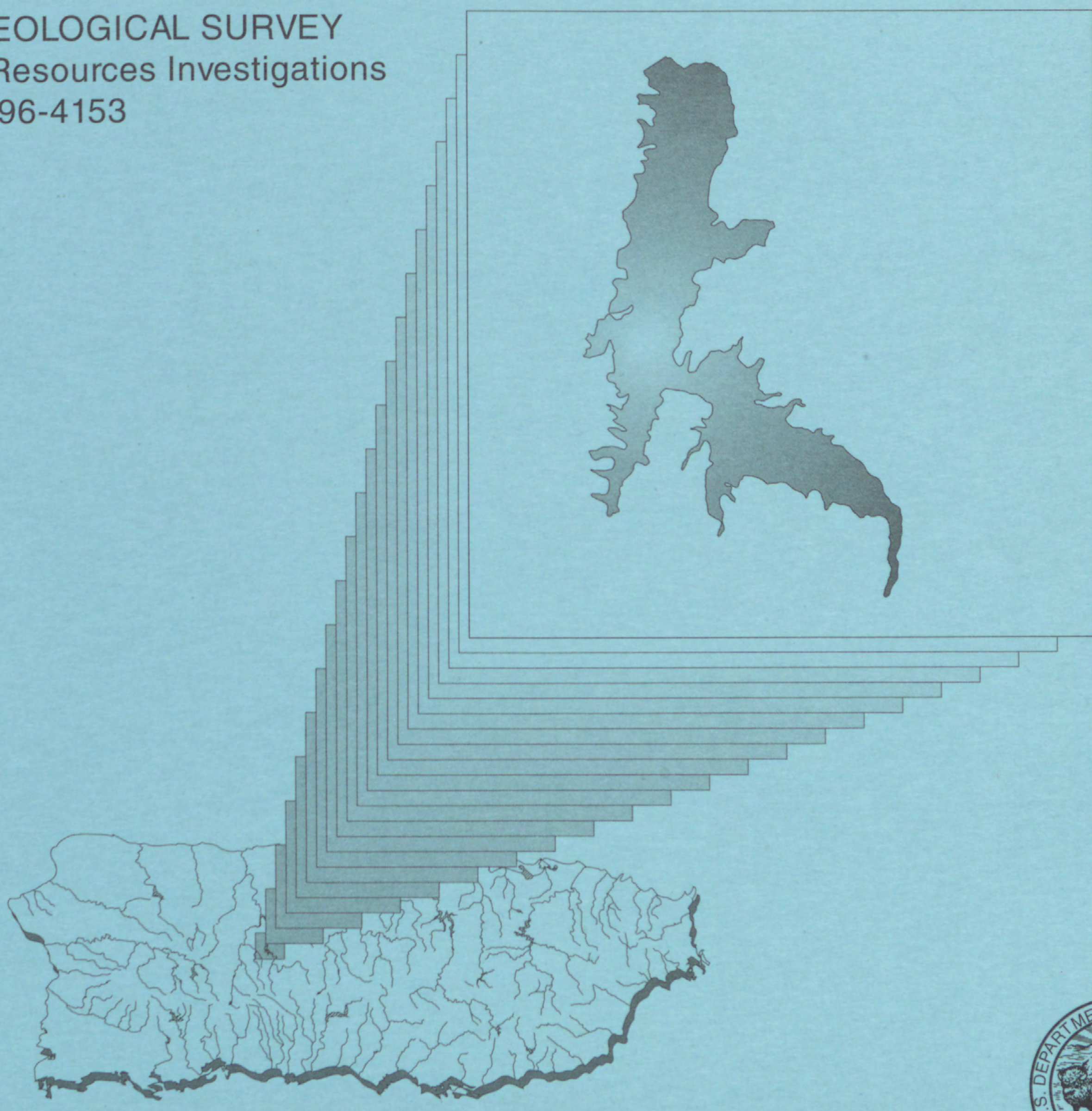
Sedimentation Survey of Lago Caonillas, Puerto Rico, February 1995

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations
Report 96-4153



Prepared in cooperation with the
PUERTO RICO AQUEDUCT AND SEWER AUTHORITY

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By Richard M.T. Webb and Luis R. Soler-López

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San Juan, Puerto Rico
1996

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Box 25286
Denver, CO 80225-0286

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PLATE

[Plate in pocket]

FIGURES

TABLES

CONVERSION FACTORS, ABBREVIATED WATER-QUALITY UNITS, AND ACRONYMS

Multiply	By	To obtain
	Length	
meter	3.2808	foot
kilometer	0.62137	mile
	Area	
square meter	10.7639	square foot
kilometer	0.62137	mile
square kilometer	0.3861	square mile
square kilometer	247.1054	acre
	Volume	
cubic meter	35.3146	cubic foot
millions of cubic meters	810.71309	acre-feet
cubic meter	0.0008107	acre-feet
	Volume per unit time (includes flow)	
cubic meter per second	35.3146	cubic feet per second
cubic meter per second	15850.326	gallon per minute
cubic meter per second	22.8258	million gallons per day
	Mass per area (includes sediment yield)	
megagrams per square kilometer	2.855	tons per square mile
megagrams per square kilometer	0.00446085	tons per acre

Datums used in report:

Horizontal Datum - Puerto Rico Datum, 1940 Adjustment

Vertical Datum - National Geodetic Vertical Datum 1929

Acronyms used in report:

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

Translations used in report:

Spanish	English
Lago	Lake
Quebrada	Creek
Río	River

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ABSTRACT

Sediment is filling Lago Caonillas, a reservoir built to be used for power generation, at an average rate of 0.26 percent per year. Over the last 47 years, the storage capacity of the reservoir has been reduced by approximately 12.4 percent from 55.7 million cubic meters in 1948 to 48.8 million cubic meters in 1995. The long-term average annual rate of storage loss to sediment deposition in the reservoir roughly doubled from 74,000 cubic meters per year to approximately 146,000 cubic meters per year when the sediment contributing area was increased 74.8 percent after the Caonillas Extension Project was completed in 1952. Based on the current contributing area of 221.44 square kilometers, the average sediment yield of the basin is estimated to be 659 megagrams per square kilometer per year. The true sediment yield in the basin may be somewhat greater as runoff from intense rainfall events may spill over the small (storage capacity of less than 1 million cubic meters) check- dams that divert water from the Río Grande de Arecibo Basin to Lago Caonillas.

INTRODUCTION

Drought conditions in 1993 and 1994 resulted in extensive water rationing in the San Juan metropolitan area. To mitigate future water shortages, the Puerto Rico Aqueduct and Sewer Authority (PRASA) began evaluating the possibility of building an aqueduct from Lago Dos Bocas, a hydroelectric project completed in 1942, to the San Juan metropolitan area. A second major hydroelectric facility, Lago Caonillas, was completed upstream of Lago Dos Bocas in 1948.

The U.S. Geological Survey conducted a study to determine the current storage capacity of Lago Caonillas, determine the storage loss due to sedimentation, and locate the areas of greatest sediment deposition within the reservoir. These data will be useful in evaluating the feasibility of tapping the Río Grande de Arecibo Basin as a public water supply. To accomplish the objectives, a bathymetric survey of Lago Caonillas was conducted in February 1995. Data of position and water depths were simultaneously acquired with a Differential Global Positioning System (DGPS) and a depth sounder and then directly stored in digital form. The digitized data were transferred into a Geographic Information System (GIS) where storage volumes and sediment accumulation rates were calculated.

The pool level during the bathymetric survey was at 234.22 meters, approximately 17.5 meters below the spillway elevation of 251.76 meters above mean sea level (amsl). To estimate the total reservoir volume, the 1995 bathymetric data were combined with a 1:4,000 scale topographic map produced using standard photogrammetric techniques and 1:20,000 scale aerial photographs taken in May 1990. The topographic map was produced by Caribbean Aerial Surveys[1] for a flood risk assessment by the Puerto Rico Electric and Power Authority (Luis Suárez, PREPA Engineer, personal commun., 1995). For the remainder of this report, the contour map developed by combining the 1995 bathymetry with the 1990 topography will be referred to as the 1990-95 bathymetry. The GIS was then used to calculate storage volumes and sediment accumulation by comparing the 1990-95 bathymetry with a 1:6,000 scale topographic map produced by the Soil Conservation Service (SCS) from aerial photographs taken in 1941(Noll, 1953), 7 years before the reservoir was completed.

DAM AND RESERVOIR CHARACTERISTICS

On June 28, 1948, the sluice gates of the Lago Caonillas dam were closed and the reservoir began to fill (Noll, 1953). The dam is located approximately 7 kilometers east of the town of Utuado (fig. 1) and was built for hydroelectric power production. The Lago Caonillas dam is among the largest in Puerto Rico with a total length of 248.4 meters and a maximum height of 76 meters above the stream bed at the time of construction. The large initial reservoir storage capacity of 55.66 million cubic meters (without flashboards) in relation to its drainage area of only 126.65 square kilometers indicates that Lago Caonillas will not completely fill with sediments for at least several hundred years. The spillway crest elevation of 251.76 meters amsl was originally increased to 252.98 meters by installing flashboards. The flashboards, which have since been removed, increased the reservoir storage by 3.3 million cubic meters. When built, the reservoir had a storage capacity of 61.86 million cubic meters at an elevation of 252.98 meters amsl (maximum pool level with flashboards) according to Noll (1953). However, a recomputation of the original reservoir storage capacity using a computer model of the 1941 topography generated during this study yielded a value of 58.95 million cubic meters at the same elevation of 252.98 meters amsl (55.66 million cubic meters at the spillway elevation of 251.76 meters amsl - without flashboards); the recomputed 1941 capacity will be used in this report and reported as the initial volume for the reservoir in 1948. The principal characteristics of Lago Caonillas reservoir and dam are listed in table 1.

METHOD OF SURVEY

The survey of Lago Caonillas involved planning, data acquisition, and data processing. A geographic information system, Arc/Info, was used to plan the cross-section locations and for analysis of the bathymetric data. Cross-section locations were established at a spacing of 50 meters (fig. 2). Data were acquired with a Differential Global Positioning System (DGPS) combined with a depth sounder. The soundings were subsequently adjusted to represent depths below the spillway elevation (datum 251.76 meters amsl). The corrected depths were then converted to elevations above mean sea level (National Geodetic Vertical Datum of 1929 - NGVD 29). A bathymetric map of the surveyed

[1]Use of trade names in this report is for identification purposes only and does not imply endorsement by the U.S. Government.

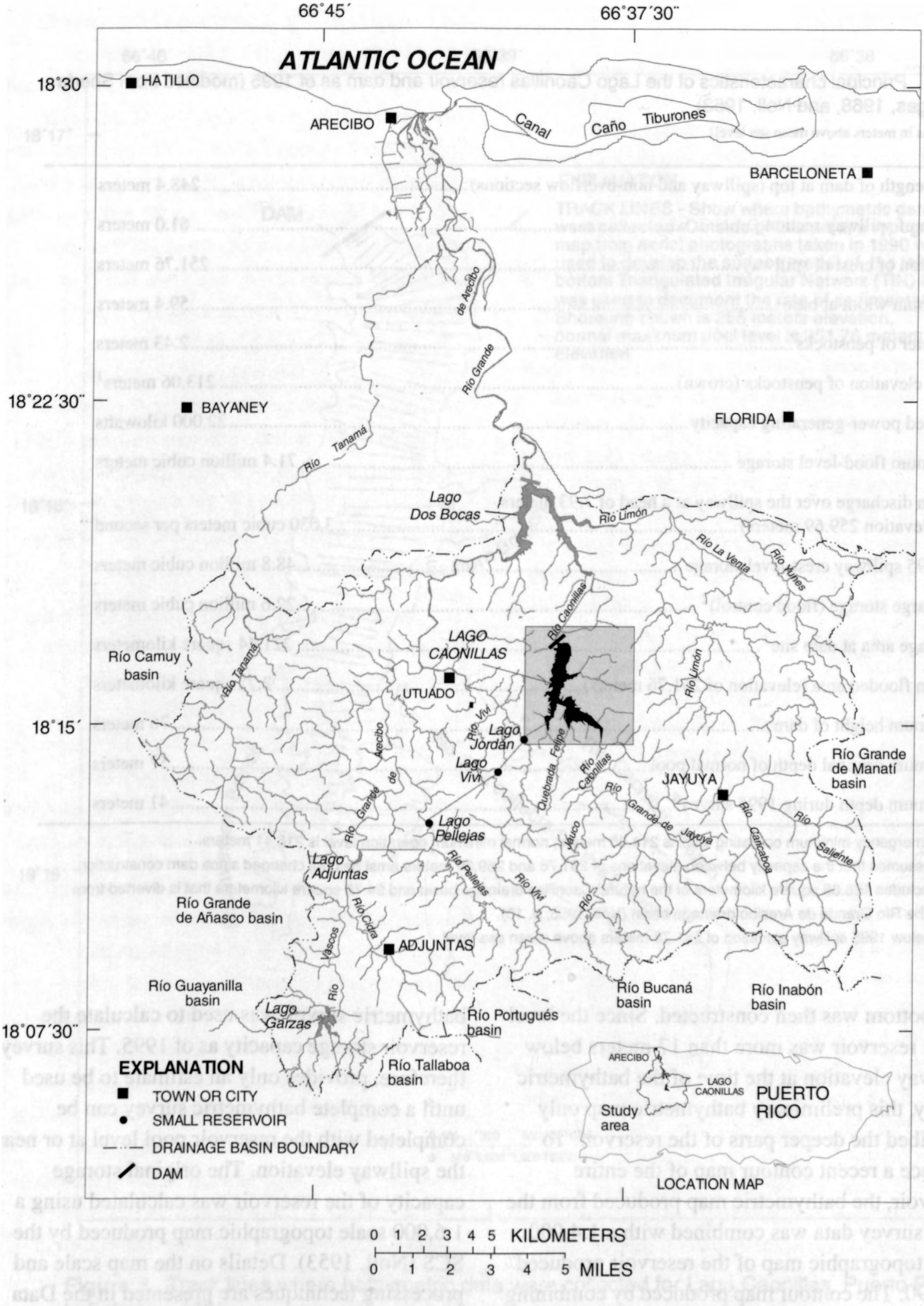

Figure 1. Location of Lago Caonillas in the Río Grande de Arecibo Basin, Puerto Rico.

Table 1. Principal characteristics of the Lago Caonillas reservoir and dam as of 1995 (modified from Sheda and Legas, 1968, and Noll, 1953)

[Elevations in meters above mean sea level]

Total length of dam at top (spillway and non-overflow sections)	248.4 meters
Length of spillway section	61.0 meters
Elevation of crest of spillway	251.76 meters
Maximum width at base	59.4 meters
Diameter of penstocks	2.43 meters
Invert elevation of penstocks (crown)	213.06 meters[1]
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
1990-95 spillway crest-level storage	48.8 million cubic meters
Surcharge storage (flood control)[2]	22.6 million cubic meters
Drainage area at dam site[3]	221.44 square kilometers
Design flooded area (elevation of 251.76 meters)	2.72 square kilometers
Maximum height of dam	76 meters
Maximum original depth of normal pool	57 meters
Maximum depth during 1995 survey[4]	41 meters

[1] Emergency minimum operating level is 214.88 meters; normal minimum operation level is 216.41 meters.

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

[3] 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).

[4] Below 1995 spillway elevation of 251.76 meters above mean sea level.

lake bottom was then constructed. Since the level of the reservoir was more than 17 meters below spillway elevation at the time of the bathymetric survey, this preliminary bathymetric map only described the deeper parts of the reservoir. To produce a recent contour map of the entire reservoir, the bathymetric map produced from the 1995 survey data was combined with a 1:4,000 scale topographic map of the reservoir produced in 1990. The contour map produced by combining the 1990 topographic survey with the 1995 bathymetric survey was used to calculate the reservoir storage capacity as of 1995. This survey, therefore, provides only an estimate to be used until a complete bathymetric survey can be completed with the reservoir pool level at or near the spillway elevation. The original storage capacity of the reservoir was calculated using a 1:6,000 scale topographic map produced by the SCS (Noll, 1953). Details on the map scale and processing techniques are presented in the Data Processing section of this report.

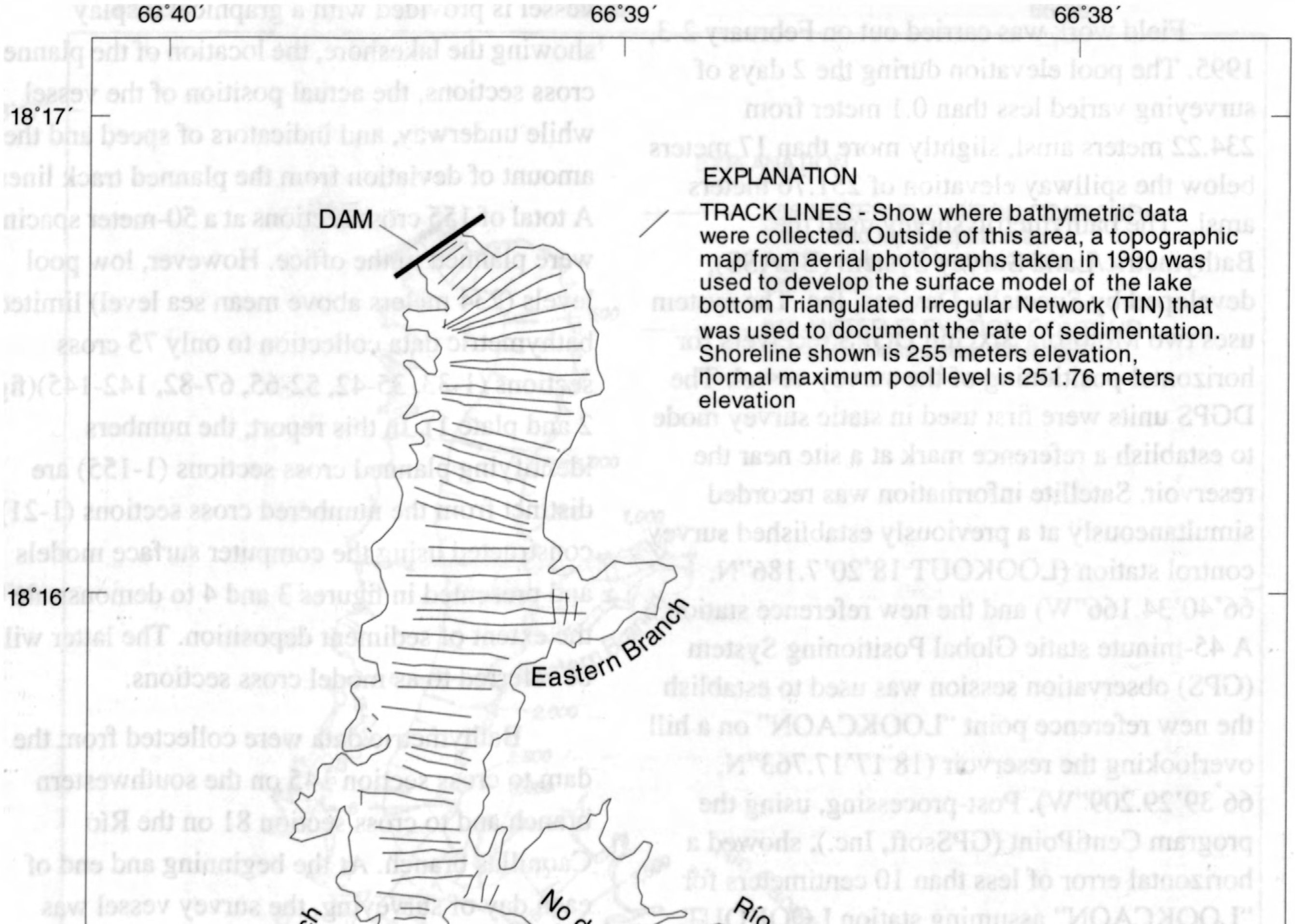

Figure 2. Track lines where bathymetric data were collected for Lago Caonillas, Puerto Rico, in February 1995.

Field Techniques

Field work was carried out on February 2-3, 1995. The pool elevation during the 2 days of surveying varied less than 0.1 meter from 234.22 meters amsl, slightly more than 17 meters below the spillway elevation of 251.76 meters amsl. The bathymetric survey used the Bathymetric/Land Survey System (BLASS), developed by Specialty Devices, Inc. The system uses two Motorola SixGun DGPS receivers for horizontal positioning of the survey vessel. The DGPS units were first used in static survey mode to establish a reference mark at a site near the reservoir. Satellite information was recorded simultaneously at a previously established survey control station (LOOKOUT 18°20'7.186"N, 66°40'34.166"W) and the new reference station. A 45-minute static Global Positioning System (GPS) observation session was used to establish the new reference point "LOOKCAON" on a hill overlooking the reservoir (18°17'17.763"N, 66°39'29.209"W). Post-processing, using the program CentiPoint (GPSsoft, Inc.), showed a horizontal error of less than 10 centimeters for "LOOKCAON" assuming station LOOKOUT had no horizontal error.

Once established, "LOOKCAON" was occupied as the master station and the other DGPS was installed in the survey vessel. The DGPS on board the survey vessel independently calculated a position every second. Once every 5 seconds the vessel's DGPS received a set of pseudo-range corrections to maintain positional precision to within 2 meters. Lake depths were measured using a SI-TEX LCS-200 echo sounder with a 200 kHz transducer with a 9-degree beam width. The echo sounder reports depths to the nearest 0.1 meter and was calibrated in water depths of 3 and 25 meters. The bathymetric survey software HYPACK (Coastal survey mode (equivalent to one point every 1.5 meters along the track line). HYPACK runs on a portable personal computer and is used both to record data and to navigate. The helmsman of the survey vessel is provided with a graphical display showing the lakeshore, the location of the planned cross sections, the actual position of the vessel while underway, and indicators of speed and the amount of deviation from the planned track lines. A total of 155 cross sections at a 50-meter spacing were planned in the office. However, low pool levels (234 meters above mean sea level) limited bathymetric data collection to only 75 cross sections (1-33, 35-42, 52-65, 67-82, 142-145)(fig. 2 and plate 1). In this report, the numbers identifying planned cross sections (1-155) are distinct from the numbered cross sections (1-21) constructed using the computer surface models and presented in figures 3 and 4 to demonstrate the extent of sediment deposition. The latter will be referred to as model cross sections.

Bathymetric data were collected from the dam to cross section 145 on the southwestern branch and to cross section 81 on the Río Caonillas branch. At the beginning and end of each day of surveying, the survey vessel was secured to an assigned point on shore and positions recorded for at least 30 seconds to verify the precision of the DGPS-calculated positions.

Random errors can appear in positional data because of GPS calculation errors; errors in depth data can occur because of bubbles on the transducer face or insufficient signal gain. Physical or electronic problems encountered in the field were corrected as soon as they were detected. If the section of missing or bad data extended more than 20 meters, that cross section was rerun. If the amount of erroneous data occurred for less than 20 meters along the cross section, and the bottom was flat or exhibited no change in slope before and after the section in which data were lost, the section was not rerun but the data file was flagged for later editing.

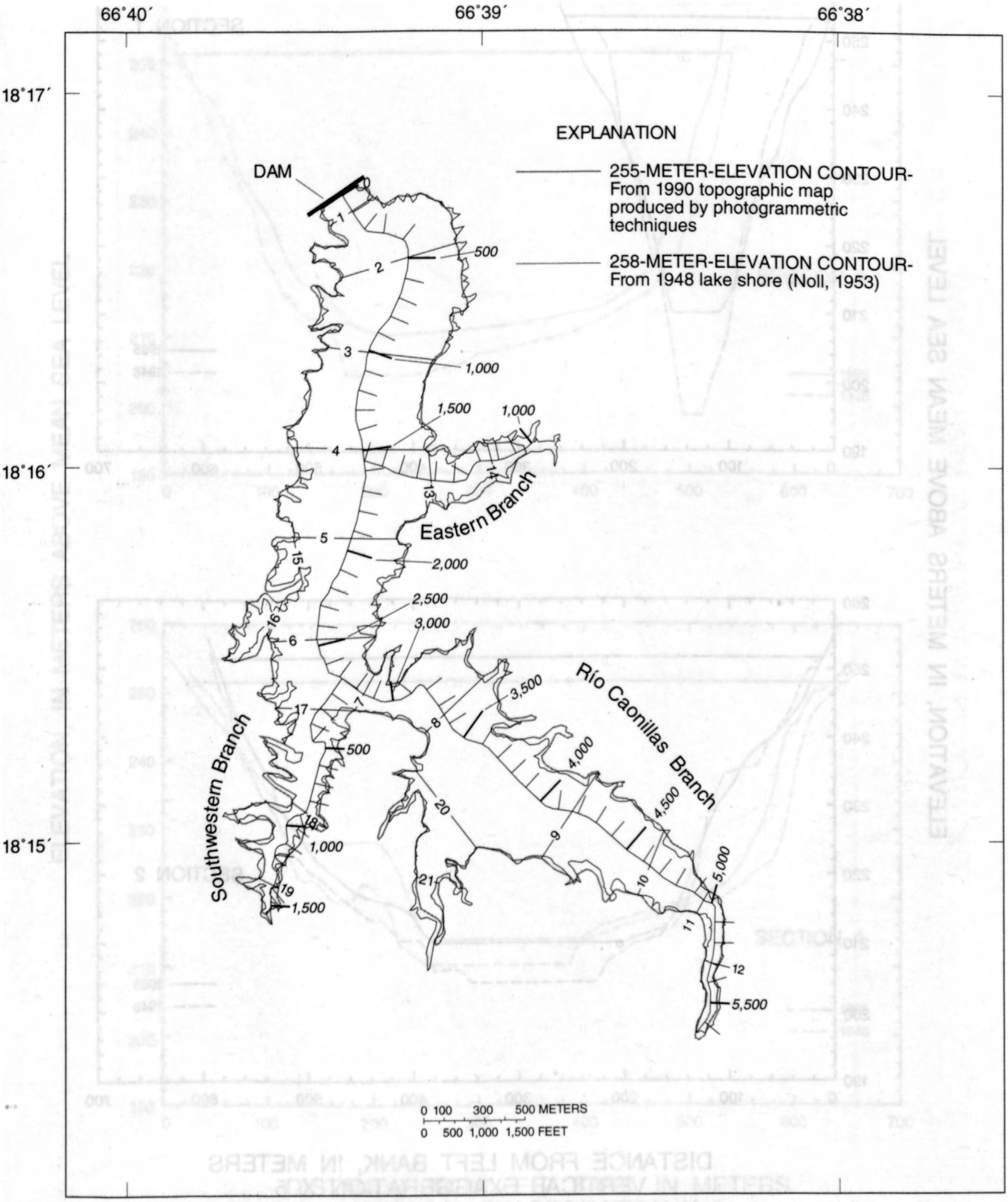

Figure 3. Lago Caonillas showing 1990 shoreline at 255 meters elevation, 1948 shoreline at 258 meters elevation, locations of model cross sections across triangular irregular network surface, and the paths and distances of longitudinal sections. Datum mean sea level.

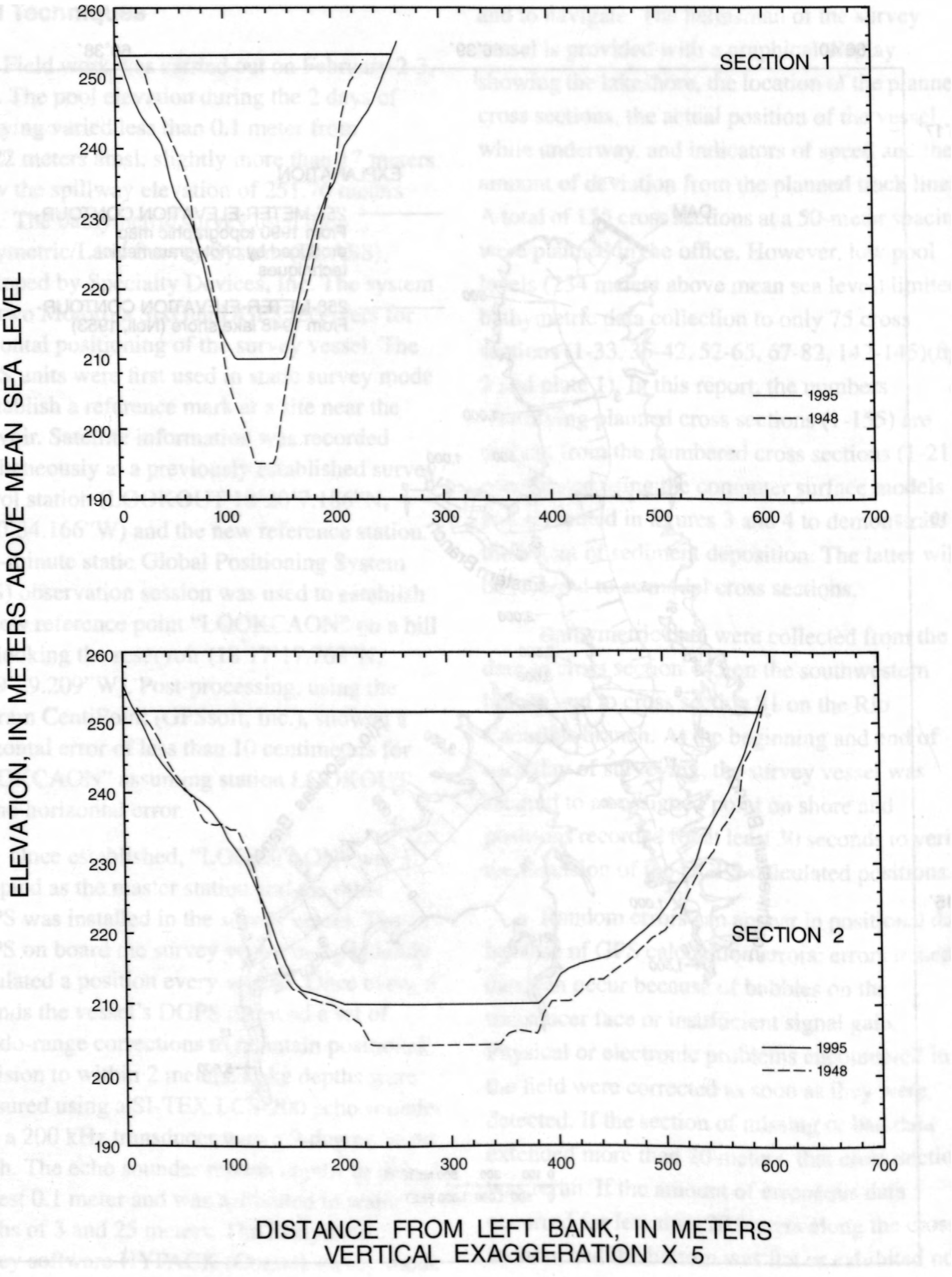

Figure 4. Cross sections generated from triangular irregular network surface model of Lago Caonillas, Puerto Rico, for 1948 and 1995. Lake surface is drawn at spillway elevation of 251.76 meters above mean sea level. Cross sections are oriented with viewer looking downstream.

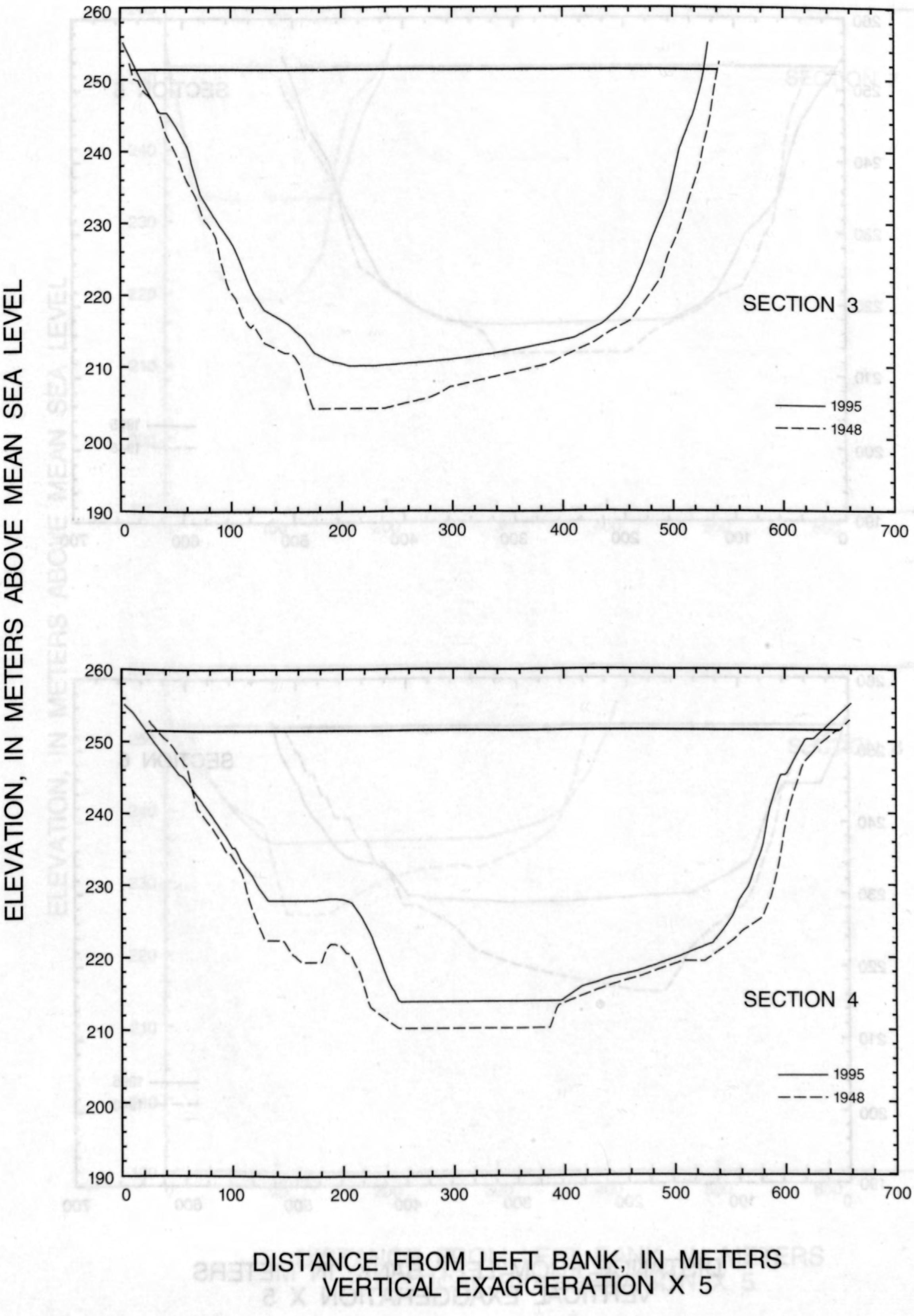

Figure 4. Cross sections generated from triangular irregular network surface model of Lago Caonillas, Puerto Rico, for 1948 and 1995--Continued.

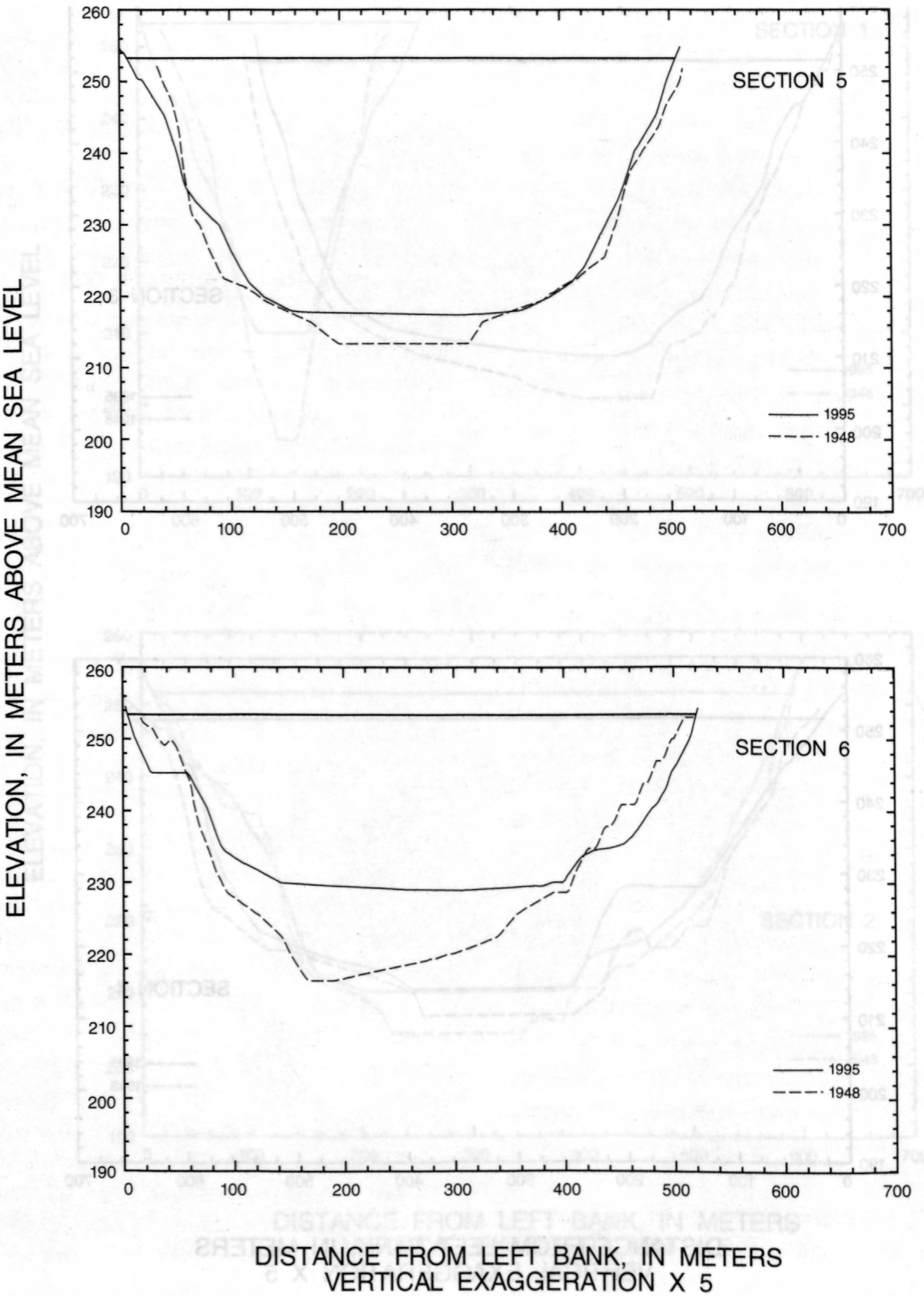

Figure 4. Cross sections generated from triangular irregular network surface model of Lago Caonillas, Puerto Rico, for 1948 and 1995--Continued.

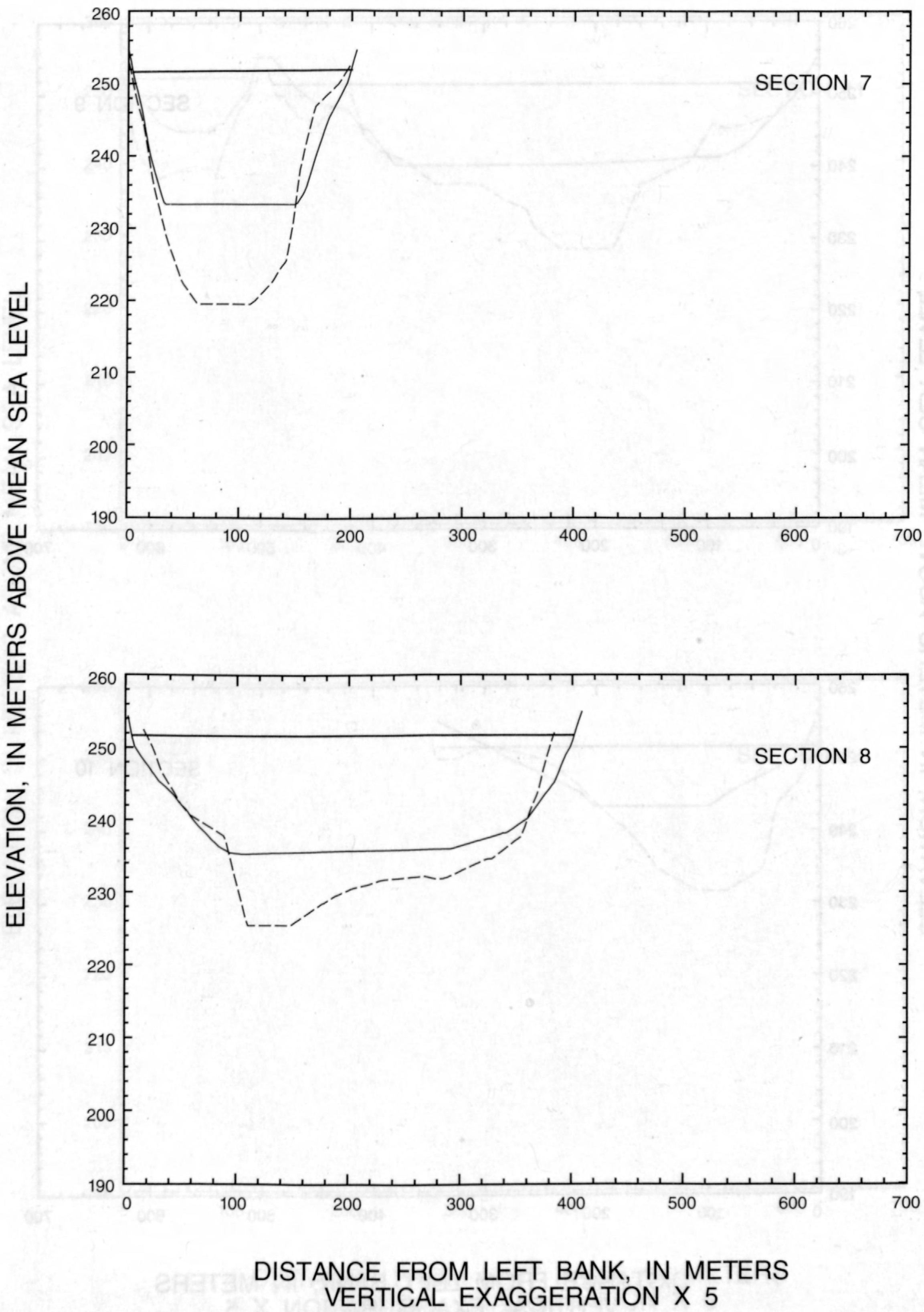

Figure 4. Cross sections generated from triangular irregular network surface model of Lago Caonillas, Puerto Rico, for 1948 and 1995--Continued.

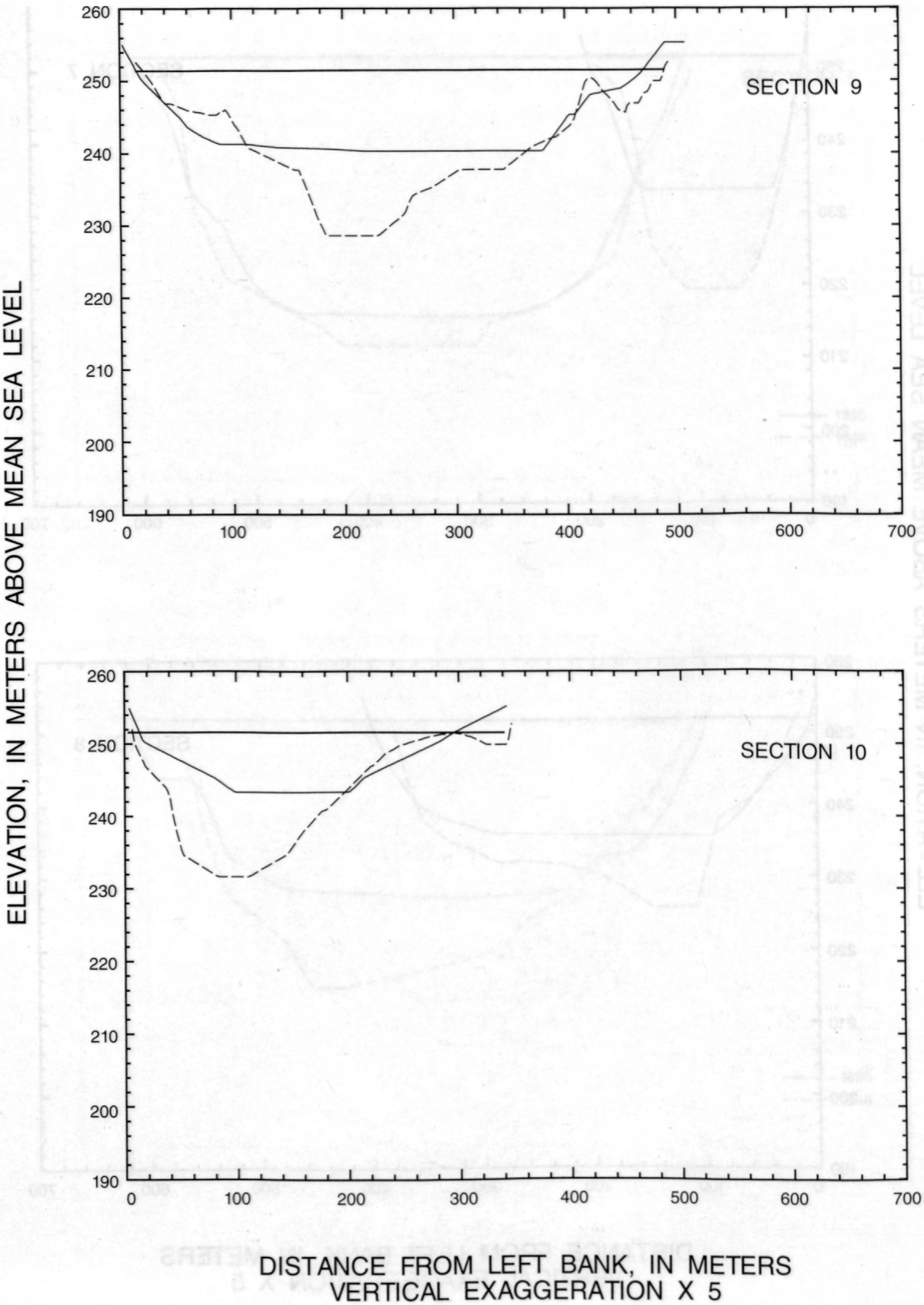

Figure 4. Cross sections generated from triangular irregular network surface model of Lago Caonillas, Puerto Rico, for 1948 and 1995--Continued.

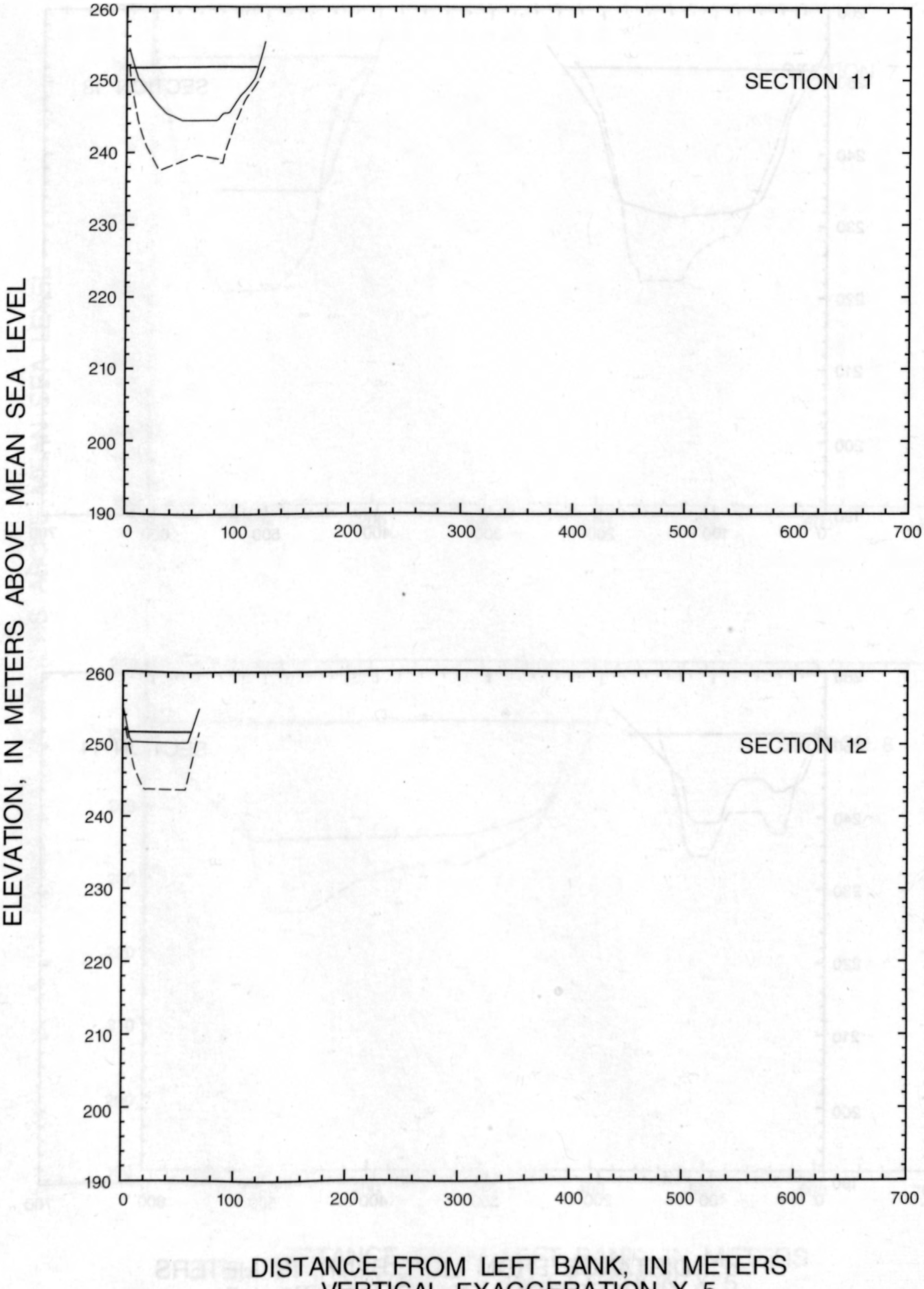

Figure 4. Cross sections generated from triangular irregular network surface model of Lago Caonillas, Puerto Rico, for 1948 and 1995--Continued.

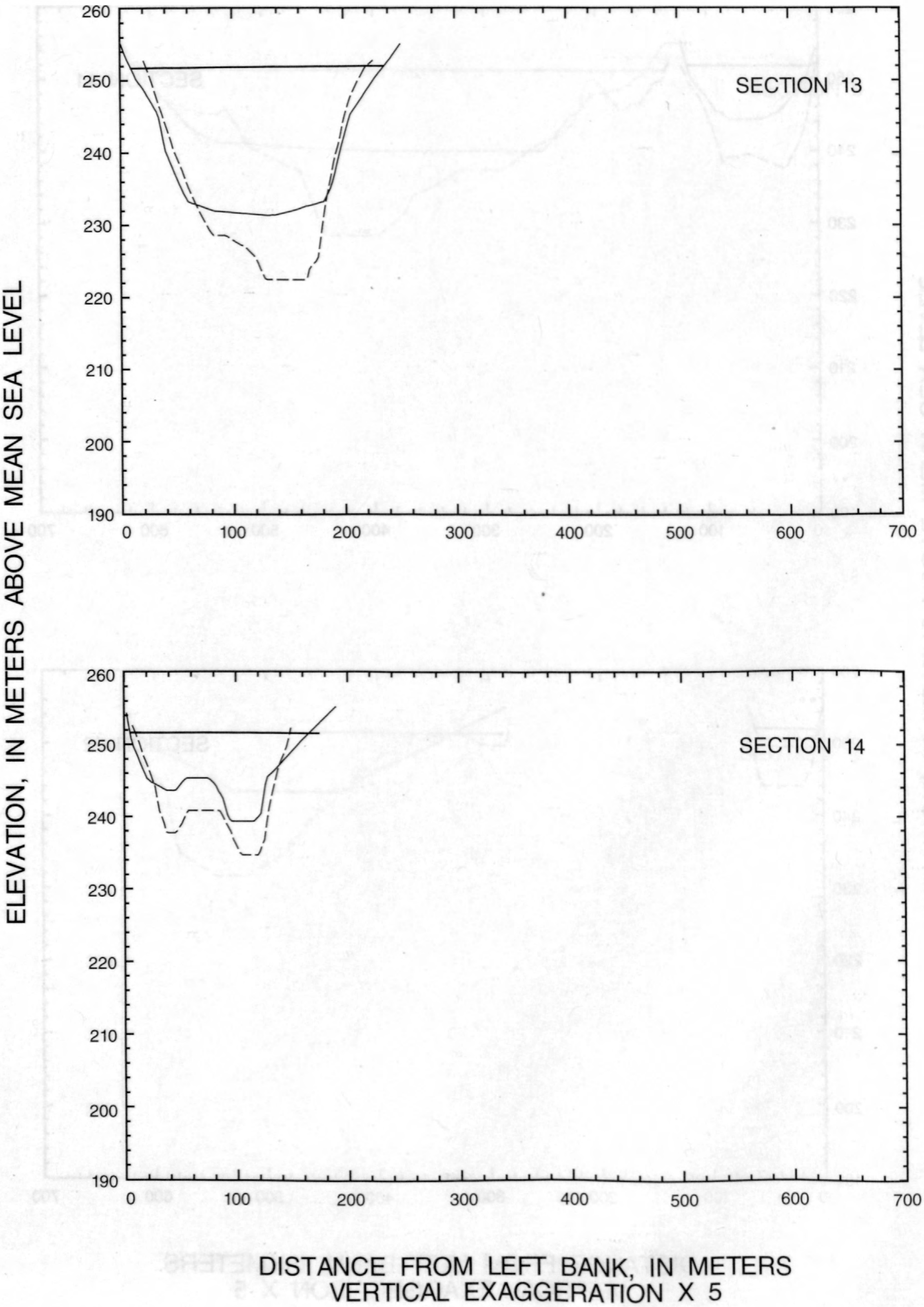

Figure 4. Cross sections generated from triangular irregular network surface model of Lago Caonillas, Puerto Rico, for 1948 and 1995--Continued.

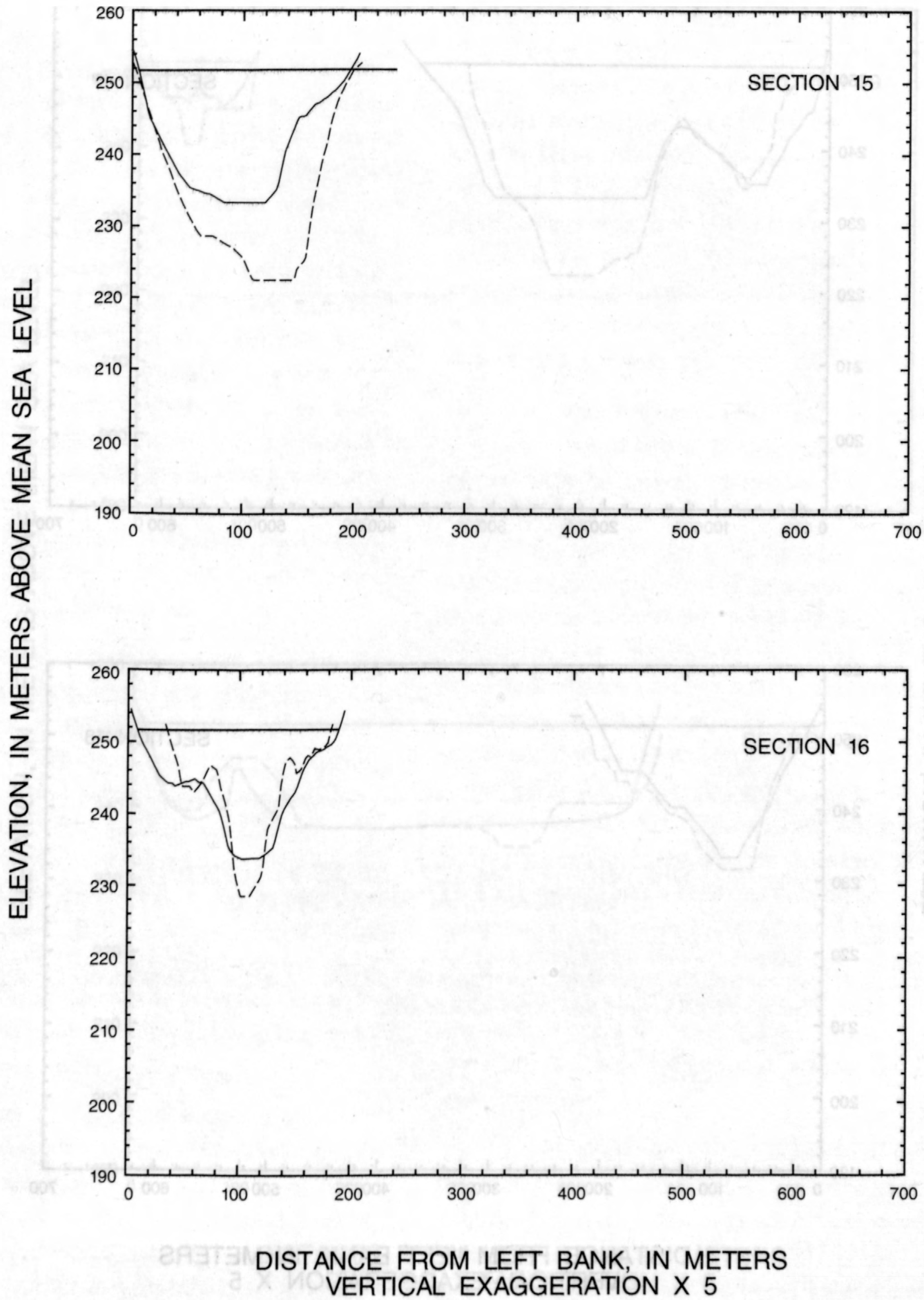

Figure 4. Cross sections generated from triangular irregular network surface model of Lago Caonillas, Puerto Rico, for 1948 and 1995--Continued.

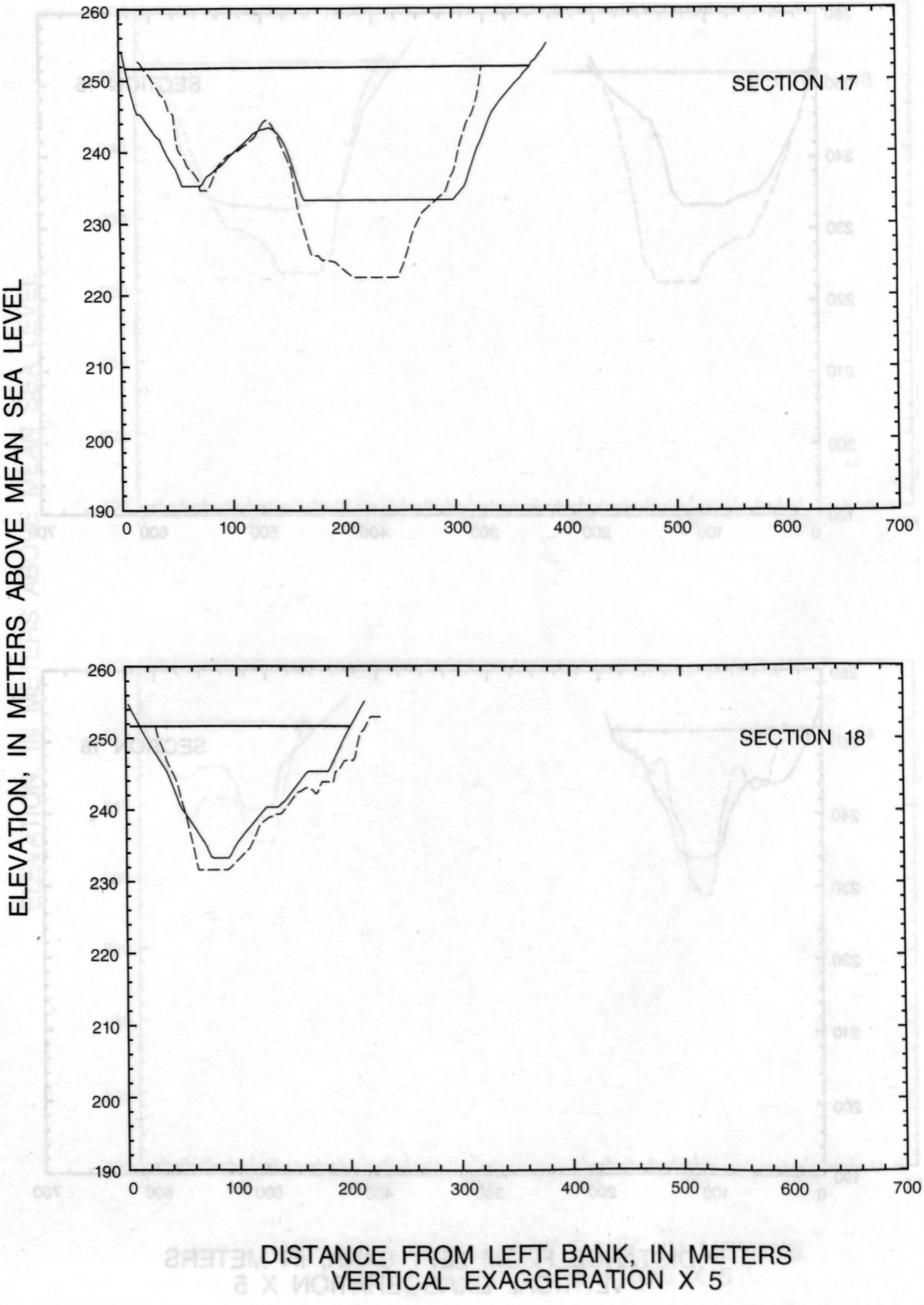

Figure 4. Cross sections generated from triangular irregular network surface model of Lago Caonillas, Puerto Rico, for 1948 and 1995--Continued.

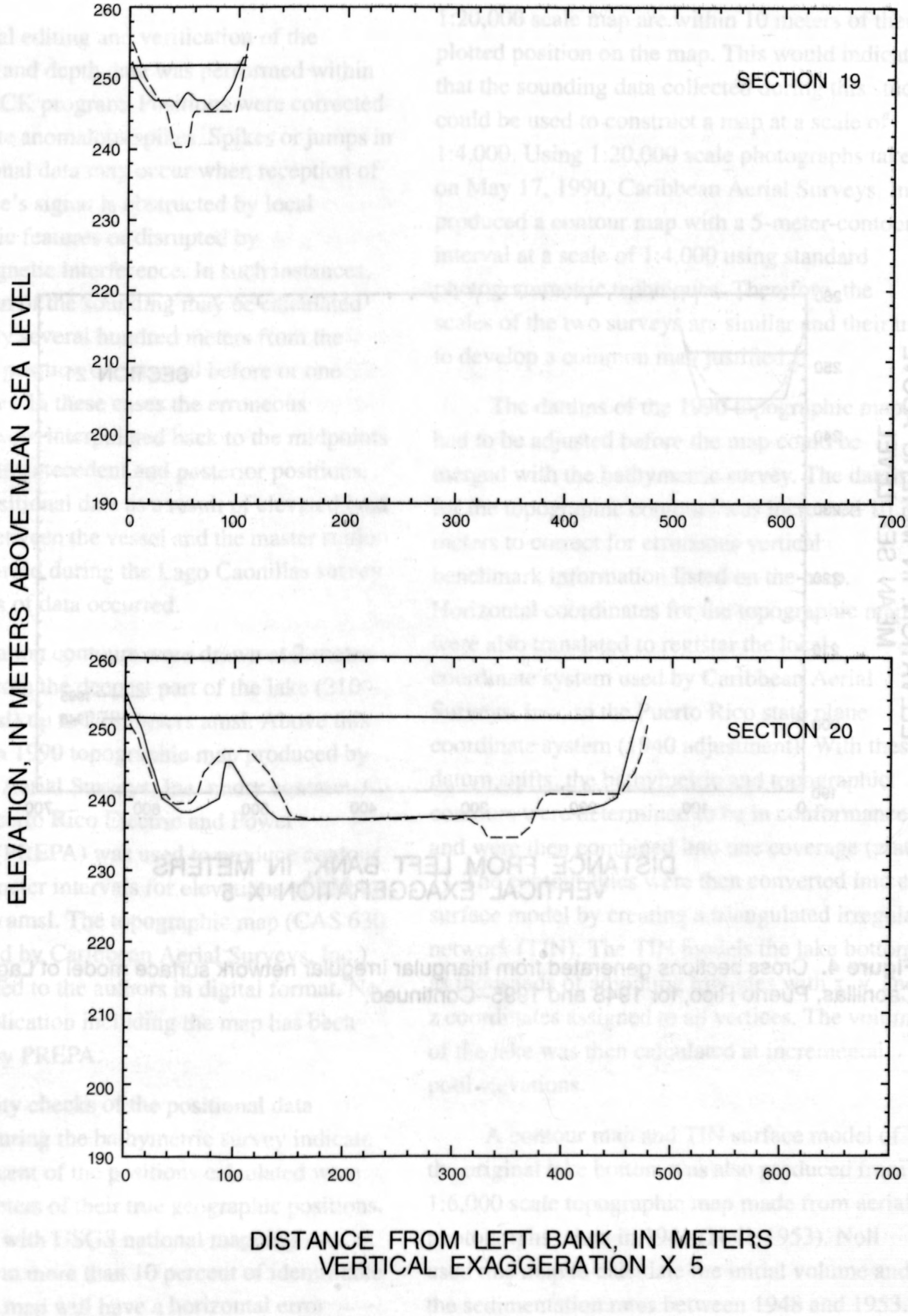

Figure 4. Cross sections generated from triangular irregular network surface model of Lago Caonillas, Puerto Rico, for 1948 and 1995--Continued.

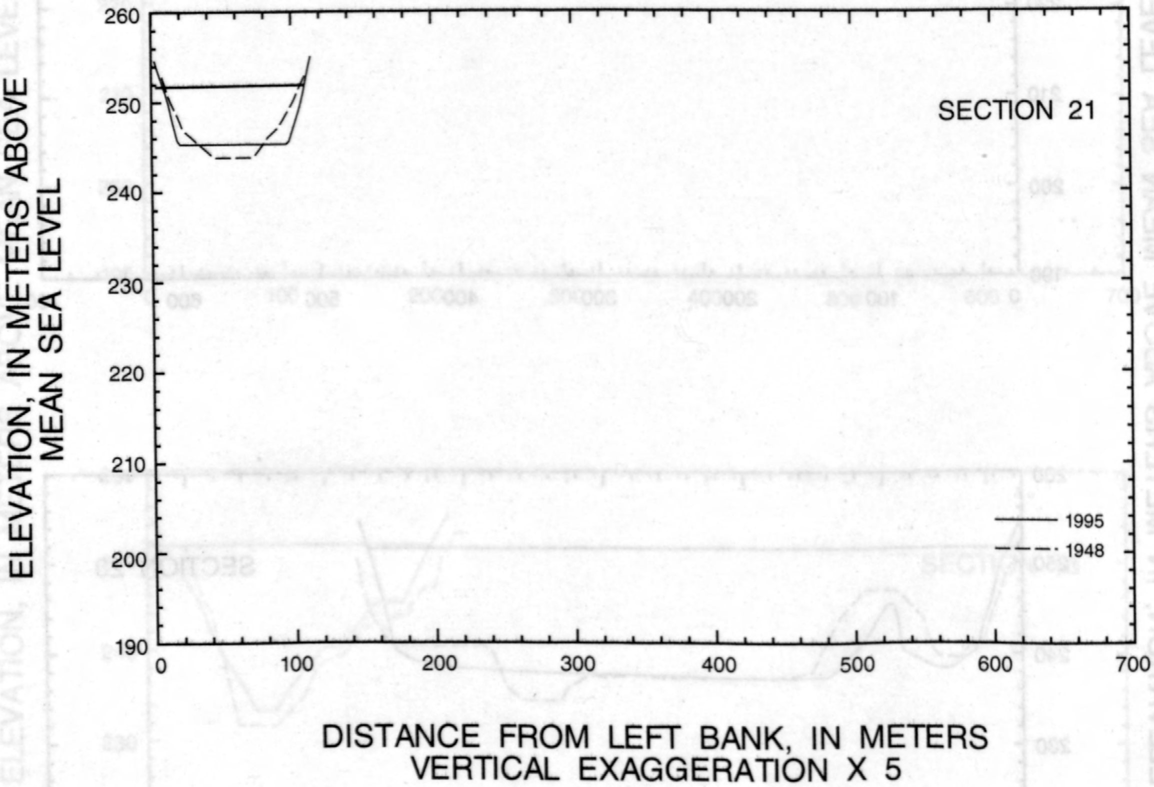

Figure 4. Cross sections generated from triangular irregular network surface model of Lago Caonillas, Puerto Rico, for 1948 and 1995--Continued.

Data Processing

Initial editing and verification of the positional and depth data was performed within the HYPACK program. Positions were corrected to eliminate anomalous spikes. Spikes or jumps in the positional data may occur when reception of the satellite's signal is obstructed by local topographic features or disrupted by electromagnetic interference. In such instances, the location of the sounding may be calculated erroneously several hundred meters from the calculated position one second before or one second after. In these cases the erroneous positions were interpolated back to the midpoints between the antecedent and posterior positions. Loss of positional data as a result of elevated land surfaces between the vessel and the master station never occurred during the Lago Caonillas survey and no loss of data occurred.

Elevation contours were drawn at 2-meter intervals from the deepest part of the lake (210 meters amsl) up to 228 meters amsl. Above this elevation, a 1990 topographic map produced by Caribbean Aerial Surveys, Inc. under contract with the Puerto Rico Electric and Power Authority (PREPA) was used to produce contour lines at 5-meter intervals for elevations of 230 to 255 meters amsl. The topographic map (CAS 630 as identified by Caribbean Aerial Surveys, Inc.) was provided to the authors in digital format. No formal publication including the map has been produced by PREPA.

Quality checks of the positional data collected during the bathymetric survey indicate that 90 percent of the positions calculated were within 2 meters of their true geographic positions. To comply with USGS national mapping standards, no more than 10 percent of identifiable points on a map will have a horizontal error greater than 0.5 mm translated by the map scale; for example, 90 percent of the points on a 1:20,000 scale map are within 10 meters of their plotted position on the map. This would indicate that the sounding data collected during this study could be used to construct a map at a scale of 1:4,000. Using 1:20,000 scale photographs taken on May 17, 1990, Caribbean Aerial Surveys, Inc. produced a contour map with a 5-meter-contour interval at a scale of 1:4,000 using standard photogrammetric techniques. Therefore, the scales of the two surveys are similar and their use to develop a common map justified.

The datums of the 1990 topographic map had to be adjusted before the map could be merged with the bathymetric survey. The datum for the topographic contours was increased 10.3 meters to correct for erroneous vertical benchmark information listed on the map. Horizontal coordinates for the topographic map were also translated to register the local coordinate system used by Caribbean Aerial Surveys, Inc., to the Puerto Rico state plane coordinate system (1940 adjustment). With these datum shifts, the bathymetric and topographic contours were determined to be in conformance and were then combined into one coverage (plate 1). The contour lines were then converted into a surface model by creating a triangulated irregular network (TIN). The TIN models the lake bottom as thousands of adjoining triangles with x, y, and z coordinates assigned to all vertices. The volume of the lake was then calculated at incremental pool elevations.

A contour map and TIN surface model of the original lake bottom was also produced from a 1:6,000 scale topographic map made from aerial photographs taken in 1941 (Noll, 1953). Noll used this map to calculate the initial volume and the sedimentation rates between 1948 and 1953. For purposes of this study, the 1948 lake bottom contours are assumed to be identical to that documented in the 1941 topographic map that depicted conditions before construction of the dam.

The resolution of the shorelines and contours of the 1948 topography is different than that of the 1990-95 bathymetric map. The original topography from 1948 had a contour interval of 10 feet (3.08 meters) for elevations of 630 feet (192.02 meters) to 830 feet (252.98 meters) amsl which corresponds to the maximum pool elevation in 1948. The 1990-95 bathymetry has a variable contour interval; from elevations of 210 to 230 meters amsl, the interval is 2 meters; from elevations of 230 to 255 meters amsl the contour interval is variable. Also the 1948 topography was apparently digitized from aerial photographs taken at a larger scale (1:10,000) than 1:20,000 scale photographs used by Caribbean Aerial Surveys as evidenced by the greater detail presented. The scale of the original aerial photographs used by SCS to create the 1:6,000 scale map was not stated in by Noll (1953) although he does state that 1:7,920 scale aerial photographs were used as a base for the soil conservation survey conducted as part of his study.

Model cross sections and longitudinal sections across the TINs were compared with the 1995 bathymetric data and the 1948 topographic map to verify that the model sections accurately reflect the lake bottom. The location of model cross sections and longitudinal sections across the TIN surface models are shown in figure 3. Because of uncertainty in the exact starting and end points, some cross sections in figure 4 were shifted either right or left to align up the salient geomorphic features of the channel cross sections. The distance between sampled elevations across the TIN was 2 meters for the model cross sections in figure 4 and 10 meters for the longitudinal sections presented in figure 5.

Using the TIN models the flooded area at the spillway elevation of 251.76 meters amsl was calculated to be 2.72 square kilometers for 1990-95 and 2.67 square kilometers for 1948, a difference of only 1.9 percent. This may reflect slumping or scouring of the reservoir banks exacerbated by regular drawdowns or may simply reflect differences in the precision of the surface models produced. The overall match between the original and current lake bottom is satisfactory for documenting how much sediment has deposited in the lake and in what areas.

The original volume (at an elevation of 252.98 meters amsl) was recalculated to be 58.95 million cubic meters using the TIN of the 1948 topography. Noll (1953) had calculated the original volume to be 61.88 million cubic meters, a difference of approximately 5 percent. Volume calculations can vary up to 10 percent for small reservoirs depending on the method and the quantity and orientation of the ranges (Heinemann and Dvorak, 1963). For this study, GIS algorithms were used to calculate volumes of the surface models represented by the 1948 and the 1990-95 contour maps (Environmental Systems Research Institute, Inc., 1992).

PREVIOUS SURVEYS

The SCS (Noll, 1953) used photographs from 1941 to produce a topographic map of the reservoir area as it was before the Caonillas dam was completed in 1948. Noll surveyed 21 cross sections in the reservoir in 1953 using a sounding line to calculate the sediments deposited since the dam's construction in 1948. In October 1952, contemporaneous with Noll's survey, the Caonillas Extension Project was completed.

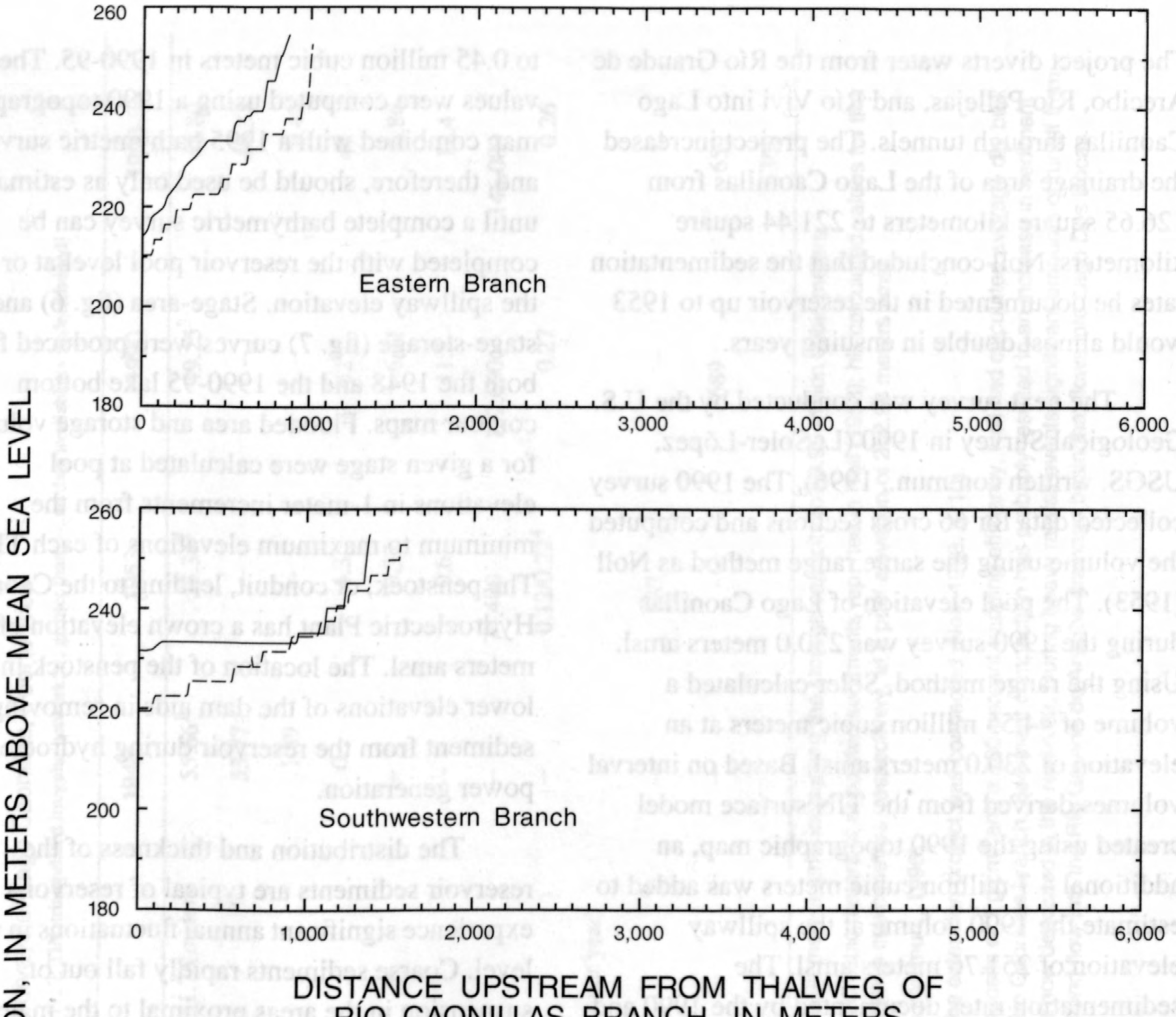

Figure 5. Longitudinal sections showing depositional patterns in three branches of Lago Caonillas, Puerto Rico. Section locations shown in figure 3.

The project diverts water from the Río Grande de Arecibo, Río Pellejas, and Río Vivi into Lago Caonillas through tunnels. The project increased the drainage area of the Lago Caonillas from 126.65 square kilometers to 221.44 square kilometers. Noll concluded that the sedimentation rates he documented in the reservoir up to 1953 would almost double in ensuing years.

The next survey was conducted by the U.S. Geological Survey in 1990 (L. Soler-López, USGS, written commun., 1996). The 1990 survey collected data for 66 cross sections and computed the volume using the same range method as Noll (1953). The pool elevation of Lago Caonillas during the 1990 survey was 230.0 meters amsl. Using the range method, Soler calculated a volume of 44.55 million cubic meters at an elevation of 230.0 meters amsl. Based on interval volumes derived from the TIN surface model created using the 1990 topographic map, an additional 4.7 million cubic meters was added to estimate the 1990 volume at the spillway elevation of 251.76 meters amsl. The sedimentation rates documented by the 1990 and the current survey verify that sedimentation rates doubled after the Caonillas Extension Project was completed. Results of the prior and current sedimentation surveys of Lago Caonillas are compared in table 2.

ACTUAL CAPACITY AND SEDIMENT ACCUMULATION

The actual capacity of Lago Caonillas was computed to be 48.8 million cubic meters. Dead storage, that volume below an elevation of 213 meters amsl, has decreased from 1.89 million cubic meters when the reservoir was filled in 1948 to 0.45 million cubic meters in 1990-95. These values were computed using a 1990 topographic map combined with a 1995 bathymetric survey and, therefore, should be used only as estimates until a complete bathymetric survey can be completed with the reservoir pool level at or near the spillway elevation. Stage-area (fig. 6) and stage-storage (fig. 7) curves were produced for both the 1948 and the 1990-95 lake bottom contour maps. Flooded area and storage volume for a given stage were calculated at pool elevations in 1-meter increments from the minimum to maximum elevations of each TIN. The penstock, or conduit, leading to the Caonillas Hydroelectric Plant has a crown elevation of 213 meters amsl. The location of the penstock in the lower elevations of the dam aids in removing sediment from the reservoir during hydroelectric power generation.

The distribution and thickness of the reservoir sediments are typical of reservoirs that experience significant annual fluctuations in water level. Coarse sediments rapidly fall out of suspension in the areas proximal to the major tributaries, whereas fine sediments remain in suspension for much longer times and finally settle out in blankets of finer material in the deeper sections of the reservoir. These two depositional zones are evident in the longitudinal profile from the dam to the Río Caonillas (fig. 5) and in a graph showing the amount of sediments deposited in each 1-meter interval from the deepest to the shallowest parts of the reservoir (fig. 8). The regular drawdowns of the reservoir remobilize the deltaic material, moving it farther into the reservoir than would be expected if the pool was maintained at a constant level near the spillway elevation.

Table 2. Comparison of prior and current sedimentation surveys of Lago Caonillas, Puerto Rico

[Elevation in meters above mean sea level, National Geodetic Vertical Datum 1929; TIN, triangulated irregular network; >; greater than; --, no data available or undetermined]

	1948	1953	1990	1990-95
Capacity (million of cubic meters) at spillway elevation of 251.76 meters	55.66[1]	55.34[2]	49.25[3]	48.80
Live storage (above penstock crown elevation of 213 meters)	53.77	--	--	48.35
Dead storage (below penstock crown elevation 213 meters)	1.89	--	--	0.45
Years since construction	0	4.3	42	47
Sediment accumulated (millions of cubic meters)	--	0.32	6.41	6.86
Storage loss (percent)	--	0.6	11.5	12.4
Annual loss of capacity (cubic meters)	--	74,400	152,600	146,000
Annual loss of capacity (percent)	--	0.12/0.22[4]	0.27	0.26
Sediment yield from basin[5] (megagrams per square kilometer per year)				
Using a 126.65-square kilometer basin (not including Río Grande de Arecibo diversion)	--	587	--	--
Using a 221.44-square kilometer basin (with Río Grande de Arecibo diversion)	--	--	689	659
Years until reservoir is filled with sediment	--			>300

[1] Originally flashboards were installed to an elevation of 252.98 meters amsl increasing the storage capacity to 58.95 million cubic meters.

[2] Recalculated here to account for the approximately 320,000 cubic meters of deposited sediments reported in Noll (1953); his calculated values for the 1948 and 1953 reservoir capacity were 61.86 and 61.55 million cubic meters, respectively, at a pool elevation of 252.98 meters amsl.

[3] Unpublished 1990 survey (L. Soler-López, USGS, written commun., 1996)

[4] Actual/predicted once the additional drainage area from the extension project was connected (Noll, 1953, p. 10).

[5] Assuming a dry bulk density for the reservoir sediment deposits of 1 g/cm^3 and a 100 percent trapping efficiency. Noll had calculated average dry bulk density of 0.49 g/cm^3 for 31 samples collected from the Río Caonillas branch. Sediment compaction has probably resulted in an increase in sediment density closer to 1 g/cm^3 for the majority of the sediments now deposited in the reservoir. During heavy rainfall events significant amounts of runoff from the extension area may spill over the diversion structures and flow into the Río Grande de Arecibo drainage basin that flows into Lago Dos Bocas.

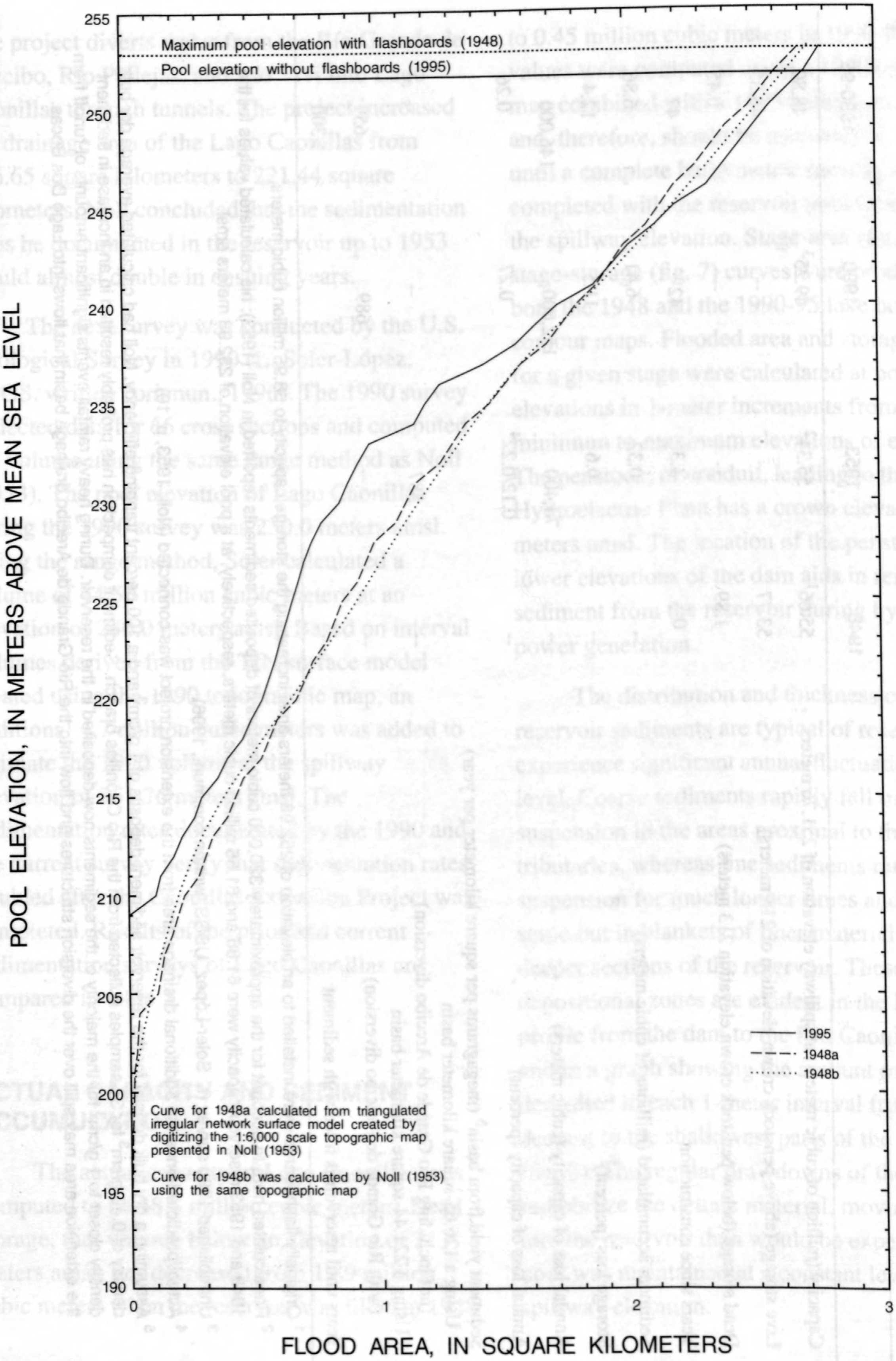

Figure 6. Relation between pool elevation and flooded area derived from triangulated irregular network surface models of Lago Caonillas, Puerto Rico.

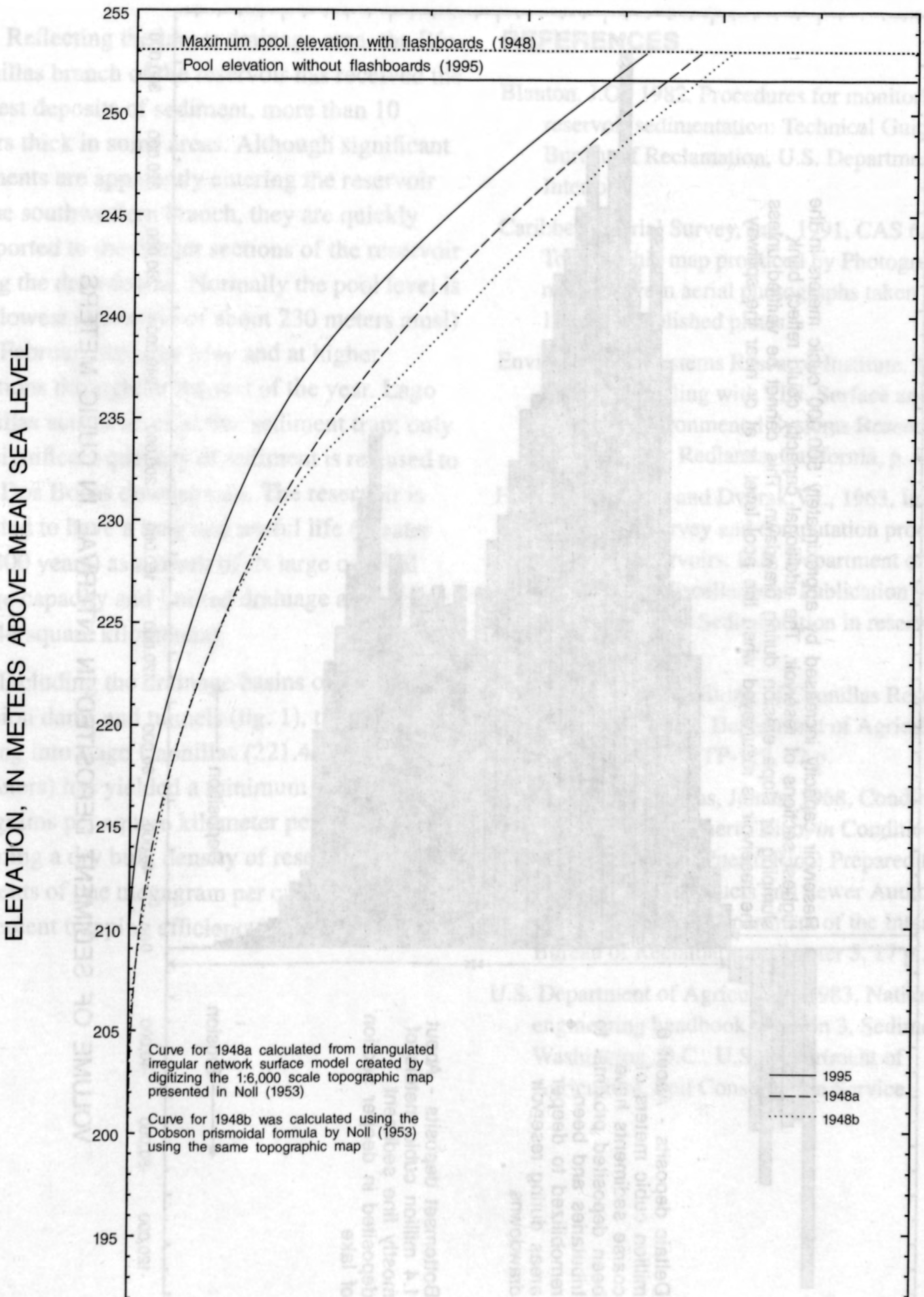

Figure 7. Relation between pool elevation and volume derived from triangulated irregular network surface models of Lago Caonillas, Puerto Rico.

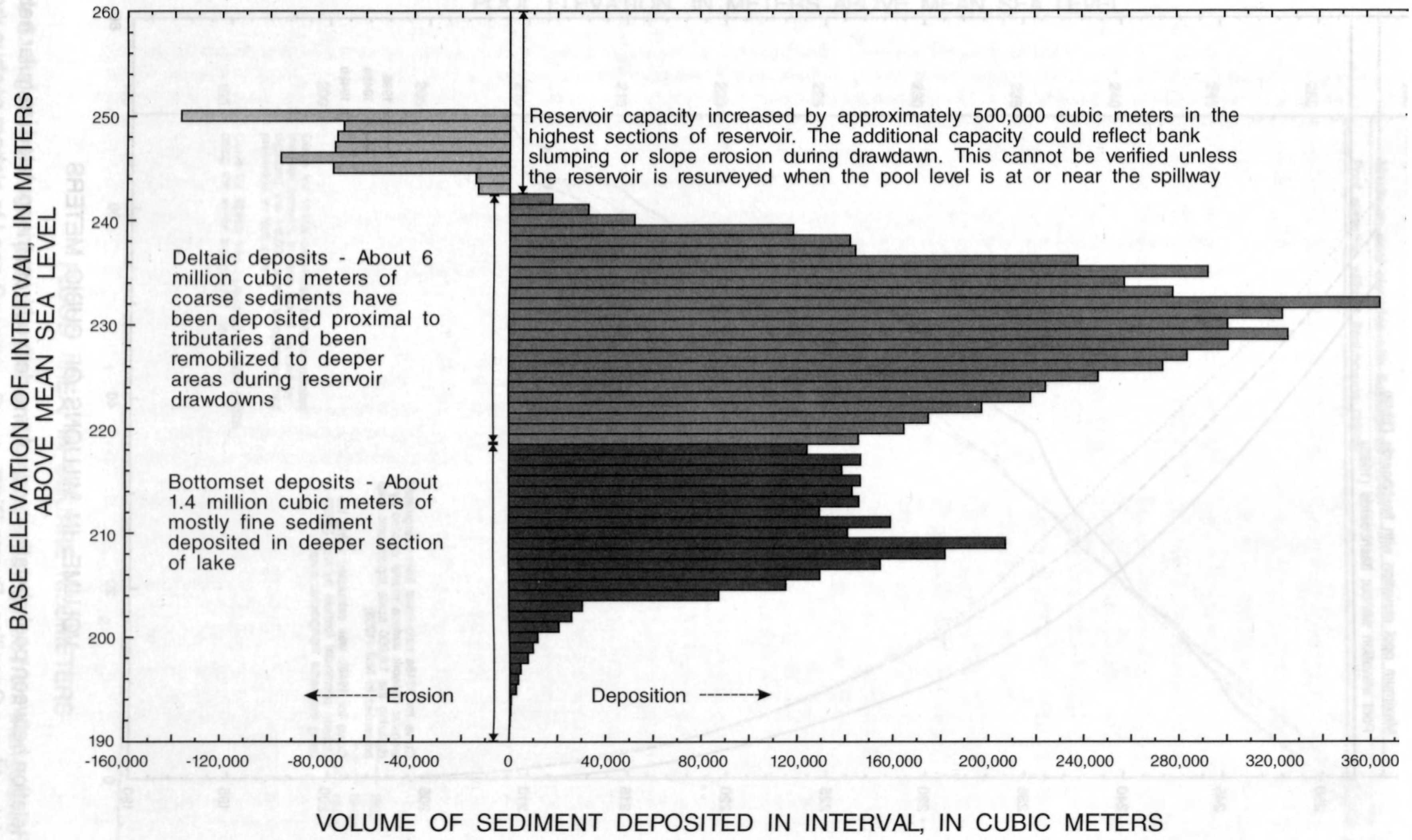

Figure 8. Volume of sediments deposited in Lago Coanillas, Puerto Rico, from 1948 to 1995 by 1-meter vertical segments.

Reflecting the larger drainage area, the Río Caonillas branch of the reservoir has received the thickest deposits of sediment, more than 10 meters thick in some areas. Although significant sediments are apparently entering the reservoir via the southwestern branch, they are quickly transported to the deeper sections of the reservoir during the drawdowns. Normally the pool level is at its lowest (elevation of about 230 meters amsl) from February through May and at higher elevations throughout the rest of the year. Lago Caonillas acts as an effective sediment trap; only an insignificant quantity of sediment is released to Lago Dos Bocas downstream. The reservoir is expected to have a long and useful life (greater than 300 years) as a result of its large original storage capacity and limited drainage area (221.44 square kilometers).

Including the drainage basins of the diversion dams and tunnels (fig. 1), the area draining into Lago Caonillas (221.44 square kilometers) has yielded a minimum of 659 megagrams per square kilometer per year (assuming a dry bulk density of reservoir sediments of one megagram per cubic meter and a 100 percent trapping efficiency).

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